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MULTI-TEMPORAL ASSESSMENT OF SELECTIVE
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# MULTI-TEMPORAL ASSESSMENT OF SELECTIVE LOGGING USING REMOTELY SENSED DATA IN THE BRAZILIAN AMAZON

By

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# ABSTRACT


MULTI-TEMPORAL ASSESSMENT OF SELECTIVE LOGGING USING REMOTELY SENSED DATA IN THE BRAZILIAN AMAZON

By

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Deforestation in tropical forests and its consequences on global climate change have been monitored using remotely sensed data. Most of the currently available land cover maps show only those sites where trees have been completely removed. Just a few attempts to detect forest areas where trees were partially removed, as in the case of selective logging, have been done. This study assesses forest impacts by selective logging and extend current multi-annual Amazon-wide land use classification to include selectively logged forests in addition to the more frequently used thematic classes (forest, deforestation, regrowth, cerrado, and water body). Remotely sensed data combined with field studies, Geographic Information Systems (GIS), and related techniques were applied in this research. This is the first multi-temporal assessment of selective logging in the Brazilian Amazon in which I estimated that at least 5980, 10064, and 26085 $Km^2$ of forest had been logged by 1992, 1996, and 1999, respectively. I also estimated that at least 3689, 5107, and 11638 $Km^2$ had been actively logged in 1992, 1996, and 1999, respectively. Finally, I found that at around of 10% of former logging areas detected in between 1992 and 1996 was revisited or logged again in 1999. I also observed that 13% of logged forests in 1992 were deforested by 1996, an additional 15% by 1999, and 11% of forests logged in 1996 were deforested by 1999.

## DEDICATION

This thesis is dedicated to my wife (Cleusa), my daughters (Camila and Marcela), and my parents (Mauro and Adelina) for their infinite love, and for their unconditional and continual encouragement in completing my Masters degree.

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# CHAPTER I

## Problem Statement

In the past four decades tropical forests in the Brazilian Amazon have been intensively deforested and selectively logged. Remote sensing techniques have been successfully applied to monitor areas where forests were converted to agriculture, pasture, or urbanization. Selectively logged forest areas have not been included in current deforestation estimates in the Brazilian Amazon because they are not easily detectable using unsupervised classification. Nevertheless, some attempts to quantify the area of selective logging have been conducted in the Brazilian Amazon, resulting in indirect estimation of areas where forests have been partially damaged by selective logging and not completely removed as in the case of deforestation. Those estimates of selectively logged forest in the Brazilian Amazon have raised questions: Is selective logging a significant disturbance in terms of area increment of total forest cleared or damaged? Can we efficiently measure it basin-wide as a form of degradation in addition to outright deforestation? Is logging causing more deforestation than would otherwise occur? These questions are addressed in this research.

### 1.1. Statement of Purpose

The Brazilian Amazon has been increasingly exposed to deforestation (Skole and Tucker 1993, Houghton et al. 2000, Achard et al 2003, INPE 2003), forest fire (Holdsworth and Uhl 1997, Uhl 1998, Cochrane 2003, Cochrane 2001, Cochrane 2002), and to selective logging (Stone and Lefebvre 1998, Nepstad et al. 1999, Souza and Barreto 2000). Recent estimate is that up to 11.7% of the tropical forest of the Brazilian

Amazon have been deforested by 2001 (INPE, 2003). Forest fires annually burn thousands of square kilometers of standing tropical moist forests in Amazonia, which become more susceptible to recurrent and more severe fire (Cochrane and Schulze, 1998). Up to 413 million cubic meters of round wood were logged from 1990 to 2002 in the Brazilian Amazon (IBGE, 2003).

The purpose of this study is to assess the extent of forest affected by selective logging in the Brazilian Amazon through a multi-temporal analysis using remotely sensed data, geographic information systems, remote sensing techniques, fieldwork observations and measurements.

Forest areas impacted by selective logging are likely to be rapidly increasing, making it a land use of growing concern in the Brazilian Amazon (Stone and Lefebvre 1998, Nepstad et al. 1999, Alvarado and Sandberg 2001). In this study, I exam how effectively selective logging can be detected and quantified both locally and basin-wide using remote sensing techniques.

## 1.2. Background

The Brazilian Amazon region contains 40% of the world's remaining tropical rainforests and it assumes an important role in maintaining biodiversity, regional hydrology and climate (Fearnside 1999), and terrestrial carbon storage (Fearnside 1999, Houghton et al. 2000).

Satellite-based remote sensing has been used for many years to monitor and evaluate land cover change in the Amazon, concentrating on forest and deforested land evaluation (Fearnside et al. 1990, Skole and Tucker 1993). Data from these studies, such as the rate of deforestation in Brazil's Legal Amazon, are often used to estimate human effects on the global carbon cycle (Fearnside 1997, Houghton 1997). However, the deforestation estimates for Brazilian Amazon have been detecting less than half of the total area of damaged or impoverished forest each year. Most of those non-detected areas are related to forest degradation by selective logging and fire (Nepstad et al. 1999).

The impacts caused by logging in tropical forests are considered significant in terms of forest degradation and fire susceptibility (Stone and Lefebvre 1998, Nepstad et al. 1999, Souza and Barreto 2000). Fearnside (1997) estimated that in the Brazilian Amazon impacts by selective logging in undisturbed forest create a net carbon flux equal to approximately 4-7% of the annual carbon released from deforestation. Therefore, the carbon flux estimates for the Amazon region may be low because of the increasing logging areas that have not been accounted for (Nepstad et al. 1999).

Selective logging concepts, its socio-economical implications, and consequences on the carbon cycle, forest fragmentation, and biodiversity as well as previous work to detect selective logging using remotely sensed data, are presented as following.

### 1.2.1. Selective Logging Concepts

The term selective logging is used to define timber extraction of a select group of tree species, usually the more economically valuable trees (Verissimo et al. 1995, Uhl et al. 1997). Unlikely deforestation, selective logging activities do not clear-cut and burn forests, but harvests a portion of trees. Though less significant than clear-cutting, selective logging can damage a large portion of forest and many others trees during logging operations (Uhl et al. 1991, Verissimo et al. 1992, Pinard and Putz 1996, Uhl et al. 1997, Huth and Ditzer 2001). Using traditional techniques, the harvesting of a single tree can directly result in the death of thirteen other trees as result of the tree felling direction and logging operations such as opening up of trails, roads, and log storage patios (Veríssimo et al. 1992).

Recent reports suggest that selective logging activities have been occurring in Brazil's tropical forests for several years (Stone and Lefebvre 1998, Nepstad et al 1999, Alvarado and Sandberg 2001). Traditionally, these activities have been restricted to flood plains (*várzeas*) due to the easy access through the rivers (fluvial transportation) in areas annually inundated. However, the road network expansion during 1960s and 1970s in the Brazilian Amazon may have permitted the expansion of selective logging to the interfluvial (*terra firme*) forest (Uhl and Vieira 1989, Uhl et al. 1997).

Based on these observations, selective logging can be characterized in terms of its spatial distribution and intensity. Spatially, selective logging occurs in 'várzea' and 'terra firme' forest in the Brazilian Amazon. Both 'várzea' and 'terra firme' selective logging vary in terms of its intensity (low, moderate, and high), depending on the volume and number of harvested trees (Uhl et al. 1997). Low impact logging (highly selective logging) removes as few as one or two high value tree species per hectare, as is the case when harvesting for Virola (*Virola surinamensis* (Rol.) Warb ) and Mahogany (*Swietenia macrophylla*, King) (Veríssimo et al. 1995, Uhl et al. 1997). High impact logging removes 100 or more species per hectare, which occurs highly managed logging regions of the Amazon basin (Uhl et al. 1997).

Uhl et al. (1997) have also described a form of logging referred to as forest 'mining', a practice which impoverishes an intact forest over 30 years through a sequence of progressively more intensive logging, leading to forest degradation or, in some cases, outright deforestation.

### 1.2.2. Impacts of Selective Logging

Selective logging leaves behind a mixed landscape of intact forest, tree fall gaps, road openings, log-loading patios, and damaged forest. It also results in large amount of dead slash or dried biomass which enhances fuel load and forest fire susceptibility (Uhl and Buschbacher 1985, Stone and Lefebvre 1998, Nepstad et al. 1999, Souza and Barreto 2000). Moreover, as many as 40% of the remaining standing trees are killed or severely damaged during logging operations (Uhl et al. 1991). These impacts can be devastating even when a small volume of timber is harvested (Frumhoff, 1995).

#### 1.2.2.1. Impacts on Carbon Cycle

The balance of net carbon flux is the balance between areas undergoing declining C-stock and areas of increasing C-stock during vegetation growth (Palm et al. 1986, Houghton 1996, Houghton 1998, Houghton et al 2000). Rates of land use are used to estimate the annual flux of carbon between terrestrial ecosystems and atmosphere. Undisturbed areas are considered to have no net carbon flux (Palm et al. 1986, Houghton 1998). Therefore, tropical deforestation as result from suite of social and economic pressure on natural resources (Skole et al. 1994), is a major component of the carbon cycle (Palm et al. 1986, Houghton 1996, Houghton 1998, Houghton et al 2000).

Carbon is released to the atmosphere following deforestation and logging through immediate oxidation of organic matter by burning and long-term oxidation through decomposition (Houghton 1998, Houghton et al. 2000). The highest carbon losses occur when high biomass forest areas are converted to low biomass systems such as pasture or agriculture (Palm et al. 1986, Houghton 1996, Houghton 1998). If tree planting or regeneration occurs in a cleared area, there is an initial loss of carbon followed by a gradual accumulation of carbon (Palm et al. 2000).

However, uncertainties in estimates of forest biomass (Houghton et al., 2001) and land use change (Achard et al. 2002) are responsible for current uncertainty in estimates of carbon flux in Amazônia, the most important region of carbon emissions. Indeed, Skole et al. (1994) affirmed that estimates of deforestation in tropical forests is a research challenge because of the geographic extent, spatial pattern, lack of accurate measurements, and its causes. Kauffman and Cummings (1995) also stated the lack of information from quantitative sources for estimating biomass loss by combustion processes.

Using rates of land use change for the period 1850 to 1990, Houghton (1998) estimated that 108 x $10^{15}$gC were released from forests to the atmosphere of which 67% was from tropical forest clearing and 33% from Boreal and temperate forest clearing. The estimate of annual net carbon flux in the 1980s was an average of approximately 2.0 x $10^{15}$gC year$^{-1}$, most of it from changes in land use in tropical regions. Recently, Achard et al. (2002) based on updated and more accurate remotely sensed information, presented a new estimates for the total global carbon emission from land use changes for the 1990s of about 0.8 to 2.4 x $10^{15}$gC yr$^{-1}$.

DeFries et al. (2002) based on remote-sensing data and a terrestrial carbon model, estimated that net mean carbon fluxes for the 1980s and 1990s from tropical deforestation and regrowth is 0.6 and 0.9 x $10^{15}$gC $yr^{-1}$, respectively. More specifically, Houghton et al (2000) based on the annual rates of deforestation and spatial distribution of biomass, deforestation and land cover changes, estimated that the Brazilian Amazon alone was a source for about 0.2 x $10^{15}$gC $yr^{-1}$ over the period 1989-1998.

In addition to outright deforestation, Amazonian forests are increasingly being exposed to logging activities (Uhl et al. 1997, Stone and Lefebvre 1998, Nepstad et al. 1999, Souza and Barreto 2000). These activities modify, at least temporally, the carbon storage in the forest (Houghton, 1998) and its impacts, yet not included in the land use classification, may add 4-7% to this carbon flux estimate. Forest fires may double the carbon flux amounts in years following drought (Nepstad et al. 1999).

The impacts of selective logging vary considerably with extraction intensity, but in worst cases the impacts can be significant in area and amount of biomass removed. Selectively logged forests 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 1995). These forests become highly degraded and may have 40 – 50% of the canopy cover destroyed during these repeated logging operations (Uhl and Vieira 1989, Veríssimo et al. 1992).

Forests heavily impacted by repeated selective logging become more susceptible to fire (Holdsworth and Uhl 1997, Cochrane 1999) and, if they burn, will contribute more emissions of carbon to the atmosphere than areas which area logged only once (Houghton, 1997). This emission of carbon can vary from 7.5 to 7 x 10 MgC $ha^{-1}$ depending on what previously happened in terms of land use and fire (Cochrane et al., 1999). Combined, selective logging and fire degrade forest structure, creating different land cover types characterized between natural forest and deforested areas (Gerwing, 2000).

#### 1.2.2.2. Forest Fire Susceptibility

The spread of forest fires in closed tropical forest is a growing problem ( Uhl and Buschbacher, 1985). The consequences of wildfire are devastating for tropical forests because their thin bark makes them naturally low in resistance to fire (Uhl and Kauffamn, 1990). Both anthropogenic and natural forest disturbances can increase forest fire susceptibility in the tropics by damaging canopies and, consequently, decreasing forest moisture content (Cochrane, 2002).

In the tropical forest, fire possibility and intensity increase as the forest becomes more fragmented through selective logging. The increase boundaries between forest and deforested areas are more exposed to agricultural practices, which use fire for land maintenance and weed control by clearing woody debris (Uhl and Buschbacher, 1985). Indeed, agricultural plots in the Brazilian Amazon are the main ignition source for fires (Uhl and Buschbacher 1985, Uhl and Kauffman 1990, Cochrane 2001).

Once burned for the first time, chances of recurring fire and intensity due to increased fuel loads and drier microclimate in the interior of the forest (Cochrane and Shulze, 1998). This fire sequence can rapidly degrade forest areas by destroying their structure and composition, creating a new land cover type more similar to secondary regrowth than to tropical forest (Gerwin, 2000).

Cochrane et al. (1999) conducted field studies and a multitemporal analysis of remotely sensed imagery to understand forest fire dynamics in a case study at Tailândia municipality in the State of Para. They established two sites of undisturbed forest as control areas, and eight sites of fire disturbed forests for field observations and measurements in 1996. They measured the rate of fire spread, fire recurrence, tree mortality, biomass combustion levels, and fire characteristics (flame heights and depths).

Based on these studies Cochrane et al. (1999) observed that the first fires within undisturbed forest are low intensity fire, which moves slowly along the ground and burns only dry leaf litter. This type of fire kills mostly trees less than thirty centimeters of dbh (diameter of breast height). The second instance of fire is faster and more intense, drastically increasing mortality of large trees. Only large, thicker barked tree may survive. Tree mortality occurred up to two years after the second fire and possibly longer.

Uhl and Kauffman (1990) studied potential for sustained fire events within different land cover types (undisturbed forest, selectively logged forest, secondary regrowth, and pasture) at Vitora ranch in Paragominas municipally of the Amazon state of Para. In this research, fuel availability, microclimate, and rates of fuel moisture loss were measured. The authors concluded that selectively logged forests are more susceptible to fire because of the high fuel mass and special conditions for rapid fuel drying created by logging activities. Specifically, the authors found that selective logging significantly increased fuel mass (180 Mg/ha) compared with other land cover types. They observed that harvesting 50 $m^3$ $ha^{-1}$ of round wood will result in 150 $m^3$ $ha^{-1}$ of woody debris or fuel for potential fires. They also observed that logged forest were susceptible to fire after 5-6 rainless days during the dry season.

Holdsworth and Uhl (1997) conducted studies of fire impacts upon structure and composition of selectively logged forests at two sites located in the municipality of Paragominas in the Amazon state of Para. They observed that fire in logged forest causes serious damages to forest structure and composition and contributes to additional forest fragmentation. Even with low-impact selective logging, which showed reduced flammability compared with high-impact logging, there was a risk for fire because adjacent areas of agricultural lands are a frequent source of fire ignition.

### 1.2.2.3. Biodiversity

Upper Amazonian[1] forests are considered to be some of the most biologically diverse biomes in the world (Gentry, 1988). Although only a few valuable tree species are harvested during selective logging, high intensity logging can have significant impact to the entire forest ecosystem (Frumhoff, 1995) damaging nearby trees and soils (Uhl and Vieira 1985, Johns et al 1996) and increasing the risk of local species extirpation (Martini et al, 1994). Furthermore, hunters will have easier access to internal forests through the road network created by logging operations, increasing species harvests by commercial and subsistence hunting, which is usually aimed at primates and duikers[2] (Frumhoff, 1995).

According to Martini et al. (1994), selective logging affects both plant and animal species, especially those species associated with the species of trees targeted for timber

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[1] The term Upper Amazonian here was used by Gentry (1988) as the Peruvian Amazon and part of the Amazon in the Venezuela-Brazil border.

[2] Duikers are small antelopes comprising two genera (*Cephalophus* and *Sylvicapra*) (Merriam-Webster Dictionary, 2003).

extraction (e.g. mammals and birds that eat fruits and disperse seeds from timber tree species). The ecosystem changes caused by selective logging leads to animal disequilibrium in terms of number of species and species diversity, where some species tend to be more abundant than others, affecting the ecological dynamics within logged forests and may also extend to undisturbed neighboring forests (Frumhoff, 1995). In terms of plants, selective logging tends to eliminate the most valuable timber species and, systematically, reduces individuals that display those traits (Uhl and Vieira, 1989).

Moreover, selective logging activities cause a loss of forest structural integrity and cause further degradation, especially in open canopy forests, which have a presence of vines (Uhl and Buschbacher, 1985). These effects of logging activities also provoke habitat modification including site desiccation (Martini et al., 1994) and soil compaction (Pinard and Putz 1996, Fredericksen and Pariona 2002). Such impacts by logging directly modify the variability of the forest ecosystem ( Uhl and Vieira, 1989), destroy habitats, and affect the abundance of amphibians and reptiles, which in turn may affect seed dispersal and forest regeneration (Martini et al., 1994). The highest impact to the natural habitat occurs in forests heavily exploited by logging that become depleted of valuable tress and conversed to other types of land use (Pinard and Putz, 1996, Huth and Ditzer, 2001).

Although selective logging in the Amazon floodplain often concentrates on few tree species, it results in profound ecological changes in the forest environment (Macedo and Anderson, 1993). They also observed a dramatic transformation of the under canopy vegetation occurred after logging, where a secondary vegetation predominantly formed by vines and herbs took place. Additionally, they conclude that there is a trend to increase logging intensity and, consequently, environmental damages in those areas.

**1.2.2.4. Socioeconomic factors**

The Brazilian economy is among the 10 largest economies in the world, with a Gross Domestic Product (GDP) of US$ 596 billion in 2000. The timber sector only contributes 10% of this or approximately 5.5 billion (ABIMCI, 2O02). The timber industries operating in the Brazilian Amazon contribute approximately 15% of the regional GDP, employing 5% of the regional workforce (World Bank, 1999). It is estimated that 61.1% of all productive native forests in Brazil are located in the Legal Amazon, the main source of raw materials for the timber industries (ABIMCI, 2O02).

Between 1992 and 1999 approximately 295 million cubic meters of round wood was harvested in Brazil's Amazonian states, an average of 36.88 million $m^3yr^{-1}$ (IBGE, 2003). Based on these data provided by IBGE (2003), of this timber production, more than 81.8% was harvested in the state of Pará, 8.8% in the state of Mato Grosso, and 3.7% in the state of Rondônia, 2.2% in state of Maranhao, 1.6% in the state of Amazonas, and 1.9% in the states of Acre, Amapa, Tocantins, and Roraima. In recent years, the state of Amazonas has shown significant annual increase in harvested timber volume from 162, 622 to 792 thousand cubic meters of round wood in 1992, 1996, and 1999, respectively, while all other Amazon states have shown overall reduction (appendix A.1).

In the state of Para only 676 timber companies processed approximately 11.3 million cubic meters of round wood in 1998, which corresponded to 4.25 million cubic meters of processed wood and 2.8 million harvested trees. The timber industries in the state of Para contributed up to US$ 1.0 billion to the regional GDP in that given year (Verissimo et al. 2002). More specifically, Veríssimo et al. (1992) observed that 112 sawmills in the vicinity of the city of Paragominas, in Pará, provided approximately 5700 jobs, including forest employees (e.g. forest timber extractors, truck drivers, machinery operators, etc.) and industry employees. More than 50% of the urban population of Paragominas was directly dependent on the timber industry for its income. Indirectly, the timber industry generates significant tax revenues, which can be used for the benefit of the local and regional population. Such work opportunities and economic benefits attracted many migrants from other neighboring states to come and live in a new frontier.

Pinedo-Vasquez et al. (2001) conducted a study case in a floodplain forest in the State of Amazonas, after a period of logging "boom"[3] or abundance of most valuable trees. In this case, the local timber industry appeared to have collapsed after the high value timber species were exhausted, which led industries and individuals to migrate to other regions searching, respectively, for raw material and job opportunities.

Verissimo et al. (2002) studied 24 timber centers located at Paragominas and Novo Progresso municipalities, in the Amazon State of Para, involving 676 timber companies by 1998. In that given year, 11.3 millions cubic meters of round wood (around 2.8 million tress) were processed by those timber companies. The authors observed that timber oriented industrial areas are economically collapsing in Paragominas, an old

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[3] Logging boom is defined as the beginning of the logging activities in a new frontier region. In this 'boom' phase many sawmills are installed nearby abundant sources (natural forests) of raw material for the timber industries. It is also defined as predatory and unsustainable forest exploitation activities (Schneider et al. 2000).

frontier, and re-emerging in Novo Progresso, a new frontier surrounded by undisturbed forest. In those regions where logging is collapsing, forest cover, industry employments, and government taxes are also abruptly decreasing. Finally, they concluded that in pursuing the same forest exploitation model, the municipality of Novo Progresso will follow the same economic growth pattern (boom-collapse) rather than a sustainable one.

### 1.2.3. Synergism between selective logging and deforestation

Brazil has the world's highest absolute rate of deforestation (Skole and Tucker 1993, Skole et al. 1994, Houghton et al. 2000, Laurance et al. 2001a). Multi-annual estimates of deforestation in the Brazilian Amazon, provided by the Brazilian Space Agency - INPE (2003), show a total of 152,200 $km^2$, 377,500 $Km^2$, and 551,782 $km^2$ deforested, respectively, by 1978, 1988, and 1998. These estimates represent an annual increment of 19,979 $km^2$ or 362% in 20 years. The most recent measurements based on remotely sensed data show a total of 587,727 $Km^2$ deforested by 2000, equivalent to 11.75% of total Brazilian Amazon (INPE, 2003).

Studies in the Brazilian Amazon suggest that deforestation is spatially concentrated in some regions. Indeed, most of deforestation growth occurs around the major roads (Alves et al. 1999, Laurance et al. 2001a, b, c) and regions of higher human population density (Laurance et al. 2001b). Other factors such as rainfall and unpaved roads seem to have lesser influence on deforestation growth (Laurance et al. 2001b).

In addition to outright deforestation, uncontrolled forest exploitation by loggers may also catalyze deforestation by opening roads into unoccupied government lands and protected areas that are subsequently colonized by ranchers and farmers, which will result in increasing deforestation and release of carbon to the atmosphere (Veríssimo et al., 1995).

Uhl and Vieira (1989) studied the indirect socio-economical impacts of selective logging in a case study from the Paragominas region of the State of Para. They also noted that the access roads remaining after selective logging operations cease, lead to the occupation of the area by landless peasants, resulting in increased deforestation and threats to indigenous communities.

Uhl et al. (1991) conducted a case study of selective logging at Tailândia municipality in the Amazon State of Para. They observed that although selective logging directly provoked mild damages in the forest, it contributed to deforestation by improving the local economy during the initial colonization in this region that otherwise would not successfully occur.

More specifically, Uhl and Buschbacher (1985) studied the synergism between selective logging and deforestation for cattle ranch in a case study at Paragominas municipality in the State of Para. The authors observed that pasture development was economically subsidized by selective logging through the timber product commercialization and the required road network for timber transportation. Furthermore, fire used by farmers to manage crops and pastures often then spread to adjacent forests. As mentioned earlier, compared to non-logged forest, fire spreads more readily in exploited forests, causing extensive damages (Uhl and Buschbacher, 1985).

However, Stone and Lefebvre (1998) observed that 5 years after logging the majority of logged forest was remaining in a case study at Paragominas municipality in the State of Para. In this case, deforestation does not appear to be following selective logging activities, even though former logging areas have been more frequently re-visited by loggers.

### 1.2.4. Previous attempts to map selective logging

Remote sensing studies of selective logging have centered on the use of Landsat TM imagery. Stone and Lefebvre (1998) quantified forests affected by selective logging in a multitemporal case study area in Eastern Pará, Brazil, using Landsat images from 1986, 1988, 1991, and 1995. Visual interpretation of satellite imagery was used to study how fast selective logging was occurring in areas west and northeast of the city of Paragominas. Timber transportation roads and patios were digitized on a computer screen with polygons registered to image coordinates and areas identified as having been affected by logging. Their results showed that most logged forests became visually indistinguishable from surrounding forests within 3 years. Stone and Lefebvre (1998) applied texture algorithm and NDVI (Normalized Difference Vegetation Index) using Landsat TM imagery to investigate whether forest canopy texture and greenness in logged forests were significantly different from that of undisturbed forest. They concluded that texture and NDVI images were not helpful in defining selectively logged forest.

Souza and Barreto (2000) conducted a multi-temporal analysis of 82.5 hectares of selectively logged forest in the State of Pará, Brazil. They used Landsat TM scenes, bands 1-5 and 7, from June 1984, July 1991, and July 1996. They applied a linear mixture model, based on spectrally pure pixels, to estimate the soil, vegetation, and shade fractions within each TM pixel. Subsequently, they used a morphologically constrained classification of the soil fraction image to identify logging patios where cut logs are temporarily stored. Based on fieldwork, Souza and Barreto (2000) determined that a buffer zone of 180 meters around the detected logging landings (patios and roads) provided an excellent estimation of the actual forest area affected by selective logging. However, Souza and Barreto (2000) cautioned that, due to the rapid vegetative regrowth, their technique detected only 60% of field-verified logging patios that were one year old and none that were three years old.

Janeczek (1999) estimated the forest area affected by selective logging throughout the Brazilian Amazonia in 1992, using Landsat TM imagery and a GIS. In this study, Janeczek (1999) used an automated texture analysis of Landsat TM band 5 to detect logging landings (patios and roads). Similar to Souza and Barreto (2000), Janeczek (1999) applied buffer zones of 180 meters around logging landings to estimate areas affected by selective logging. In addition, Janeczek mapped selective logging activities (visible canopy disturbance on Landsat images) through visual interpretation, and circumscribed them digitally on a computer screen. In the analysis, 84% of the logging landings were detected automatically when compared with the visual identification on the Landsat images. Areas that were missed using automatic analysis were added by visual interpretation. A total of 5,406 $km^2$ of forest was estimated to have been selectively logged over 1-2 years.

Nepstad et al. (1999) interviewed 1393 sawmills located in 75 timber polos in the Brazilian Amazon in order to estimate areas affected by selective logging basin-wide. They used sawmill records of the amount of harvested round wood for 1996 and 1997 and the round wood harvest intensity, expressed in cubic meters of timber per hectare of forest. Based on these information, they estimated that 10 to 15 thousand $Km^2$ of undisturbed forests were annually harvested in 1996 and 1997. In this research, Nepstad et al. (1999) concluded that, besides deforestation, selective logging in the Brazilian Amazon has been contributing to increase $CO^2$ in the atmosphere.

Asner et al. (2002) conducted a field study of forest canopy damages at Cauaxi ranch in the Paragominas municipality of the Amazon State of Para, Brazil. The field studies encompassed 50 hectares of non-logged forest, 200 hectares of high intensity logged forests, and 200 hectares of low intensity selectively logged forests. They surveyed and mapped those areas before and after selective logging, where trees and log landings (roads, patios, skid and trails) were identified and located. They also measured canopy gap fraction to report leaf area index (LAI). Additionally, they performed visual analyzes using different bands and texture analysis on Landsat images from different years and compared with field study results.

Asner et al. (2002) noted that only the highest canopy damage type of selective logging damages can be easily detected using Landsat multi-spectral images. In that case study, Landsat reflectance or texture analysis could detect and estimate forest damage when the forest gap fraction is less than 50%. They concluded that although basic Landsat reflectance data and texture analysis could not quantify logging intensity in that study site, these data and technique are useful for broad scale logging detection, as is needed for environmental monitoring in the Brazilian Amazon. The author suggested efforts are needed to develop alternative approaches using high spatial resolution and hyper-spectral imagery in order to quantify selective logging intensity.

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# CHAPTER II

## Method for Detection and Validation

### 2.1. Abstract

Selective logging is an important issue in terms of forest degradation and fragmentation. However, few attempts have been made to detect and estimate the area of forest where trees were partially removed, as in the case of selective logging. Most attempts to detect selectively logged forest in the Brazilian Amazon are based on remote sensing techniques combined with fieldwork information. Although these studies have important findings in terms of the specific sites, the majority of them are located in the Amazon State of Pará.

This research tested previously developed remote sensing techniques to detect and estimate forest impacted by selective logging in a case study in the Amazon State of Mato Grosso. Field studies, automatic analysis, and visual interpretation of Landsat ETM+ and Ikonos images were used. The results suggest that (1) visual interpretation of Ikonos imagery can detect most of the forest impacted by selective logging (2) by combining automatic analysis (textural algorithm plus a buffer of 180 meters) and visual interpretation using Landsat ETM+ image it was possible to detect around 91.3% of the selectively logged forest detected using Ikonos imagery (3) the total amount of logged forest estimated using Landsat image omitted 8.7% and created 19.3% of commission areas when compared with results obtained using Ikonos imagery, (4) the total logged forest estimated using Landsat ETM+ is approximately 11% overestimated in comparison with Ikonos results, (5) the total forest area impacted by selective logging in the study area is almost twice the amount of actual deforestation.

## 2.2. Introduction

As presented in the previous chapter, the process of logging can result in a heavily degraded forest environment. In spite of its damages and consequences, few attempts to detect and quantify areas impacted by selective logging using remote sensing have been made. Furthermore, most of these attempts were conducted in study cases in the Amazon State of Pará, Brazil, such as the studies by Watrin and Rocha (1992), Stone and Lefebvre (1998), Sousa and Barreto (2000), and Asner et al. (2002).

Stone and Lefebvre (1998) applied supervised and unsupervised classification and visual interpretation techniques of Landsat imagery to detect selective logging in a case study in the State of Pará. In this study, the authors could quantify areas impacted by selective logging by performing visual interpretation of Landsat images. However, the authors affirmed that images have to be acquired within a short period following logging and eventual extrapolation to larger areas has to be cautioned.

Sousa and Barreto (2000) developed an alternative approach to estimate selective logging areas in a case study in the State of Pará. Based on field studies, they applied a buffer radius of 180 meters around log landings detected on satellite images by using a linear mixture model to estimate forest areas previously logged, but not detectable on satellite imagery. The authors concluded that further research is necessary to test the applicability of this methodology for other regions.

In a broader study, Janeczek (1999) applied visual interpretation and automatic analysis of Landsat imagery in order to estimate selective logging. She quantified the amount of selective logging in the Legal Amazon Basin for 1992. The author concluded that these techniques could be improved by integrating with high spatial resolution satellite imagery, such as that provided by Ikonos, which would increase accuracy of estimating selectively logged areas.

In a more recent study, Asner et al. (2002) compared fieldwork information with Landsat textural analysis to assess selective logging in a case study also in the State of Pará. The authors conclude that even though textural analysis is useful for broad delineation of logged forest, this technique cannot assess the intensity of canopy damage. They suggested new approaches using high spatial resolution and hyperspectral satellite imagery in order to improve assessment of selective logging impacts.

In this research, I tested remote sensing and Geographic Information System techniques to detect and measure forests impacted by selective logging in a study case in the Amazon State of Mato Grosso, Brazil. Logged forests were mapped using satellite imagery from different sensors (Landsat ETM+ and Ikonos). Automatic detection developed by Janeczek (1999) plus a 180 meter buffer radius suggested by Sousa and Barreto (2000) as well as visual interpretation using Landsat image were applied.

Applying visual interpretation to Ikonos imagery and complementary field observations, the total area of forest impacted by selective logging was digitized. I mapped logged forests into different GIS layers. Finally, I compared and analyzed the results of different remote sensing techniques in order to assess their efficiency and accuracy.

## 2.3. Methodology

### 2.3.1. Site description

The study area is located in the Brazilian Amazon State of Mato Grosso, about 55 kilometers North of the city of Sinop at 11° 34' S latitude and 54° 39' W longitude (center point). This area encompasses 4,893.00 hectares (approximately 7 Km x 7 Km), completely covered by an Ikonos scene and by part of a Landsat scene. In this analysis, the Ikonos scene defines a portion of the Landsat scene and the study area. Most of this study site is part of the Continental ranch in Sinop municipality of Mato Grosso State (appendix B.1).

The climate at Continental ranch is humid tropical with annual precipitation averaging 2000 mm. The mean annual temperature is 24° C. The predominant natural vegetation is semi-deciduous forest with emergent canopy, on dystrophic red-yellow Latossols (RADAMBRASIL, 1980). The land use has been partially changed from undisturbed forest to pasture, reforestation, and selectively logged forest.

### 2.3.2. Data Set

The data used in this study are drawn from the collection of Amazonian imagery at the Center for Global Change and Earth Observations (CGCEO), Michigan State University. This included deforestation layers and digital Ikonos and Landsat ETM+ images. The Lansat and Ikonos images were acquired on April 30 and June 18, 2000, respectively These dates roughly correspondto the end of the wet season and to the beginning of the dry season in this part of the Brazilian Amazon. Additional Landsat images from 1992 to 1999 were also examined to search for selective logging in the previous years. The satellite images (appendix B.2) covering the study site, evidencing selective logging, free of clouds and shadows, were used in this analysis.

The deforestation GIS layer was generated using unsupervised classification of Landsat imagery. This layer was reviewed and updated using the high spatial resolution Ikonos pan-sharpened image. Subsequently, the deforestation layer was used to mask non-forest and forest, whether selectively logged or not, on both Ikonos and Landsat images.

#### 2.3.2.1. Calibration and Geometric Rectification

Geometric rectification was done on the Ikonos scene using Bicubic resampling method, supplied with the Ikonos images at the time of ordering. Additionally, the Ikonos image rectification was tested using collected GPS ground points in July 2002, from several locations in the study area. A portion of the Landsat scene covering whole study area also was rectified using control points derived from Ikonos image scene and nearest-neighbor resampling method.

#### 2.3.2.2. Pan-Sharpening Ikonos image

Pan-sharpening is a remote sensing technique that improves the spatial resolution of a multi-spectral image by using a higher spatial resolution band. This spatial resolution improvement can be done by using principal component merge and nearest neighbor resampling techniques, which improves the spatial resolution and maintains the spectral information (Erdas, 1997).

In this specific case, the resolution merge technique combined one panchromatic high spatial resolution (1 m) Ikonos image with another multi-spectral lower spatial resolution (4 m) Ikonos image, which generated a new multi-spectral image with 1 m spatial resolution.

### 2.3.3. Detection of areas of selective logging

To detect and map selectively logged forest, visual interpretation was used on both Ikonos and Landsat image. Additionally, automatic analysis (texture algorithm + buffer zone) was applied to the Landsat image, band 5.

#### 2.3.3.1. Digitization of areas of selective logging

Visual interpretation to detect selectively logged forests was done using RBG 3/4/2 and 5/3/2 color composites of pan-sharpened Ikonos and multi-spectral Landsat image, respectively, displayed at full resolution on a computer screen. The logged forests were digitized manually on each image at varied scales from 1:1,500 to 1:100,000 using Arc/Info. The minimum scale for digitizing manually on Landsat image was 1:25,000.

The logged forests were identified by obvious canopy degradation, since logging activities leave log landings, and tree-fall gaps along with obvious canopy disturbance. According to Janeczek (1999), 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 (figure 2.1).

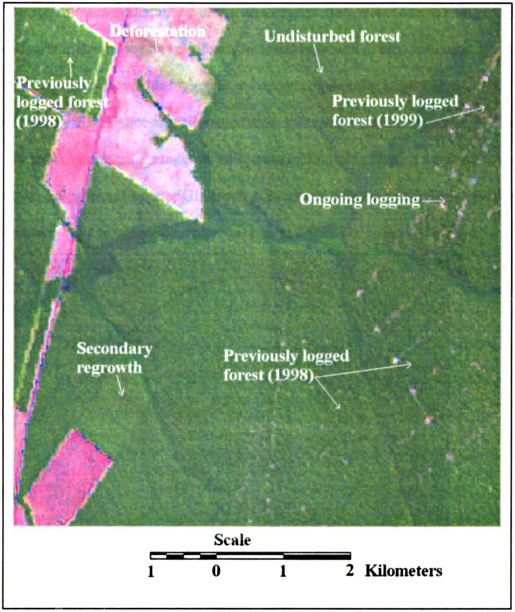



Figure 2.1. Visible logged forest areas on Landsat ETM+ image, RGB 5/3/2, June 18, 2000.

According to Janeczek (1999), areas of obvious logging have well defined logging roads and patios and extensive canopy degradation. Areas of subtle logging, have lesser degrees of canopy disruption or visible infrastructure, either due to being early in the logging process or because of substantial forest regrowth in previously logged forests.

In this research, visible logged forest includes spectrally bright patios, roads, and obvious canopy disturbance as well logged areas that exhibit faded log landings. The areas around the log landings together with areas of obvious canopy degradation were digitized as polygons into vector GIS layer, classified as logged forest. The digitizing was done on the very edge of canopy disturbance (figure 2.2).

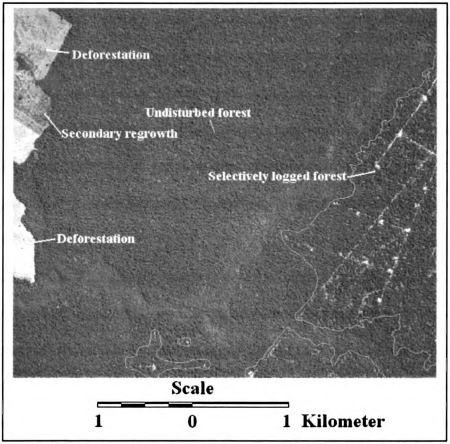



Figure 2.2. Visible logging on Ikonos image RGB 3/4/2, 2000.

Logged forests that did not have visible canopy disturbance on satellite images were not digitized. In this analysis, a single individual made all visual interpretations.

#### 2.3.3.2. Automatic detection of selective logging

As previously discussed, log landings are small clearings cut into the forest for the purpose of temporary storage and staging areas (patios) for timber transportation to the sawmills by loggers (Stone and Lefebvre, 1998, Sousa and Barreto, 2000).

Janeczek (1999) tested a textural algorithm on Landsat bands 3, 4, and 5 individually (red, near infrared, and middle infrared, respectively) to detect forests directly affected by selective logging activities or log landings. Log landings were identified most effectively with band 5, because dry bare soil reflects more incoming radiation at that wavelength than vegetation, resulting in a good contrast on the images.

According to Pratt (1991) cited in ERDAS (1997), the textural algorithm can be used to segment an image and classify its segments, giving the image sharper edges. It generally indicates the spatial variation in neighboring pixel values. The addition of texture, to an image, adds structural information that assists in the detection of cryptic deforestation.

In order to automatically detect patios and logging roads in the areas affected by selective logging, a textural algorithm was applied to Landsat imagery of the study area. The texture analysis algorithm used in this study produced a variance from texture analysis on band 5. The texture algorithm used was the 5 x 5 moving window operator described above. All details and steps applied in the automatic analysis to detect logged forest, including texture analysis, noise reduction, mask, buffer zones, and coverage overlaps, are shown in figure 2.3.

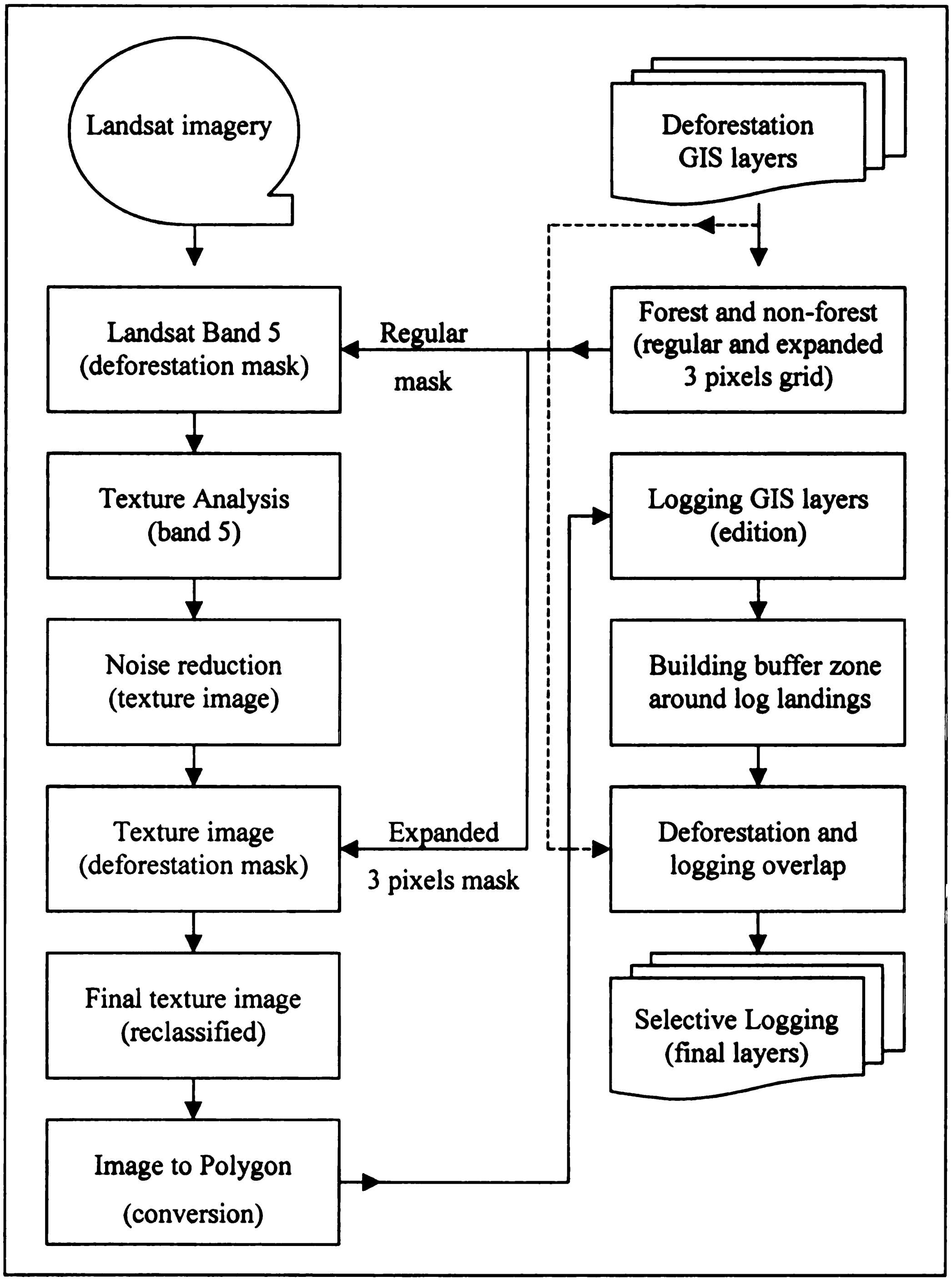



Figure 2.3. Methods used in the logging automatic detection

As part of the deforestation analysis, the image was classified by the Center for Global Change and Earth Observations (CGCEO) using an unsupervised image classification model of bands 2, 3, 4, and 5, into seven thematic classes: forest, deforestation, regeneration, cerrado, clouds, shadows, and water. Non-forest areas (deforestation, cloud, shadow, cerrado, water body, and regenerating vegetation) were subsequently masked out of band 5 of the Landsat image. The texture analysis was then run on the masked image (band 5) using a variance algorithm with a 5x5 window. A median filter was applied to the resulting texture analysis to reduce 'noise'. Thus, the automatic analysis (textural algorithm) to detect selective logging using Landsat and Ikonos images was applied solely on areas classified as forest, either selectively logged or undisturbed.

The images were masked a second time using an expanded non-forest mask. Specifically, the mask was expanded by 3 pixels so as to remove artifacts in the texture analysis caused by the 5x5 variance window near forest/mask edges. This greatly reduced the editing time necessary.

The texture layer was then reclassified using ERDAS, selecting and capturing the pixels values (mostly from 6 to 11), correlated to areas directly affected by selective logging, such as patios and roads (figure 2.4). Janeczek (1999) tested bands 3, 4, and 5 using 3x3 and 7x7 windows in the texture analysis algorithm, but the 5x5 window provided the best results.

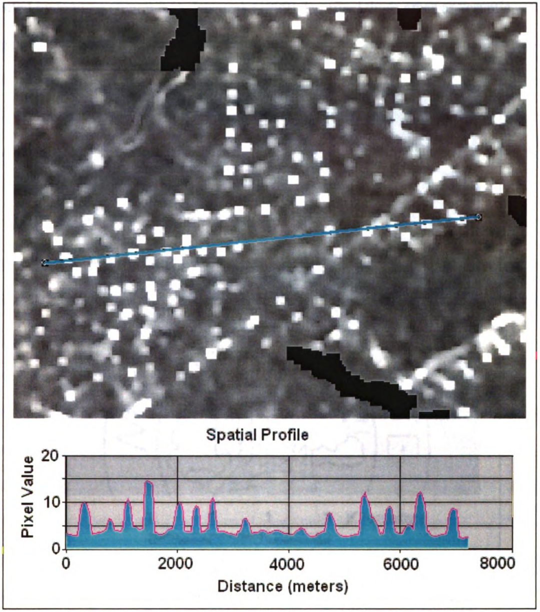



Figure 2.4. Spatial profile of a textural image (Landsat ETM+ , band 5).

The classified texture images were converted to vector format and edited to remove any remaining extraneous features that were not associated with logging. A buffer radius of 180 meters, as suggested by Souza and Barreto (2000), was applied to the detected log landings (patios and roads) in order to estimate the amount of forest actually affected by logging (figure 2.5). Janeczek (1999) described those areas as "cryptic logging".

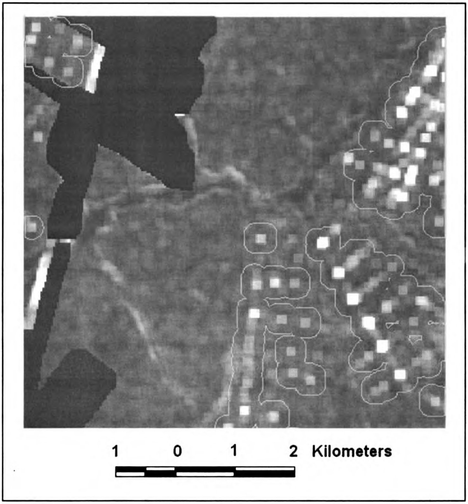



Figure 2.5. Textural image (band 5) and buffer radius of 180 meters around the log landings (patios and roads).

Subsequently, the non-forest mask was applied again to remove any regions where the suspected-logging areas overlapped with non-forested land cover classes. Different buffer radiuses of 150, 210, 240, and 270 meters were also tested to assess the efficiency and accuracy of automatically detecting selectively logged forest.

### 2.3.4- Logging Area Estimates on Landsat imagery

The final estimate of logged forest areas was made using the union of the logged forest polygons detected by the automated analysis and visual interpretation. The overlap between areas of logged forest and non-forest (deforestation) was removed to avoid double counting.

## 2.4. Field studies

This field study was conducted during July 2002, the dry season in the Brazilian Amazon. These studies consisted basically of empirical observations of the previously logged forests identified on the satellite images. Measurements and personal communication with the landowner and technical staff from the Continental ranch responsible for enforcing the logging operation plans and activities were also conducted. Areas of logged and non-logged forests were identified by empirical observations of selective logging evidence such as former patios and roads and damaged forests (tree-fall gaps, stumps, wood debris, etc.). Patio and road dimensions were measured in different sites several years after logging. Forest regeneration within previously logged forest was also examined.

By examining Landsat imagery from 1992 to 2000, no evidence of selective logging activities prior to 1997 were found. From 1998 to 2000, selective logging became a predominant land use type in the area. In personal communication with the Mr. Annor Zanchette (landowner of the Continental ranch), it was confirmed that in the study area selective logging had begun by 1998.

Undisturbed forests were also observed in 2002 during the field studies, though they are located mostly in wetlands and areas protected for scientific purposes.

The harvested volume in the study site was around of 40 $m^3$/ha, involving roughly 50 tree species (personal communication with Mr. Annor Zanchette, 2002). The average diameter of the 10 patios in logged forest prior to 2001, was 61.7 meters. The average width of former access roads in the same logged forests was 10.7 meters.

Tree fall gaps, stumps, logging access roads, skidder trails, and patios were quite evident a year after selective logging activities, though forest regeneration or secondary regrowth was already taking place. Two years after logging, the patios and roads were still visible, but showing a stronger regeneration and most of the tree fall gaps and skidder trails were covered by secondary regrowth (vines, fast-growth tree species, etc). Three years after selective logging, most of the forest damage caused by logging activities were covered by strong secondary regrowth.

However, some areas severely impacted by heavy trucks and other machinery, such as main access roads and patios, lacked regeneration. These areas were evident because of the compacted soil and soil exposure left behind by logging activities. Four years after logging, forest regeneration was very strong and only a few areas were showing partial soil exposure, though it was quite clear that those areas were previously logged because of the damaged forest canopy and secondary regrowth. Wild fire does not seem to have affected the study area so far.

## 2.5. Results

General results of this research showed that 14% of the study area had been deforested by 2000 and 60.1% had been preserved as undisturbed forest (table 2.1). Additionally, a total of 1,266.5 hectares (25.9%) of selectively logged forests were detected by using visual interpretation of an Ikonos image. This area was adopted as ground truth, hence it represented the total of selectively logged forest, used in this analysis to compare with results obtained using Landsat imagery.

Table 2.1. Land use in the study area by 2000

| Land Use | Area (ha) | % |
|---|---|---|
| Logged forest | 1266.50 | 25.9 |
| Undisturbed forest | 2939.80 | 60.1 |
| Deforestation | 686.68 | 14.0 |
| **Total** | **4,894.81** | **100.0** |

Source: Visual interpretation on Ikonos image

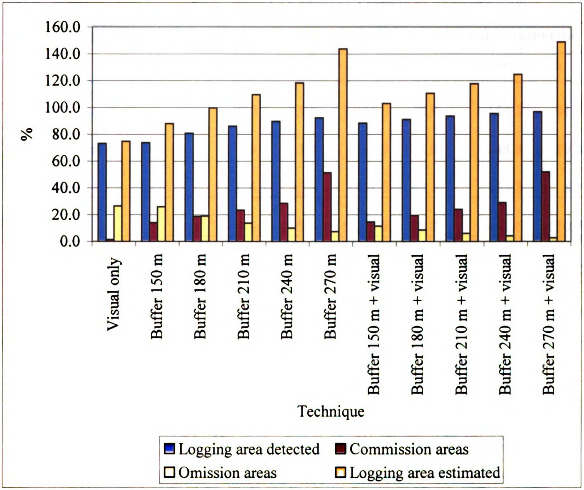
The deforestation layer was used to mask out non-forest on satellite imagery, hence the logging detection methodologies were applied only for forest areas, either selectively logged or not.

Small features left behind in ongoing selective logging areas such as tree-fall gaps, and skidder trails were detected by visual interpretation on pan-sharpened Ikonos image, hence the border between logged and undisturbed forest was well defined. Logged forests prior to 1999 were also detected by visual interpretation on the Ikonos image, but the definition of the border between logged and undisturbed forest was made more difficult by forest regeneration. Logged forests in 1998 showed a few spots with soil exposure. The former log landings (patios and access roads) were substituted by fast-growing secondary vegetation. Thus, besides log landings, the additional criteria to differentiate logged an undisturbed forest was the presence of secondary regrowth in between the tree-canopies.

**2.6. Analysis of accuracy assessment of the remote sensing techniques**

In this research visual interpretation and automatic analysis of Landsat imagery techniques, developed by Janeczek (1999), were applied in order to detect selective logging. For the automatic analysis method, a different buffer radius, varying from 150 meters to 270 meters, in multiples of 30, according to the Landsat spatial resolution were tested. The overlap, omission, and commission areas mapped using Landsat image were than compared with the ground truth (Ikonos + field work) results (appendix B.2).

Visual interpretation only detected around 76.4% of the total logged forest (1,266.5 hectares) estimated using Ikonos and complementary field studies. By increasing the buffer radius the omission area decreased and the commission area increased, creating an overestimation of the total of logged forest. By increasing the buffer radius from 150 meters to 270 meters, detection of logged forest significantly increased from 74% to 92.5% of the total area, and the omission area decreased from 26.6% to 7.5%, respectively. When combining visual interpretation and automatic analysis using different buffer radiuses and Landsat image, the detection of selective logging areas increased from 88.4% to 97.1% and the omission area decreased from 11.6% to 2.9%, for buffer radiuses ranging from 150 to 270 meters in 30 meter intervals (figure 2.6).




**Note:** Total logged forest (Ikonos): 1,266.5 hectares (100%)

Figure 2.6. Selective logging detection using visual interpretation and automatic analysis on Landsat ETM+ , testing different buffer radiuses.

Specific results of testing visual interpretation, automatic analysis using a buffer radius of 180 meters developed by Sousa and Barreto (2000), and both techniques combined are presented as following (table 2.2).

Table 2.2. Logged forest detected using visual interpretation and buffer radius of 180 meters on Landsat ETM+ image

| Logged forest | Technique | | | | | |
|---|---|---|---|---|---|---|
| | Visual | | Automatic | | Visual + Automatic | |
| | Area (ha) | % | Area (ha) | % | Area (ha) | % |
| Detected (overlap between Ikonos x Landsat) | 930.3 | 73.5 | 1,025.0 | 80.9 | 1,156.7 | 91.3 |
| Commission | 19.1 | 1.5 | 238.7 | 18.9 | 244.8 | 19.3 |
| Omission | 336.1 | 26.5 | 241.5 | 19.1 | 109.8 | 8.7 |
| Total | 949.4 | 75.0 | 1,263.7 | 99.8 | 1,401.6 | 110.7 |

**Note:** Total logged forest (Ikonos): 1,266.5 hectares (100%)

Using automatic analysis (textural analysis plus a buffer radius of 180 meters) I could detect more selectively logged forest than visual interpretation, 80.9% and 73.5%, respectively, resulting in less omission areas (underestimation) than visual interpretation, 19.1% and 26.5%, respectively. However, automatic analysis created more commission areas (overestimation) than visual interpretation, respectively, 18.9% and 1.5%. When compared the total area (detected plus commission areas) of logging estimated using automatic analysis, visual interpretation and both techniques, automatic analysis showed to be more accurate in estimating the total logging areas (99.8%) than visual interpretation and both techniques (75% and 110.7%, respectively). In spite of overestimating in 10.7% the total logging areas, when combining automatic analysis and visual interpretation, it substantially increased precision by reducing omission areas from 19.1% and 26.5% (automatic analysis and visual interpretation only, respectively) to 8.7% (figure 2.7).

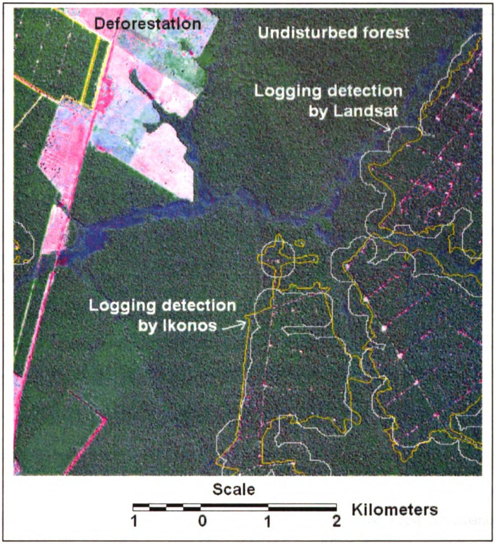



Figure 2.7. Selective logging detected on Ikonos and Landsat ETM+ imagery displayed on Ikonos image RGB 3/4/2, April 30, 2000.

Automatic analysis only detected 99.8% of the total of logged forest while visual interpretation underestimated by 25.0% and both techniques overestimated by 10.7%. Visual interpretation only contributed about 11% in detecting selectively logged forest while automatic analysis about 20%. Both techniques overlapped around 69% in areas of selective logging (figure 2.8).

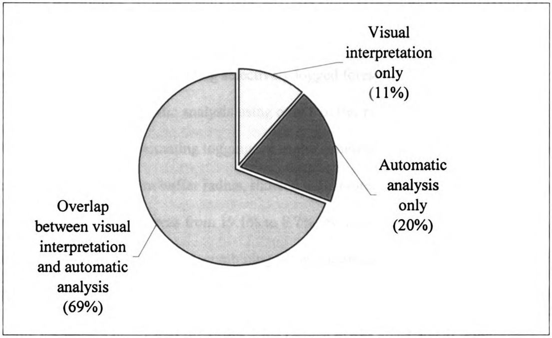



Figure 2.8. Visual interpretation only, automatic analysis only (buffer radius of 180 m), and overlap between logging areas detected by both techniques.

**2.7. Conclusion**

Based on these research results and fieldwork observations, forest disturbances by selective logging activities are visible and measurable using high spatial resolution (1m pan-sharpened) Ikonos and Landsat imagery. Ongoing or recent selective logging damage such as patios, roads, skidder trails, tree-fall gaps, etc, are visible on Ikonos imagery while on Landsat imagery only patios, roads, and the heaviest canopy damage are visible. Hence, visual interpretation on Ikonos imagery and complementary field studies could support a reliable estimate of selective logging for the study site. The Ikonos product therefore is useful to test other sensors and satellites with coarse spatial resolution.

In spite of the spatial resolution limitation, the Landsat ETM+ image showed reasonable efficiency and accuracy in estimating logged forests using different remote sensing techniques. Although automatic analysis alone created more commission errors, which varies according to the buffer radius size, it showed to be more efficient than visual interpretation in estimating selectively logged forests.

Although automatic analysis using only a buffer radius of 180 meters showed to be more accurate in estimating logging areas, the combination of visual and automatic analysis using the given buffer radius, showed to be more precise by significantly reducing the omission areas from 19.1% to 8.7%, even though it overestimated in 10.7% the total logging areas. Indeed, combining visual interpretation and automatic analysis (buffer radius of 180 meters) I could detect 91.3% of the total logged forests detected using the Ikonos image and fieldwork observations in this study site at Sinop municipality in the State of Mato Grosso.

Visual interpretation alone showed to be more interpreter dependent and results are expected to vary between individuals. Additionally, neither visual interpretation nor automatic analysis on Landsat images could detect small forest disturbances, detectable using Ikonos imagery.

Finally, both automated detection and visual interpretation combined form an efficient methodological approach for estimating areas affected by selective logging in similar sites. However, the amount of selective logging detected, commission, and omission areas are variable according to the buffer radius. It is important therefore to dedicate more effort to testing different buffer radiuses for other sites or regions, considering that the Brazilian Amazon is a vast area with different ecosystems, land use, and logging patterns and intensities.

## 2.8. References

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# CHAPTER III

## Assessment of selective logging detection for the Amazon State of Rondônia

### 3.1. Abstract

This Chapter assesses the methods for estimating forest areas affected by selective logging in the Amazon State of Rondônia. I combined a detailed field study with remote sensing techniques to estimate selectively logged forest areas. The study site encompassed 2,460 hectares of logged forest, where 37,966 commercial trees were inventoried prior to harvesting. Post-harvesting inventory reported that 4,138 commercial trees were logged. The trees, access roads, and log storage patios were properly located and plotted. Different buffer radiuses were tested around patios located during the fieldwork in order to quantify the spatial overlap between the buffer zones and selectively logged forest areas. An automated method (textural algorithm) on band5, Landsat ETM+, path 232 row 066, was applied to detect forest impacted by selective logging. Different buffer radiuses around log landings (patios and roads) detected by the automated method on Landsat imagery were compared with field information. I found that a 540 meter buffer radius around the patios located on the ground could estimate about 90% of the forest affected by logging, creating no commission areas. By applying a 450 meter buffer radius around log landings captured on satellite imagery, it overlapped about 89% of the forest affected by logging, creating no commission areas. Visual interpretation was also tested but it was unsuccessful because selective logging in this study site was not intensive and therefore canopy degradation was not enough to be visible on Landsat imagery.

### 3.2. Introduction

Selective logging is a process of removing a limited number of trees that leaves behind a mixture of undisturbed forest with canopy damaged forest and soil exposure areas such as access roads, storage patios, tree fall gaps, and skidder trails (Uhl and Buschbacher 1985, Stone and Lefebvre 1998, Nepstad et al. 1999, Souza and Barreto 2000).

Various alternative approaches based on remotely sensed imagery have been developed in order to detect and estimate areas of selective logging in the Brazilian Amazon. Most of these attempts have been conducted in the State of Para, for example the case studies by Watrin and Rocha (1992), Stone and Lefebvre (1998), Sousa and Barreto (2000), and Asner et al. (2002).

Sousa and Barreto (2000) applied linear texture model to detect log landing on Lansat images. In complementary field studies, they defined a 180 meters buffer radius around areas of evident soil exposure, which estimated accurately areas affected by selective logging in that study site. However, the authors affirmed that further work is necessary to test the applicability of the methodology for other sites.

Janeczek (1999) developed the first approach for detecting selective logging Amazon-wide, using remotely sensed data. In this research, Janeczek (1999) improved a procedure to locate and estimate the extent of cryptic logging and degradation in the Brazilian Amazon. The author applied techniques from previous studies (visual interpretation) and developed an automated method to detect logged forests. The automated method was based on textural analysis of the Landsat, band 5, and incorporated the 180 meters buffer radius studied by Sousa and Barreto (2000) for the case study in the State of Para. Although Janeczek's results were successful in that research, she concluded that "it would be beneficial to further test the accuracy of the 180 meters, such as measuring the distance between patios to determine the spatial variability".

Specifically in the State of Rondônia, Janeczek (1999) classified this State as "low logging region", because she could not detect a significant amount of logged forest using her procedures and methods. In spite of this result, the State has been systematically logged and deforested since the 1970's. The total deforested area increased from 420 $Km^2$ in 1978 to more than 5000 $Km^2$ in 1999 (INPE, 2003). More than 14.9 million $m^3$ of round wood was exploited from natural forest in the period of 1990-2002, an average of 1.2 $m^3$ $yr^{-1}$ (IBGE, 2003).

The applicability of these methods and techniques for other regions therefore requires additional examination and validation. The purpose of this study was to test the methods and techniques for estimating areas affected by selective logging activities in the Amazon State of Rondônia. I conducted a detailed field study in 2,460 hectares located at Manoa ranch in the Cujubim municipality. I also tested visual interpretation and the automated method developed by Janeczek (1999) on Landsat ETM+ band 5. Finally, the different buffer radiuses were compared with fieldwork and remote sensing results for validation.

## 3.3. Methodology

### 3.3.1. Study site and data set

This study was conducted at the Manoa ranch, located in Cujubim municipality of the Amazon State of Rondônia, Brazil, approximately 70 kilometers North of the city of Cujubim at (center point) 8° 59' S latitude and 62° 20' W longitude (appendix C.1). The study area encompasses 2,460.86 hectares of selectively logged forest.

The climate at Manoa ranch is humid tropical. The mean annual precipitation is 2,400 mm. A dry season extends from June through September. The mean annual temperature is 26° C. The predominant soil types are red-yellow and yellow latossols covering with open canopy tropical forest (RONDÔNIA, 2002). The predominant land uses are undisturbed forest and a small amount of logged forest.

Digital Landsat ETM+ image (path 232, row 066) from the Center for Global Change and Earth Observation at Michigan State University, acquired in August 5, 2002 was used. This Landsat scene covering the entire study area was rectified using ERDAS nearest-neighbor resampling method and 15 ground control points. The control points were acquired using GPS Trimble Pro-XR a Trimble GeoExplorer II.

### 3.3.2. Field studies

This study area was previously forest inventoried in 1999. A forest engineer, Vilmar Ferreira, and a forest technician, Hermínio Fernandes da Silva Neto, conducted this inventory. This forest area was selectively harvested during the dry season (May to October) of 2001. Eraldo Matricardi, Walter Chomentowski, Stephen Cameron, and

Hemínio F. da Silva Neto conducted complementary post-logging field verification in June 2002.

During the last field verification in June 2002, almost a year after logging, the forest regeneration was very strong. The patios and roads were still visible and most of the tree fall gaps and skidder trails were covered by secondary regrowth such as vines and fast-growth tree-species. The complete soil exposure was observed only on the main and secondary roads and partial soil exposure on storage patios. There was no evidence of wild fire in this study area.

All patios and access roads were located using GPS. All trees with Diameter at Breast High (DBH) of more than 45 centimeters were identified, measured, and located within the forest. Transects were plotted within the forest area heading North direction, 100 meters distant from each other. During the previous forest inventory, trees were located within the ranges of 50 meters in the left and right side of each transect. After logging, the location of logged trees was once again examined. The total of 4,138 trees were harvested from a total of 37,966 commercial trees inventoried. The total volume harvested was 27,847 $m^3$ of round wood, which correspond to an average of 11.3 $m^3 ha^{-1}$, considered a low intensity selective logging. Subsequently, the log landings and tree locations were plotted on a map (appendix C.2).

A total of 65 patios were built in the study area. The patio diameters vary from 25 to 35 meters taking into account the edge-affected forest. The width of main access road varies from 10 to 12 meters wide, while a secondary access road ranges from 6 to 8 meters wide. The skidder trails are 2 to 3 meters wide and the forest canopy covered most of them by June 2002. According to Vilmar Ferreira (in personal communication during the fieldwork) the tree-fall gaps vary in dimensions depending on the size of the harvested trees, though an average of 300 $m^2$ of undisturbed forest are damaged by harvesting a single tree.

Based on a possible relationship between the distance of the harvested trees and the log storage patios, different buffer radiuses varying from 150 to 720 meters were tested. The buffer zones were then used to estimate the amount of logged forest.

### 3.3.3. Detection of selectively logged forest

As presented in the Chapter 2, the technique developed by Janeczek (1999) was applied to this case study. A textural algorithm was performed on band 5 of Landsat ETM+. The textural algorithm can be used to segment an image and classify its segments, giving the image sharper edges. It generally indicates the spatial variation in neighboring pixel values. The addition of texture, to an image, adds structural information that assists in the detection of cryptic deforestation (ERDAS, 1997).

The textural image creates a good contrast between dry bare soil and forest canopy. This image was re-classified to separate log landings from the undisturbed forest canopy and, subsequently, was converted to Arc/Info coverage in order to remove any remaining extraneous features that were not associated with logging.

Different buffer radiuses were tested. I used a multiple of the Landsat ETM+ pixel size (30 m) for the buffer routines, varying from 150 to 720 meters. These buffer radiuses were applied around log landings that were detected using automatic analysis (textural algorithm) in order to estimate the amount of forest areas actually affected by logging but not necessarily visible on satellite imagery. Janeczek (1999) described those areas as "cryptic logging".

Although logging roads and patios were easily observed by visual interpretation, this technique was unsuccessful in this study area because of the low intensity logging characteristics, which do not create significant amount of soil exposure or canopy damage to be detectable on Landsat imagery.

### 3.4. Buffer radius assessment

According to the field study results 2,460.86 hectares were logged until June 2002. Approximately 27 hectares was classified as log landings (patios and timber access roads) showing evident soil exposure. The storage patios only occupied 7 hectares. The total of 65 patios were located and measured in the study area, showing an average of 32.5 meters of diameter. The total of 20 hectares was occupied by timber access roads, showing the total length of 9.3 kilometers and the width of 11 meters for the main access roads and the length of 13.6 kilometers and the width of 7 meters for the secondary access roads.

Although Stone and Lefebvre (1998) and Janeczek (1999) could detect selective logging using visual interpretation in the Amazon state of Pará and basin-wide, respectively, in this study this technique did not produce satisfactory results because of the low intensity selective logging observed at the study site.

Sousa and Barreto (2000) tested different buffer radiuses around log landings in order to estimate selectively logged forest for a case study in the Amazon State of Para. They concluded that a 180 meter radius was the optimal distance for the buffer. In the research presented here, I tested different buffer radiuses, varying from 150 meters to 720 meters, around storage patios located during the fieldwork. The buffer zones were spatially overlapped with the logged forest area to determine the best buffer radius for estimating selective logging. The overlap between areas of logged forest and within the buffer zone was identified as logged forest detected. Additionally, I measured the omission and commission areas of selective logging, created by the buffer zones (figure 3.1).

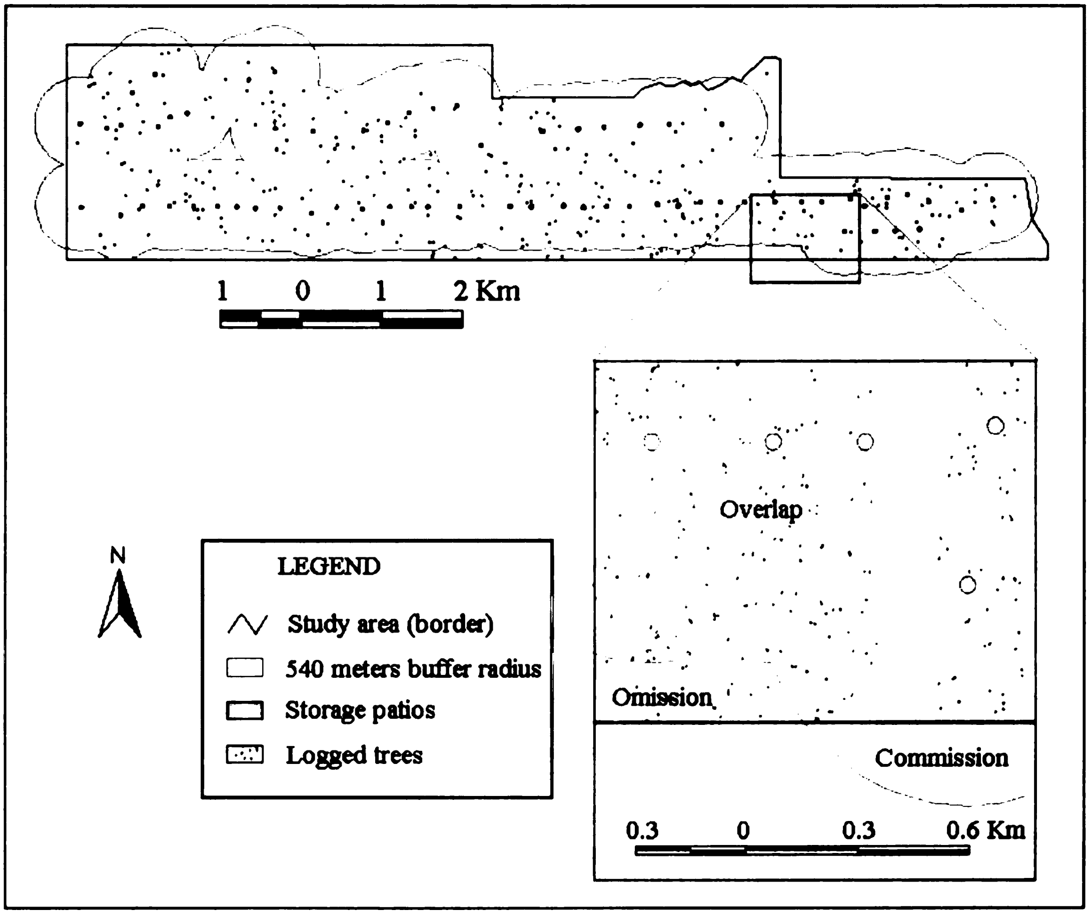


Figure 3.1. Buffer radius around patios intersecting selectively logged forest

The buffer radius of 150 meters overlapped only 27.7% of the total logged trees (stumps) and 22.7% of the total logged forest area from the ground truth data. This buffer radius omitted 77.3% of the total logged forest and 72.3% of the total stumps (logged trees). The buffer radiuses from 180 to 540 meters significantly increased detection of selectively logged forest from 29.3% to 89.4%, respectively. Additionally, these buffer radiuses reduced the omission areas from 70.7% to 10.6%, respectively, and showed no commission errors (appendix C.4).

Buffer radiuses from 570 to 720 meters showed an increase in the detection of selectively logged forest from 91.6% to 97.8%, respectively, and a slight decrease in the omission area, from 8.4% to 2.2%, respectively. Practically 100% of the logged forest and stumps were detected using 720 meter buffer radius. However, this buffer distance created 2.2% and 21.9% of the omission and commission errors, respectively, which represent a reduction of only 0.9% of the omission errors, and an increment of 18% of the commission areas when compared with the 570 meters buffer radius (figure 3.2).

By using remotely sensed data and a textural algorithm, a total area of 243.26 hectares of log landings (patios and roads) were detected. The initial buffer radius of 150 meters around those detected log landings intersected with 45.8% of the total logged trees (stumps) and 43.3% of the total logged forest, omitting 56.7% of the total logged forest (appendix C.5).

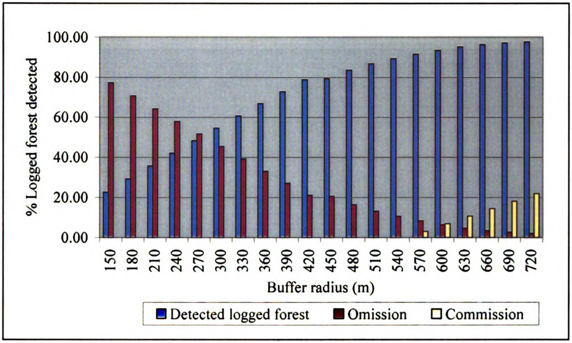


Figure 3.2. Different buffer radiuses around storage patios (from the field studies)

By increasing the buffer radius from 180 to 450 meters (appendix C.3), the detection of selectively logged forest significantly increased from 49.3% to 88.1%, respectively, while the omission errors decreased from 50.7% to 11.9% of the total logged area. Commission errors were not present in these cases. Increasing buffer radiuses from 480 to 720 meters, also increased the detection of selective logging from 90.1% to 98.3% of the total logged forest, respectively, and slightly decreased the omission area from 9.8% to 1.7%, respectively. However, it created more than 29% of commission (overestimation) errors, increasing from 1.1% to 30.7% (figure 3.3).

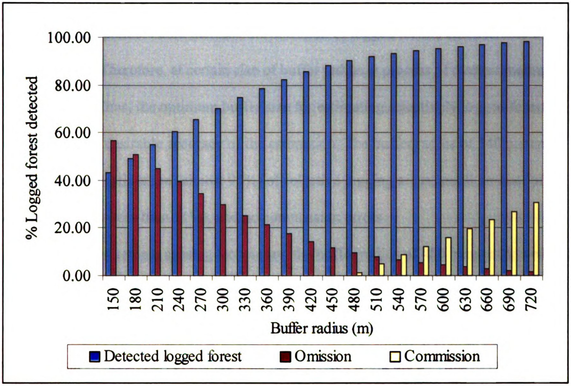


Figure 3.3. Different buffer radiuses around log landings detected using textural algorithm, Landsat ETM+, band 5.

### 3.5. Discussion and conclusion

This research developed an alternative approach to estimate selectively logged forest using remote sensing techniques, based on the field study conducted in the Amazon State of Rondônia.

There is a growing demand for research to better understand selective logging in the Brazilian Amazon due to its potential effects on the environment and its interaction with the process of land use and land cover change (Stone and Lefebre 1998, Nepstad et al. 1999, Sousa and Barreto 2000, Alvarado and Sandberg 2001).

Based on the ground truthing data, I observed that the increasing size of the buffer around storage patios would increase the detection of logged forests and decrease the missing areas. Therefore, at certain size of buffer radius, a process of overestimating would begin. Thus, the optimum buffer size for estimating selectively logged forest depends on the desirable accuracy of the estimation. The buffer radius of 540 meters showed a good estimation (almost 90%) of selective logging areas, small amount of omission errors (less than 11%), and no commission errors.

Based on remote sensing techniques, the buffer radius of 480 meters showed to be more precise for logging detection, overlapping more than 90% of the logged forest, creating less than 10% of omission errors, and approximately 1% of commission errors. I observed an exaggeration of the log landings detected using the automated method because of effect of the textural algorithm, moving window 5 x 5 pixels, applied on Landsat ETM+ band 5. Hence, the smaller buffer radius produced a similar buffer zone compared to larger buffer radiuses based on the ground truthing data.

It is noted that the detection and estimation of low intensity selective logging using Landsat imagery depends on the contrast between forest and soil exposure, observed mostly in patios and road areas. In this study area, soil reflectance in tree-fall gaps and skidder trails were not noticeable enough to be visually or automatically detected on Landsat ETM+ imagery because of the low intensity (11.3 $m^3$ $ha^{-1}$) of logging. Consequently, the total area impacted by selective logging had to be estimated by using automatic analysis only (texture algorithm plus buffer radius around log landings).

Finally, I observed that loggers often use the road network built to serve the colonization settlement in the Cujubim municipality as forest access road. In this case, no infrastructure is installed prior to logging operations. Logs are dragged hundreds of meters from the forest interior to the roads using small trucks, winch tractors, or skidders. I also observed that the margins of the roads are often used as temporary log storage area, serving as an intermediate stage between forest and the sawmills, thus limiting the number of patios. In this case, evidence of selective logging and forest degradation are not easily detectable using satellite imagery because of lacking of soil exposure by logging features on the ground. Therefore, other experimental efforts to develop methodological approaches to estimate these types of selective logging are needed.

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CHAPTER IV

Inter and Intra-annual Analysis

## 4.1. Abstract

This chapter addresses the annual rates and the fates of forests impacted by selective logging through inter and intra-annual analyzes of remotely sensed data and field observations conducted in two study sites in the Brazilian Amazon. The study areas are covered by two Landsat scenes, path 232 row 067 and path 226 row 068, located in the Amazon States of Rondônia and Mato Grosso, respectively. Visual interpretation and an automated method (texture analysis) were applied. The fieldwork examined the consistency of the remote sensing techniques by visiting areas identified as logged forests on Landsat imagery. Based on this research results, I found that selective logging increased 1,028 $Km^2$ per year while deforestation increased 371 $Km^2$ per year during 1993 to 2002 in the State of Mato Grosso study site. However, compared with the total area detected, the increment of new selective logging areas in the Mato Grosso study site decreased 22% from 1992 to 1999, respectively. More than 18% of the total logged forest detected from 1992 to 2001 was deforested by 2002 in that study site. Deforestation immediately following logging was observed in 2.9% of the total logging increment from May 2001 to April 2002, which represents 13.22% of the deforestation increment in this given period. In the Rondônia study site, new areas of selective logging increased an average of 91.42% per year compared with the total area of logging detected from 1989 to 2001, which corresponds to an increase of 40 $Km^2$ per year of new selective logging areas. From the total of 479 $Km^2$ of selectively logged forests detected on satellite imagery in the given period, more than 15% was deforested by 2001.

## 4.2. Introduction

As presented in the previous Chapters, although selective logging only harvests a portion of trees, it can damage a large portion of forest and many others trees during logging operations (Pinard and Putz 1996, Nepstad et al. 1999, Huth and Ditzer 2001).

The damages caused by selective logging vary according to the extraction intensity and and affect the ability of the forest to recover if it is abandoned after the harvest. If logged forests are revisited several times to harvest additional tree species (Uhl et al. 1997, Veríssimo et al 1995), these forests become highly degraded and may have 40 – 50% of the canopy cover destroyed during the logging operations (Uhl and Vieira 1989, Veríssimo et al. 1992).

Stone and Lefebvre (1998) observed different intensities of selective logging in the case study in the State of Para, Brazil. The study showed that the intensity of logging directly affected the extent of forest damages. The impacts of heavy machinery were observed within the forest even several years after the harvest. The authors affirmed that although selective logging impacts were evident in the field observations, it was very difficult to distinguish logged and undisturbed forest four years following harvest using satellite imagery.

Sousa and Barreto (2000) reported that log landings (patios and access roads) from 1987 could not be detected using remote sensing techniques in 1991. Even areas of logging in 1993 could not be detected in 1996. The authors stated that forest regeneration covered the areas of bare soils, which became difficult to detect using remotely sensed data. Hence, they suggested that a multi-temporal analysis of selective logging must use images acquired no more than two years apart.

In this study, multi-annual and intra-annual analysis were performed using remotely sensing data, acquired annually from 1989 to 2002, and complementarily field verification, in two case studies located in the States of Mato Grosso and Rondônia. These analyzes are intended to assess annual rates of selective logging increment and the fate of logged forests such as subsequent logging or deforestation following harvest.

## 4.3. Regional settings: Southern and Southwestern Brazilian Amazonia

This study was conducted at the Sinop municipality in the state of Mato Grosso, Southern Brazilian Amazon, and at the Ariquemes municipality in the state of Rondônia, Southwestern Brazilian Amazon. Two Landsat scenes defined the subsequent areas of study used in this analysis path/row 226/068 for the state of Mato Grosso and path/row 232/067 for the state of Rondônia. Each scene encompasses approximately 187 x 186 km (appendix D.1).

### 4.3.1. Description of the study area in the State of Rondônia

The climate at the study area in the state of Rondônia is humid tropical with annual precipitation of 2400 mm. A dry season extends from June through September. The mean annual temperature is 26° C. The predominant vegetation type is open canopy tropical forest, though savanna and dense forest occur sparsely (RADAMBRASIL, 1978). Changes in land use reflecting an increase in selective logging and pasture have affected the previous closed canopy forest cover.

According to Pedlowski et al. (1997), the state of Rondônia was part of the new frontier occupation program created and enforced by the Brazilian federal government. This program supported a road network improvement and construction in order to promote the occupation of a new frontier with landless people from other Brazilian regions and, at the same time, to promote economic growth (Dale et al. 1993, Pedlowski et al. 1997).

As a consequence of this occupation process, the State of Rondônia has experienced increasingly rapid landscape change. The area of deforestation increased from 4.2 thousand $Km^2$ to 58.1 thousand $Km^2$ from 1978 to 2000, an increase of approximately 1383%, which corresponds to 9.9% of the total Brazilian Amazônia deforestation (INPE, 2003). Additionally, more than 15 million $m^3$ of round wood had been exploited in the State of Rondônia from 1990 to 2001 (IBGE, 2003).

### 4.3.2. Description of the study site in the State of Mato Grosso

The climate in the study area (path/row 226/068) in the state of Mato Grosso is humid tropical with annual precipitation of 2000 mm. The mean annual temperature is 26° C. A dry season extends from June through September. This area was originally completely covered by semi-deciduous forest with emergent canopy. The predominant soil type is dystrophic red-yellow Latossols (RADAMBRASIL, 1978).

In the state of Mato Grosso land use has been significantly changed from natural vegetation to pasture and agricultural lands. Deforestation increased from 20 $Km^2$ in 19?? to 143.9 thousand $Km^2$ by 2000, an increase of 719%, corresponding to 24.49% of the total Brazilian Amazonia deforestation (INPE, 2003). The round wood production from 1990 to 2001 reached more than 36 million $m^3$ exploited from natural forest (IBGE, 2003).

## 4.4. Methods

### 4.4.1. Satellite imagery and geometric rectification

Digital Landsat ETM+ images for the state of Mato Grosso (path 226 row 069) and for the state of Rondônia (path 232 row 067) from the Center for Global Change and Earth Observation (CGCEO) at Michigan State University were used. These images were acquired annually from 1989 to 2001 (appendix D.2) and from 1992 to 2002 (appendix D.3) for the States of Rondônia and Mato Grosso, respectively. Three additional images (path 226 row 068) were acquired in 2001 for an intra-annual analysis. The images from different years were rectified using ERDAS nearest-neighbor resampling method and ground control points acquired using a GPS Trimble Pro-XR and Geo-Explorer II within each Landsat scene.

### 4.4.2. Detection of selectively logged forest

Automatic analysis and visual interpretation techniques for selective logging detection were applied. Inter-annual analysis of selective logging was performed on the Landsat images acquired annually. Additional intra-annual analysis of selective logging in the state of the Mato Grosso was performed using different acquisition dates within 2001.

The automated method, discussed in the chapter 2 and 3, created textural images from Landsat TM and ETM+, band 5. Sequentially, these images were re-classified to separate log landings from the undisturbed forest canopy and converted to Arc/Info coverage in order to remove any remaining extraneous features that were not associated with logging. A buffer radius of 180 meters around log landings was applied basin-wide, except for the State of Rondônia and Acre (as discussed in the chapter 3), where a regional buffer radius of 480 meters was applied. These buffer radiuses were applied in order to estimate the amount of forest areas actually affected by logging and not necessarily visible on satellite imagery. Janeczek (1999) described those areas as "cryptic logging".

As presented in the Chapter 2, visual interpretation to detect selectively logged forests was done using RBG 5/3/2 color composite of the Landsat images, displayed at full resolution on a computer screen. In this research, the areas of visible logging were described as obvious logging. Logged forests were manually digitized on each image at varied scales from 1:100,000 using Arc/Info. The minimum scale for manually digitizing on Landsat imagery was 1:25,000. In this research, visible logged forest includes spectrally bright patios, roads, and obvious canopy disturbance as well as logged areas that exhibit faded log landings. The areas around the log landings together with areas of obvious canopy degradation were digitized as polygons into vector GIS layer. They were then classified as logged forest. The digitizing was done on the very edge of canopy disturbance. Logged forests that did not have visible canopy disturbance on satellite images were not digitized.

## 4.5. Field studies

### 4.5.1. State of Mato Grosso

The field study was conducted during July 2002 in the at Sinop municipality. A Landsat scene (path 226 row 068) encompassed the whole study area. In this part of the research, two senior students from Forest Engineering (Fernando Raiter and Jansen Luiz

Trienweiler), Federal University of Mato Grosso, and two researchers from the Michigan State University (Walter Chomentowski and Stephen Cameron) contributed with this field verification. We visited abandoned and current selective logging sites. We visited and verified areas of selective logging previously detected on Landsat imagery, focusing on the image acquired in 2001 (the year prior our visit).

Selective logging activities in the State of Mato Grosso were shown to be intensive and mostly located on 'latifundios' (extensive areas of private land). Therefore, unequivocally we observed evidence of logging such as forest canopy damages, tree fall gaps, and logging infrastructure such as access roads and patios.

As already presented in the Chapter 2, selective logging damage such as tree fall gaps, stumps, logging access roads, skidder trails, and patios are quite evident in the field two years after selective logging activities. These forest disturbances were evident in the field from three to five years after logging and most of the forest damages, caused by logging activities were covered by a strong secondary regrowth. In some cases of severe impacts by logging activities, evidence of soil exposures (roads and patios) were still observed even after 5 years after logging.

According to Annor Zanchette (the owner of Continental ranch), personal communication 7/2002), the regional average of logging harvest is around of 25 $m^3$ of round wood per hectare. This harvesting intensity is variable depending on the market demand for timber species and forest characteristics in terms of volume availability.

Wild fire does seem to affect logged forest in this study area. Indeed, Cochrane (2001) affirmed that selective logging increases forest fragmentation and, consequently, forest fire susceptibility. Logged forest and deforested areas converted to pasture or agriculture are sharing the same space in that region. According to Uhl and Buschbacher (1985), Uhl and Kauffman (1990), and Cochrane (2001) agricultural plots in the Brazilian Amazon are the main widespread ignition source of fire. Some of the areas visited showed intensive forest degradation. Evidence of fire was observed in all of them, which can be classified as a new land use type. Those areas form a blend of logged forest and secondary regrowth. When using unsupervised classification of landsat images, most of these areas were classified as secondary regrowth or deforestation. Gerwing (2000), observed that a combination of selective logging and fire degrades forest structure and creates different land cover types characterized between natural forest and deforested areas.

#### 4.5.2. State of Rondônia

The field study was conducted during June 2002 at Ariquemes, Campo Novo, Buritis, and Monte Negro municipalities in the State of Rondônia. The study area was all included in a Landsat ETM+ scene (path 232 row 067). Two local forest engineers (Wilson Soares Abdala and Vilmar Ferreira) contributed with this field study.

We visited selective logging areas previously detected on satellite imagery. Twenty sites out of one hundred and six digitized polygons on Landsat imagery acquired in 2001, were visited. We observed that all of them were logged in the previous year, still showing clear evidences of selective logging such as visible canopy disturbances, temporary logging roads, and patios. Although the patios and roads were still visible in the field, we observed a strong regeneration and most of the tree fall gaps and skidder trails were already covered by secondary regrowth (vines, fast-growth tree-species, etc).

In general, we observed that loggers distribute the patios and roads randomly within the forest rather than following previous planning. The logging roads seemed to be plotted according to the source of the most market valuable trees (raw material for timber industries), therefore showing irregularly curves. Nearby logging areas at the margins of the road network are often used as temporary log storage area.

According to the forest engineers Abdala and Ferreira (2003), an average of around 15 $m^3$ per hectare had been harvested in the visited areas. Additionally, they demonstrated that selective logging infrastructures (patios and roads) are very expensive. Loggers prefer to drag logs farther away (as far as a thousand meters) rather than building more access roads and patios. In this case, rather than trucks, loggers are likely to use more skidders or tractors for the inside forest logging operations, therefore, there are less visible features on satellite imagery such as access roads and patios.

Although the purpose of this research was the ground verification of selective logging sites detected on satellite imagery, many other sites showed evidence of selective logging , at certain stages of recovery. Those sites are located at the Burareiro and Marechal settlement projects.

In these settlement projects, I observed that most of the remaining forests are part of legal reserves required by the national forestry code (federal law) for individual farms. Although deforestation is not allowed in those legal reserves, logging is permitted under special requests to the local Federal Environmental Agency (Instituto Brasileiro do Meio Ambiente e Recursos Naturais Renovaveis – IBAMA). Consequently, the logging harvest cycle depends on the economic or timber demand of the landowner. Furthermore, selective logging requires low investment in infrastructure in those areas since a road network is already present to serve each individual farm. We observed that the road network built to serve the settlers for agro-products transportation and access was often used as a log storage and loading areas at its margins.

We also observed a low to very low intensity of logging in these settlement projects, varying from 3 to 10 $m^3$ $ha^{-1}$. Logs are dragged hundreds meters from the interior forest to the roads using winch tractors, small trucks, or skidders.

In spite of the low intensity of logging, from the ground, logged forests were easily identified because of the visible forest damages (logging trails, tree-fall gaps, and stumps) caused during logging activities. However, we observed that forests disturbed by logging were rapidly recovering from the direct logging impact. Those areas showed very strong vine and fast-growth species regeneration. These might be the reasons why detection of selective logging using Landsat imagery is very difficult in that study area.

## 4.6. Results

### 4.6.1. Case study: the State of Mato Grosso

The results of this research show that deforestation area derived from the Landsat scene, path /row 226/068, increased from 12% to 24% of the total study area between 1992 and 2002. Cumulative selective logging areas in the study site increased from 4% to 36% of the total study site area by 1992 and 2002, respectively. By 2002, only 40% of the study area remained as undisturbed forest (figure 4.1).

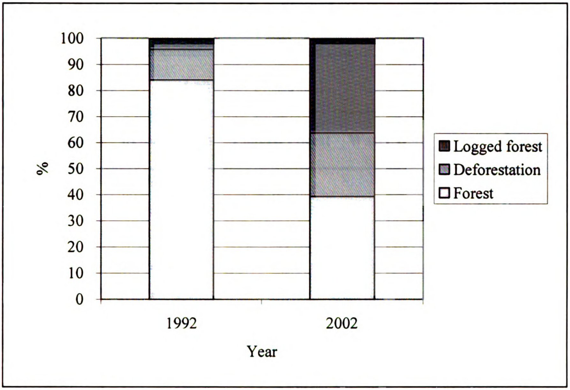


Figure 4.1. Land use and land cover change in the study site (path/ row 226/068)

An average of 371.4 $Km^2 yr^{-1}$ were deforested from 1992 to 2002. The total areas of selective logging detectable from satellite imagery increased from 1.2 thousand $Km^2$ in 1992 to 4.4 thousand $Km^2$ in 2002, accounting for an increase of 366% (table 4.1).

Table 4.1. General results for the path/row 226/068

| Year | Land Use ($Km^2$) | | | | Deforestation Increase ($Km^2$) |
|---|---|---|---|---|---|
| | Forest | Deforestation | Logged Forest | Water Body | |
| 1992 | 24,527.1 | 3,403.6 | 1,166.0 | 36.1 | - |
| 1993 | 23,335.5 | 3,900.3 | 1,860.9 | 36.1 | 496.7 |
| 1994 | 22,961.0 | 4,246.4 | 1,889.6 | 35.9 | 346.0 |
| 1995 | 22,956.0 | 4,663.3 | 1,477.2 | 36.4 | 416.9 |
| 1996 | 22,457.5 | 5,036.8 | 1,602.1 | 36.5 | 373.5 |
| 1997 | 21,584.1 | 5,420.8 | 2,091.4 | 36.5 | 384.0 |
| 1998 | 20,370.2 | 5,733.4 | 2,992.8 | 36.3 | 312.6 |
| 1999 | 18,646.2 | 6,221.4 | 4,228.8 | 36.4 | 488.0 |
| 2000 | 18,425.7 | 6,357.7 | 4,313.0 | 36.4 | 136.3 |
| 2001 | 17,914.4 | 6,844.0 | 4,338.0 | 36.4 | 486.3 |
| 2002 | 17,581.7 | 7,117.5 | 4,397.2 | 36.4 | 273.5 |
| **Annual rate of deforestation ($Km^2$)** | | | | | **371.4** |

**Note:** A mask of 972 $Km^2$ of the overall clouds, shadows, and smoke was applied.

The increase of new areas of selective logging observed from 1993 to 2001 was about 1,080 $Km^2$ $yr^{-1}$. A small reduction was verified during the 1994 through 1996 period, an average of 730 $Km^2$ $yr^{-1}$. A significant increase was verified in 1999, an average of 1,800 $Km^2$ $yr^{-1}$. From 2001 to April 2002, an increase of approximately 600 $Km^2$ was observed, causing a partial increment for that given year. Although overall areas of selective logging have been increasing from 1993 to 2002, the relative annual increase (total increase compared with total logging detected) has been decreasing from 62.99%, 49.44%, to 27.22% in 1993, 1997, and 2001, respectively (table 4.2).

Table 4.2. Selective logging and deforestation increase for the path/row 226/068

| Year | Logging | | | Deforestation | | |
|---|---|---|---|---|---|---|
| | Area ($Km^2$) | | | Area ($Km^2$) | | |
| | Total | Increment | % | Total | Increment | % |
| 1992 | 1,165.98 | - | - | 3,403.65 | - | - |
| 1993 | 1,860.92 | 1,172.13 | 62.99 | 3,900.32 | 496.67 | 12.73 |
| 1994 | 1,889.56 | 719.99 | 38.10 | 4,246.36 | 346.04 | 8.15 |
| 1995 | 1,477.16 | 676.18 | 45.78 | 4,663.27 | 416.91 | 8.94 |
| 1996 | 1,602.11 | 802.44 | 50.09 | 5,036.81 | 373.54 | 7.42 |
| 1997 | 2,091.44 | 1,033.94 | 49.44 | 5,420.82 | 384.01 | 7.08 |
| 1998 | 2,992.83 | 1,113.02 | 37.19 | 5,733.44 | 312.62 | 5.45 |
| 1999 | 4,228.75 | 1,838.86 | 43.48 | 6,221.43 | 487.99 | 7.84 |
| 2000 | 4,313.00 | 1,169.78 | 27.12 | 6,357.70 | 136.27 | 2.14 |
| 2001 | 4,337.99 | 1,180.95 | 27.22 | 6,843.99 | 486.29 | 7.11 |
| 2002 | 4,397.24 | 575.38 | 13.09 | 7,117.50 | 273.51 | 3.84 |

Deforestation of logged forests is more likely to occur in the oldest logging areas. For example, deforestation of previously logged forests by 2002 decreased from 23%, 14%, 6%, to 0.8% for areas detected as logging in 1992, 1995, 1998 and 2001, respectively (table 4.3).

Table 4.3. Deforestation and selective logging for the path/row 226/068

| Year of logging | Total logged forest | Logging areas deforested by 2002 | |
|---|---|---|---|
| | Area ($Km^2$) | Area ($Km^2$) | % |
| 1992 | 1165.98 | 265.30 | 22.75 |
| 1993 | 1860.92 | 338.60 | 18.20 |
| 1994 | 1889.56 | 307.97 | 16.30 |
| 1995 | 1477.16 | 206.76 | 14.00 |
| 1996 | 1602.11 | 158.06 | 9.87 |
| 1997 | 2091.44 | 138.89 | 6.64 |
| 1998 | 2992.83 | 185.59 | 6.20 |
| 1999 | 4228.75 | 145.60 | 3.44 |
| 2000 | 4313.00 | 122.74 | 2.85 |
| 2001 | 4337.99 | 36.15 | 0.83 |

Remote sensing analysis showed that selective logging could be detected on satellite imagery for years. However, according to the field observations logging generally stays active at a specific place no more than a year. Based on that, I estimated that, from 1993 to 2000, an average of 7% of the active or ongoing logging was, in fact, a 'revisit' of previously logged forest. The areas of revisit logging had increased from 32, 319, to 455 $Km^2$ in 1994, 1998, and 2002, respectively (table 4.4).

Table 4.4. Selectively logged forest revisited (path/row 226/068)

| Year | Total logging | Net logging increment | Revisited logging | |
|---|---|---|---|---|
| | Area ($Km^{2}$) | Area ($Km^{2}$) | Area ($Km^{2}$) | (%) |
| 1992 | 1,165.98 | | | - |
| 1993 | 1,860.93 | 1,172.13 | - | - |
| 1994 | 1,889.56 | 719.99 | 31.99 | 1.69 |
| 1995 | 1,477.16 | 676.18 | 51.43 | 3.48 |
| 1996 | 1,602.11 | 802.44 | 101.55 | 6.34 |
| 1997 | 2,091.44 | 1,033.94 | 148.91 | 7.12 |
| 1998 | 2,992.84 | 1,113.02 | 319.28 | 10.67 |
| 1999 | 4,228.75 | 1,838.86 | 431.70 | 10.21 |
| 2000 | 4,313.00 | 1,169.78 | 491.61 | 11.40 |
| 2001 | 4,337.99 | 1,180.95 | 394.53 | 9.09 |
| 2002 | 4,397.24 | 575.38 | 455.26 | 10.35 |

Although revisited logging areas are relatively small compared with the total selective logging, they account more than 23% of the total increase of new logging areas from 1992 to 2001.

#### 4.6.1.1. Intra-annual analysis

The intra-annual analysis was conducted using four Landsat images (path/row 226/068), three acquired in May, August, October 2001, and one acquired in April 2002 (appendix D.3). The average of the total logging area detected was 4,134 $Km^2$ for the four scenes. The increase of new logging areas was 1,248.84 $Km^2$ from May 2001 to April 2002. The total deforestation estimated for the given period was 273.51 $Km^2$. Part of this total deforestation (36.15 $Km^2$) was from land previously affected by selective logging (appendix D.4). Those areas were deforested immediately after logging and represent 2.9% of the total net logging increase detected on satellite imagery in that period of time (table 4.5).

Table 4.5. Intra-annual increment of selective logging (path/row 226/068)

| **Period of time** | **Logging net increment Area ($Km^2$)** |
|---|---|
| May 2001 to August 2001 | 483.42 |
| August 2001 to October 2001 | 273.53 |
| October 2001 to April 2002 | 491.45 |
| **Total net logging increment (2001 to 2002)** | **1,248.4** |
| **Total of logged forest deforested by 2002** | **36.15** |

Although deforestation immediately following selective logging is only 2.9% of the logging increment, it represents 13.22% of the deforestation increment in the period of 2001 to 2002.

### 4.6.2. Case study in the State of Rondônia

The results of this research show that it is not possible to detect selectively logged forest from Landsat imagery in this study area as much as in the case study in the State of Mato Grosso.

Based on the time-series imagery 1989 to 2001 of the path/row 232/067, the total selective logging detected averaged only 43.4 $Km^2$ $yr^{-1}$. Approximately 8.3% of detected logging on satellite imagery was derived from the previous year logging. An additional 0.3% was detected from two years previous logging. Consequently, most of logging areas detected using Landsat imagery (91.4%) were considered new logging areas averaging 39.9 $Km^2 yr^{-1}$ of net increase (table 4.6).

Table 4.6. Selectively logged for the path/row 232/067

| Year | Selective logging | | |
|---|---|---|---|
| | Total | Net increment | |
| | Area ($Km^2$) | Area ($Km^2$) | % |
| 1989 | 40.29 | | |
| 1990 | 33.84 | 22.08 | 65.24 |
| 1991 | 24.48 | 23.26 | 95.02 |
| 1992 | 10.32 | 10.32 | 100.00 |
| 1993 | 66.38 | 63.78 | 96.08 |
| 1994 | 15.48 | 9.28 | 59.96 |
| 1995 | 18.47 | 14.33 | 77.58 |
| 1996 | 28.53 | 27.69 | 97.06 |
| 1997 | 49.95 | 42.92 | 85.92 |
| 1998 | 31.67 | 29.52 | 93.21 |
| 1999 | 124.27 | 121.41 | 97.70 |
| 2000 | 37.67 | 35.70 | 94.77 |
| 2001 | 82.93 | 78.74 | 94.95 |
| **Total** | **523.98** | **479.02** | **91.42** |

### 4.7. Discussion and conclusion

According to the results from the case study in the State of Mato Grosso, the total area of selective logging significantly increased from 1992 to 2002. The increase of new areas of selective logging has been slightly changed the last ten years. The average increase of new areas of selective logging was 39.15% of the total detected from 1992 to 2001. Nevertheless, the relative increase of new areas compared with the total logging area detected using Landsat imagery has decreased from 60.2% in 1992 to 47.52% in 1996, and to 37.97% in 1999, represented by the following linear equation with R2= 0.5757.

$$Y = -3.1794x + 6393.6$$

where:

Y= % of increment of selective logging areas compared with total detected or mapped on Landsat imagery

x = year of logging detection

Based on these research results, deforestation is not significantly following selective logging activities in the Mato Grosso case study, even though the total of around 1.9 thousand $Km^2$ or 18.11% of logged forest were deforested from 1992 to 2001. Moreover, loggers are revisiting former logging areas more often and, consequently, increasing forest degradation in the State of Mato Grosso study case. Hence, based on the studies by Uhl and Kauffman (1990), Holdsworth and Uhl (1997), and Cochrane et al. (1999), it is more likely that forest fire will be a significant risk for selectively logged forest in that region.

Results from the intra-annual analysis in the Mato Grosso study area show that deforestation immediately following logging activities may be reduced by 2.9% of the total logging areas detected on satellite imagery. These areas are classified as deforestation instead.

In the State of Rondônia study area, the total of 479 $Km^2$ of logged forest was detected from 1990 to 2001. The average increase of new selective logging areas compared with the total logging detected in this study site was 91.42% or 40 $Km^2\ yr^{-1}$ in the given period. The same increment showed to be slightly increasing from 82.5%, 87.87%, to 91.94% in 1992, 1996, and 1999, respectively, when applying the following linear equation with R2= 0.132.

$$Y = 1.3565x - 2619.7$$

where:

Y= % of increment of selective logging areas compared with total detected or mapped on Landsat imagery

x= year of logging detection

The total of 72.6 $Km^2$ (15.2%) of logged forest were converted to agricultural land use by 2001. Although the field verification targeted logged areas previously detected on the satellite imagery, I observed several logged forest areas that were not detected on satellite imagery.

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## CHAPTER V

## Amazon-Wide Selective Logging Detection and Measurement

### 5.1. Abstract

Amazonian deforestation is a significant perturbation of the global terrestrial carbon cycle. In the Amazon, forest clearing is quite apparent using Landsat satellite imagery. Most available land cover data maps show only sites where trees have been completely removed, not partially removed or degraded as in the case of selective logging. Large-scale selective logging is a relatively new activity in the Amazon, the full consequences of which have yet to be evaluated. Forest degradation caused by logging and accidental fire is visible in Landsat ETM+ images, however, rapid regrowth (within one to five years) can quickly obscure these areas. Forest impoverishment due to logging in Amazonia has been estimated to create a net carbon flux equal to approximately 4-7 % of the annual carbon release from deforestation. Therefore, current carbon flux estimates for the region may be low because the growing effects of logging have not been accounted for. In this research, visual interpretation and textural analysis remote sensing techniques were applied to identify and map selective logging in tropical "terra-firme" (high land) forests together with the correlated multi-annual measurement results for 1992, 1996, and 1999, for the Brazilian Amazon. Logged areas detected using this methodology indicate that selective logging is increasing rapidly in both intensity (regional) and area (basin-wide). Specifically, by 1992, at least 5,980 $Km^2$ of forest had been logged. During the 1992-1996 and 1996-1999 intervals, the area impacted expanded by an additional 10,064 $Km^2$, and 26,085 $Km^2$, respectively. Based on a multi-annual analysis, it was estimated that part of this total logged forest, at least 3,689 $Km^2$ had

being actively logged by 1992, an additional 5,107 $Km^2$, and 11,638 $Km^2$, had been logged by 1996 and 1999. It was also estimated that at least 10% of logging areas detected in 1999 were previously logged. This methodology is considered conservative since it may miss very-low intensity logging and logging in riparian forests. The data presented here represent the first multi-temporal assessment of the amount and locations of selective logging in the Brazilian Amazon.

## 5.2. Introduction

Satellite-based remote sensing has been used for many years to monitor and evaluate land cover change in the Amazon, concentrating on forest and deforested land evaluation (Fearnside et al. 1990, Skole and Tucker 1993). Data from these studies, such as the rate of deforestation in Brazil's Legal Amazon, are often used to estimate human effects on the global carbon cycle (Fearnside 1997, Houghton 1997). Nevertheless, according to Nepstad et al. (1999), "present estimates of annual deforestation for Brazilian Amazonian capture less than half of the forest area that is impoverished each year, and even less during years of severe drought."

In addition to outright deforestation, Amazonian 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 a 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 40% of the remaining trees being killed or severely damaged (Uhl et al. 1991). The impacts of selective logging vary with extraction intensity, but can be substantial. 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 very degraded and may have 40 – 50% of the canopy cover destroyed during these 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 (Martini et al 1994), and emissions of carbon (Houghton 1996). Furthermore, uncontrolled exploration by loggers catalyzes 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 activity in Amazonian forests. Using field surveys of 1393 wood mills in the Brazilian Amazon, Nepstad et al. (1999) estimated that 10,000 to 15,000 $km^2yr^{-1}$ of forest are severely damaged by logging. Moreover, IBGE (2003) estimates that, between 1990 and 1999, more than 413 million cubic meters of round wood was extracted from the North region of Brazil, an average of almost 41.3 million $m^3yr^{-1}$.

Selective logging has been occurring in Brazil's tropical forests for several years, but, although the damages are readily visible in some Landsat TM images, the activity has not been detected or quantified by most Landsat TM classification techniques. For example, previous estimates of deforestation for Brazil's Legal Amazon, reported by Michigan State University - MSU and the Brazilian Space Agency - INPE, did not include most selectively logged areas (Janeczek, 1999).

Visual interpretation and a textural algorithm were applied to identify and map selective logging areas 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, regrowth, cerrado, cloud, cloud shadow, and water.

## 5.3. Methodology

### 5.3.1. 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. It is $5x10^6$ $km^2$ 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 the more than 600 Landsat images, covering the Legal Amazon, that are part of the ongoing deforestation monitoring at the Center for Global Change and Earth Observations (CGCEO) at 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 5.1). These images defined the subsequent areas of study used in this analysis.

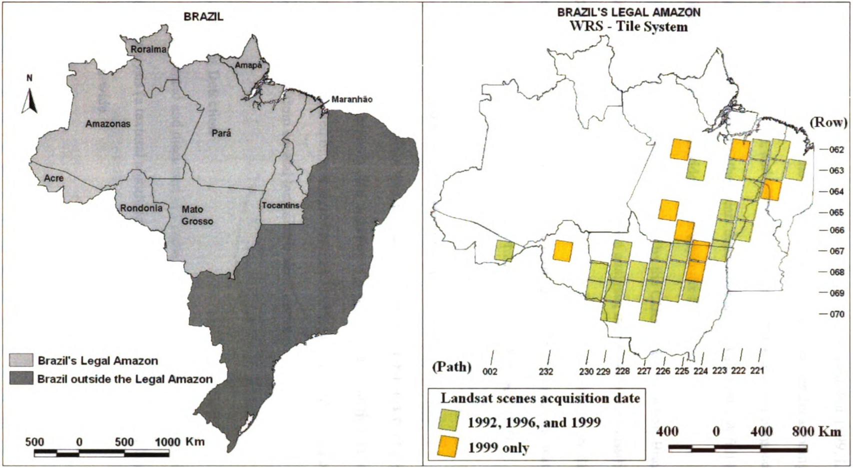


Figure 5.1. Images used in the logging Analysis.

For dates prior to 1999, Landsat 5 TM imagery was used. For 1999, Landsat 7 ETM+ imagery was used for the analyses. Although I classify results as being from three different years (1992, 1996, and 1999) for measurement and analysis purposes, some of the imagery was acquired in other years depending on its availability. A full listing of the individual scenes used is provided in the appendix E.1.

The deforestation dataset produced by the CGGEO for the whole Brazilian Amazon was also used. In the deforestation analysis, the imagery was classified, using an unsupervised image classification model of bands 2, 3, 4, and 5, into seven thematic classes: forest, deforestation, regeneration, cerrado, clouds, shadows, and water. This dataset is available in Arc/Info and Grid format for 1992, 1996, and 1999.

### 5.3.2- Calibration and Geometric Rectification

Geometric rectification was done using nearest-neighbor resampling with the four points derived from ephemeris data, supplied with the images at the time of ordering. Additionally, the rectified images were validated and tested at BSRSI using collected GPS ground points from several locations in the Amazon.

### 5.3.3. Logging Detection

As presented and discussed in Chapters 2, 3, and 4, visual interpretation and automatic analysis (a textural algorithm) were applied to detect and quantify selective logging Amazon-wide.

#### 5.3.3.1. Automatic Analysis

The automatic analysis consisted in applying a textural algorithm (variance), 5 x 5 moving window operator, on band 5 of Landsat TM and ETM+. The resultant texture images were used to detect log landings, 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 5.2). Those images were re-classified using Erdas modeling tools, selecting and capturing the pixels values (mostly from 6 to 11) correlated to areas directly affected by selective logging, such as patios and roads.

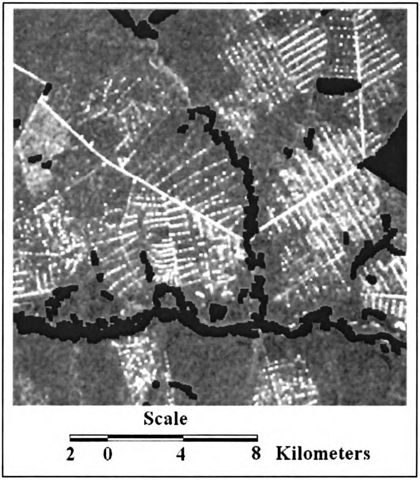


Figure 5.2. Log landings detected using textural algorithm, band 5, 226/068, 2002.

The classified texture images were converted to vector format and edited to removing any remaining extraneous features that were not associated with logging. A buffer radius of 180 meters, as suggested by Souza and Barreto (2000), was applied around the detected log landings (patios) in order to estimate the amount of forest actually affected by logging (Figure 5.3). A buffer radius of 450 meters, as presented in the Chapter 3, was applied for the State of Rondônia and Acre, because of their specific characteristics in terms of selective logging. Those areas of selective logging detected using a buffer radius here are described as Cryptic Logging.

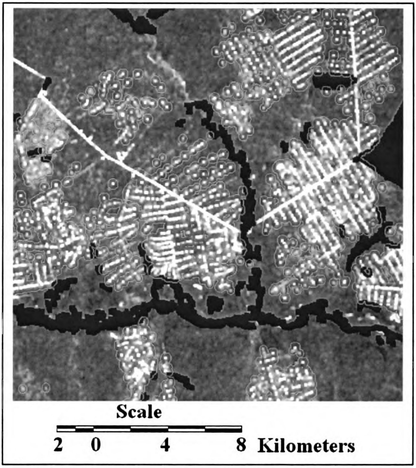


Figure 5.3. Buffer radius of 180 meters around of log landings detected using textural algorithm on band 5, path/row 226/068, 2002.

Non-forest areas (deforestation, cloud, shadow, cerrado, bodies of water, and regenerating vegetation) were subsequently masked out of band 5 of the Landsat images.

Subsequently, the non-forest mask was applied again to remove any regions where the suspected-logging areas overlapped with non-forested land cover classes.

**5.3.3.2. Visual Interpretation**

Visual interpretation of logged forests was done using RBG 5/3/2 color composite images, displayed at full resolution. The logged forests were digitized manually on each image at varied scales 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 log landings, and tree-fall gaps along with obvious 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 logging were identified, they were digitized into vector GIS layers. The digitizing was done on the very edge of canopy disturbance. The logging areas were classified into two separate vector coverages; "obvious" and "subtle" logging. "Obvious" logging includes spectrally bright patios, roads, and obvious canopy disturbance (figure 5.4).

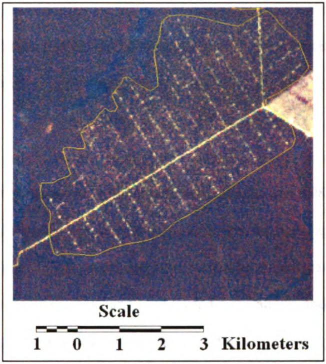


Figure 5.4. Obvious logging on Landsat image, 226/068, RGB 5/3/2, 2001.

Subtle logging refers to logged areas that exhibit visible canopy disturbance and faded log landings, or no log landings (figure 5.5).

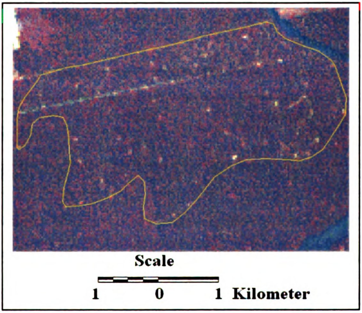


Figure 5.5 - Subtle logging on Landsat image, 226/068, RGB 5/3/2, 2001.

Logged forests that did not have visible canopy disturbance on satellite images were not digitized.

## 5.4. Results

In 1992, the basin-wide estimate of logged forests was 5,980 $km^2$. The detected logging areas were 10,064 $km^2$ in 1996 and 26,085 $km^2$ in 1999 (appendix E.2 for details by Landsat path/row). These areas were not detected by the deforestation classification, done by the Center for Global Change and Earth Observations, and represent an increment of degraded forest areas over those estimates.

In the period of analysis, the results show that visual interpretation detected an average of 83.4% (66.2% classified as "obvious logging" and 17.2% as "subtle logging"), while texture analysis ("cryptic logging") detected an average of 63.7% of the total logged forests (table 5.3).

Table 5.3. Selective logging by visual interpretation and automatic analysis

| Year | Visual interpretation | | | | Automatic analysis | | Total (*) |
|---|---|---|---|---|---|---|---|
| | Obvious | | Subtle | | Cryptic | | |
| | Area ($Km^2$) | % | Area ($km^2$) | % | Area ($Km^2$) | % | |
| 1992 | 3,946.41 | 66.00 | 1,269.36 | 21.23 | 3,163.03 | 52.90 | 5,979.80 |
| 1996 | 6,553.37 | 65.12 | 1,359.23 | 13.51 | 7,451.55 | 74.04 | 10,064.10 |
| 1999 | 17,600.08 | 67.47 | 4,428.84 | 16.98 | 16,767.06 | 64.28 | 26,085.40 |

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

Areas of selective logging detected in common between visual interpretation and automatic analysis were 36%, 53%, and 49%, respectively, in 1992, 1996, and 1999. Visual only contributed in detecting an additional of 47%, 26%, and 36%, respectively in 1992, 1996, and 1999 (table 5.4).

Table 5.4. Logging area by visual interpretation and automatic analysis

| Year | Visual only | | Automatic only | | Overlap (V/A) | | Total |
|---|---|---|---|---|---|---|---|
| | $Km^2$ | % | $Km^2$ | % | $Km^2$ | % | ($Km^2$) |
| 1992([1]) | 2,817.17 | 47.11 | 1,009.01 | 16.87 | 2,153.63 | 36.02 | 5,979.80 |
| 1996([2]) | 2,615.61 | 25.99 | 2,155.10 | 21.41 | 5,293.39 | 52.60 | 10,064.10 |
| 1999([2]) | 9,323.76 | 35.74 | 4,060.90 | 15.57 | 12,700.74 | 48.69 | 26,085.40 |

[1] done by Janeczek (1999) and revised by Matricardi (2003); [2] done by Matricardi (2003)

A state by state analysis of the results show 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 5.5).

Using this methodology, no logging was detected by in the states of Amazonas, Amapá, and Roraima. Additionally, only a small amount of logged forests was detected in states of Acre and Rondônia, even by applying a bigger regional buffer radius for these states presented in the Chapter 3.

Table 5.5. Selective-logging areas detected by State in the Brazilian Amazon

| **State** | **1992** | | **1996** | | **1999** | |
|---|---|---|---|---|---|---|
| | **Area (Km2)** | **%** | **Area (Km2)** | **%** | **Area (Km2)** | **%** |
| Acre | 7.84 | 0.13 | 29.52 | 0.29 | 23.94 | 0.09 |
| Amapá | - | - | - | - | - | - |
| Amazonas | - | - | - | - | - | - |
| Maranhão | 506.12 | 8.46 | 571.87 | 5.68 | 2,276.91 | 8.73 |
| Mato Grosso | 3,013.58 | 50.40 | 4,196.50 | 41.70 | 12,662.47 | 48.54 |
| Pará | 2,405.45 | 40.23 | 5,051.16 | 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 | 5,979.80 | 100.00 | 10,064.10 | 100.00 | 26,085.40 | 100.00 |

Moreover, multi-annual comparisons of detected logging in 1992-1996, 1992-1999, and 1996-1999 indicate areas in common of 267, 253, 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 of 148 $km^2$.

Multi-annual 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 1,074 $km^2$ (11%) of the logged forests in 1996 were deforested by 1999. Around of 342, 587, 2,706 $Km^2$ of overlap between deforestation and visual interpretation of selective logging, respectively by 1992, 1996, and 1999 was observed. Those areas were detected as logged forest and had been classified as deforestation, mostly as secondary regrowth, by using unsupervised classification in the deforestation analysis, because of their heavy canopy degradation. In this logging analysis, after fieldwork observation, those areas were re-classified as selective logging.

Approximately 123, 204, and 820 $km^2$ of overlap between logged and deforested areas, respectively, in 1992, 1996, and 1999. These overlap areas were due to the buffer zones that expanded beyond the forest areas into deforested areas. These areas of overlap were not included in the total area of logging.

## 5.5. Discussion and Conclusions

### 5.5.1. Accuracy assessments

Ecosystem damages from selective logging and subsequent impacts following the operation such as desiccation, fire, and access-based colonization are severe (Verissimo et al. 1992, Nepstad et al. 1999), causing canopy disturbance and soil exposure (Souza and Barreto, 2000). These changes are detectable using remote sensing and allow for estimation of the area of selectively logged forests in the Brazilian Amazon. Although these techniques are not applicable to all forests (e.g. varzea forests), they are applicable in areas of "terra firme" (dry land), which make up 80% of all forests and account for the vast majority of logging in the Amazon.

By using a "textural algorithm", the buffer radius developed by Souza and Barreto (2000), and a buffer radius developed in this research for States of Rondônia and Acre (Chapter 3), automatic analysis incorporated roughly 64% of the total (automated plus visual) estimated logging areas in 1992, 1996, and 1999. Visual interpretation incorporated approximately 83% of the total in the given years. These areas were classified as either 'obvious' or 'subtle' depending on their characteristics. 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 regrowth in previously logged forests. The division of the total detected logged forests by class, obvious (visual), subtle (visual), and cryptic (automatic) is presented in figure 5.6.

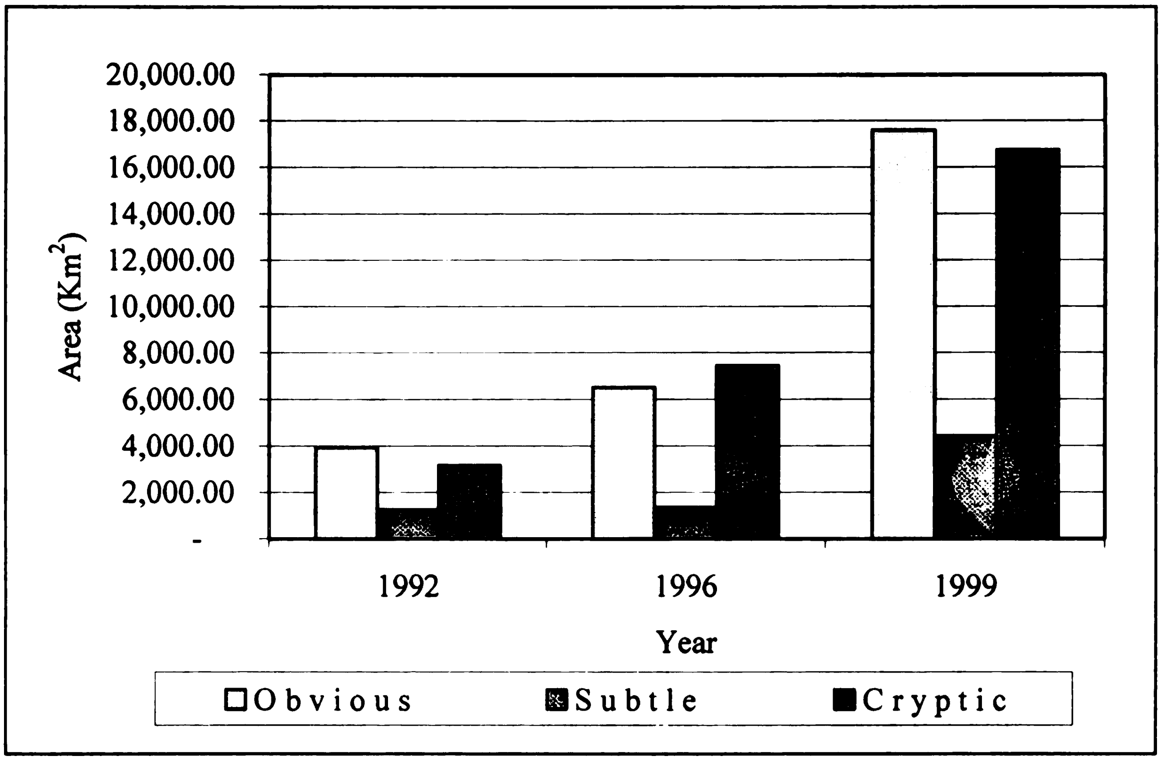


Figure 5.6. Logging areas classified according to the used detection methodology - Cryptic (texture analysis) and Obvious and Subtle (visual interpretation)

Visual interpretation only provided roughly 47%, 26%, and 36% of the detected logged forests, in 1992, 1996, and 1999 respectively, while texture analysis 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 the study years (figure 5.7).

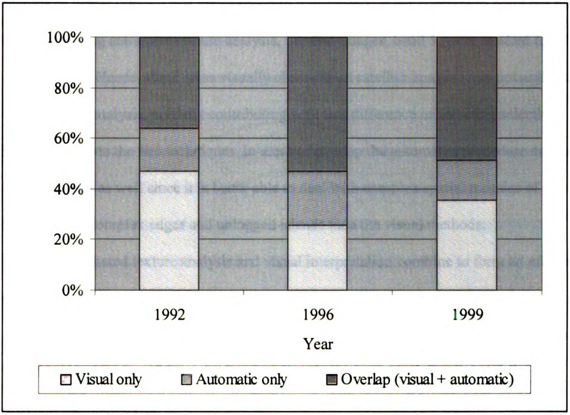


Figure 5.7. Visual interpretation, automatic analysis, and overlap areas.

Although visual interpretation was more successful in detecting logged forests than automated detection, it was also more time-consuming. Furthermore, visual interpretation is interpreter dependent and results are expected to vary among individuals. In this analysis, all visual interpretations were made by a single individual, Eraldo Matricardi.

Automated texture analysis provides a standardized technique for detecting selectively logged forests that are relatively rapid and interpreter independent. Although the technique provided less unique area (17-21%) of selective logging than the 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. It is important to point out that before applying automatic texture analysis, Landsat images, band 5, were masked for deforestation. Hence, some areas visually observed on satellite images were not analyzed by automatic analysis, partially contributing with this difference in detecting selective logging between the two techniques. In areas of overlap the automated procedure may be more accurate as well since it is better able to deal with complex spatial mosaics of logging with complex edges and unlogged islands than the visual methods.

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.

### 5.5.2. 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 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 concentrated in Pará and Mato Grosso (90%), with 75% of all logging concentrated in the vicinity of two major logging centers, Paragominas, State of Pará and Sinop, State of Mato Grosso (see appendix E.3, E.4, and E.5). 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 methodologies. Thus, the present methodology is considered conservative, since, in different circumstances, logging areas cannot be detected, especially in wetlands (várzeas) 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.

### 5.5.3. 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, treefall 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 $km^2yr^{-1}$, using survey data (Nepstad et al. 1999) to as little as 1,561 $km^2yr^{-1}$, using visually interpreted Landsat prints (Krug 2000). The resultant polemic over the importance and scale of selective logging in the Amazon has recently been discussed by Alvarado and Sandberg (2001).

The controversy about selective logging 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 this research, mapped distributions of logging activity in Amazonian forests are presented for 1992, 1996 and 1999.

Due to the rapid disappearance of detectable selective logging from 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 2-3 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 (Chapter 4) performed for two case studies in the states of Mato Grosso and Rondônia 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 (appendix E.2), 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 used 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, 39.5% and 91.42% respectively.

The second method made use of the observable trend 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 rate changes were calculated using separate equations for each case study region (see chapter 4). 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%, 91% for 1992, 1996, and 1999, respectively.

The differences between the total area detected and that which was new logging areas was quite large in the Mato Grosso region (60.5%) but much smaller for Rondônia (8.58%). These residual areas were considered to mostly be 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 in the Chapter 4 can be extrapolated basin-wide, the total increment of new selective logging areas in 1992 was, at least 3,689 $Km^2$. By 1996 and 1999, the annual selective logging rate expanded to 5,107 $Km^2$, 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 2,197 $Km^2$ in 1992, to 5,031 $Km^2$ 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 5.6.

Table 5.6. Total detected and increment of new logging areas Amazon-wide

| Year | Amazon-wide logging area (Km2) | | |
|---|---|---|---|
| | Total detected | Increment of new logging | |
| | | Based on equations (*) | Based on annual average (*) |
| 1992 | 5,979.80 | 3,689 | 2,547 |
| 1996 | 10,064.10 | 5,107 | 4,361 |
| 1999 | 26,085.40 | 11,638 | 11,889 |

* Note: Extrapolated from the Mato Grosso and Rondonia case studies (see chapter 4)

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

Based on the results of the case study in the State of Mato Grosso, presented in the Chapter 4, formerly logged areas are increasingly being re-logged. An average of 2.9%, 8.6%, and 10.3% of the total logged forest where 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 searching for previously non-commercial sized or species of trees.

Despite the methodological limitations discussed above, the logging estimates from this study (1996, 10,064 $km^2$ overall logging detected and 5,107 $km^2$ of new logging areas estimated) are well in the range of other published estimates for 1996, 1,561 $km^2$ (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 5,980 $km^2$ 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 3,936, 6,524, 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 $km^2$ of forest were logged from 1992 to 1999 of which approximately 26,085 $km^2$ was still extant on the landscape in 1999.

### 5.5.4. Final considerations

Factors that could help explain the apparent large increase in logging rates during the 1996-1999 time period as compared with 1992 to 1996 period include the legislative, resource and climate/disturbance explanations.

One hypothesis is that the changes in apparent logging rates are the result of the logging 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 the 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 hypothesis is related to forest production and productivity. According to IBGE (2003), the round wood production in the Brazilian Amazon did not increase during 1997 to 1999, being approximately estimated of 20, 16, and 16 millions of cubic meters per year, respectively in 1997, 1998, and 1999. If the round wood production did not increase, it may be that forest productivity was drastically lowered after 1996. This would be a function of 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 9 of the 38 images indicating logging activity supports this hypothesis.

A third hypothesis is that climate events, such as the1997-1998 "El Nino", 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.

All three hypotheses may partially explain the observed changes in detectable logging. Actual growth in the logging industry across the Amazon Basin 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 in Amazonian forests.

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# CHAPTER VI

## Concluding Remarks

### 6.1.Seating the current study in the context of global change research

The impact of logging in tropical forests is considered significant in terms of forest degradation and fire susceptibility (Stone and Lefebvre 1998, Nepstad et al. 1999, Souza and Barreto 2000). Fearnside (1997) estimated that in the Brazilian Amazon, the impact of selective logging in undisturbed forest creates a net carbon flux equal to approximately 4-7% of the annual carbon release from deforestation.

In spite of the important contribution of selective logging in global change, the majority of selective logging has not been detected by remote sensing techniques and, therefore, the total area of forest damaged by human activities has been underestimated. Consequently, the current carbon flux estimates for the Amazon region may be low because logging areas have not been accounted for (Nepstad et al. 1999).

As presented in the Chapters 1 and 5, Nepstad et al. (1999), Janeczek (1999), and Krug (2000) have provided Amazon-wide estimates of selective logging impacts. Based on a survey data of sawmill production, Nepstad et al. (1999) estimated that 10,000-15,000 $km^2yr^{-1}$ of undisturbed forests were selectively logged in the period of 1996-1997. Based on visual interpretation of Landsat imagery, Krug (2000) estimated as little as 1,561 $km^2yr^{-1}$ in the given period. Based on visual interpretation and an automated method of Landsat image analysis, Janeczek (1999) estimated a total of 5,406 $km^2$ of forests were selectively logged over 1991-1992.

In this research, I presented new estimates through a multi-temporal assessment of selective logging Amazon-wide for 1992, 1996, and 1999, based on remotely sensed data and field studies. The results show that the total active areas of selective logging in the Brazilian Amazon have significantly increased from 3,689 to 5,107 and from 5,107 to 11,638 $Km^2$ in 1992-1996 and 1996-1999 periods, respectively. It represents an increment of roughly 38% and 128% in the given periods, respectively.

Furthermore, based on visual interpretation and field observations, I observed that most of the forests heavily impacted by selective logging were previously misclassified as deforested areas using an unsupervised classification of Landsat imagery. The total of 341, 586, and 2,706 $Km^2$ of forests showing highly damaged canopy and soil exposure on Landsat imagery were reclassified as selective logging for 1992, 1996, and 1999, respectively. It is likely that logging intensity and forest fire occurrence were higher in 1999 than in the previous years of this analysis.

It was also observed that in 1999 loggers revisited logged forest more often than in 1992, increasing the rate of revisiting from 1.2% to about 10% of the total logged area detected in 1999. It shows that loggers are now re-visiting former logging areas searching for previously non-commercial tree species that presently are market demanded due a possible raw material scarcity in the Amazon timber centers. That said, it is expected that selective logging is more likely to expand into new frontiers as well as into protected areas, where raw material for timber industries is still abundant.

Finally, it is noted that the methodology used in this study is considered conservative since it may omit very-low intensity logging areas and logging in riparian forests. Nevertheless, the data presented here represent the first multi-temporal assessment of the amount and locations of selective logging in the Brazilian Amazon.

### 6.2. Research questions revisited

- Is selective logging a significant disturbance in terms of area increment of total forest cleared or damaged?

By applying visual interpretation and automated methods presented in this research, selective logging was shown to be rapidly increasing in the Brazilian Amazon. A total of 5,980 $Km^2$ of forests were selectively logged by 1992, 10,064 $Km^2$ by 1996, and 26,085 $Km^2$ by 1999. Assuming that the results of the multi-annual analyzes in two case studies, in the State of Mato Grosso and Rondonia, represent a general trend and therefore can be extrapolated basin-wide (see Chapter 4 and 5 for further details), it is reasonable to estimate that the total area of undisturbed forests selectively logged in 1992, 1996, and 1999 was roughly 3,689, 5,107, and 11,638 $Km^2$, respectively. I also estimate that revisited logging areas are increasing from 1.7% to more than 10% from 1992 to 2002, respectively. In any case, the areas impacted by selective logging are rapidly increasing, making it a land use of growing importance in the Brazilian Amazon.

- Can we efficiently measure it basin-wide as a form of degradation in addition to outright deforestation?

The automated texture analysis and visual interpretation combined to form an efficient methodological approach for estimating the area affected by selective logging in the

Amazon region. Based on the findings of the field studies and remote sensing analyzes conducted in research for the entire Brazilian Amazon, the most impacted selective logging areas were surely detected and mapped. Even areas of reduced impact logging could be estimated. However, this methodology is considered conservative, since, in different circumstances, logging areas could not be detected.

- Is logging causing more deforestation than would otherwise occur?

Based on the basin-wide results of this research, 13% (796 $Km^2$) of logged forests in 1992 were deforested by 1996, plus 15% (896 $Km^2$) by 1999. An additional 11% (1,074 $Km^2$) of logged forests in 1996 were deforested by 1999. Based on the study case in the State of Mato Grosso, around of 1,900 $Km^2$ of logged forests were deforested between 1992-2002, which represents about 17% of the total (11,449 $Km^2$) logged forest in that given period. In the State of Rondônia case study, 15% (72.6 $Km^2$) of logged forests between 1989-2001 were deforested in this given period. Although deforestation does not appear to be following selective logging in the period of analysis, it is more likely to occur in the oldest logging areas. Moreover, as discussed in Chapter 1, there is a synergism between selective logging and deforestation and further consequences on natural forest are expected from it. In this regard, forest fire seems to be the most eminent risk enhanced by selective logging in the Brazilian Amazon as result of its increased impact in area and intensity (re-visited areas) of forest degradation. Other indirect impacts also have to be considered, such as the financial support for agricultural systems, access opening to new frontier, etc.

## 6.3. Significance and implications of this study

This study is the first multi-temporal assessment of the amount and locations of selective logging in the Brazilian Amazon. The results presented here are fundamental to evaluating the consequences of land cover change in terms of global climate change and carbon cycle studies. These studies have yet to take into account the amount of carbon released in the atmosphere from the large-scale selective logging. Complementarily, this research provides useful information to promote sustainable management of tropical forests.

In terms of land use and land cover change, this study extends the current multi-annual Amazon-wide image classification techniques to include selectively logged forests in addition to the more frequently used thematic classes (forest, deforestation, regrowth, cerrado, cloud, cloud shadow, and water).

## 6.4. Opportunities for further studies

Although selective logging could be detected using the methodology presented in this study, the intensity of forest damage caused by selective timber harvesting has not yet been efficiently measured using remote sensing techniques. New approaches using finer spatial resolution and hyperspectral satellite imagery as well as other alternative approaches should be developed in order to improve the assessment of selective logging impacts.

Dr. Jiaguo Qi, from Michigan State University, has been developing methodological approaches to evaluate forest fragmentation using remotely sensed data. These ongoing studies are based on fractional percentage of green vegetation technique that may be used to estimate forest degradation. However, this method may be tested in different study sites before application to the entire Brazilian Amazon. The combination of visual interpretation, automated methods, and fractional coverage may be a methodology approach to fully support the research on global changes.

In this study, I showed a 10 year trend of logging in the Amazon, but the long-term impacts of selective logging are unknown. The process of selective logging and its synergism with tropical deforestation is poorly understood in the Brazilian Amazon. Thus, future research is needed to fully understand the process of land use and land cover change in which selective logging is inserted. Finally, the development of scenarios for the timber sector could support public policies to achieve a sustainable development in the region.

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# APPENDICES

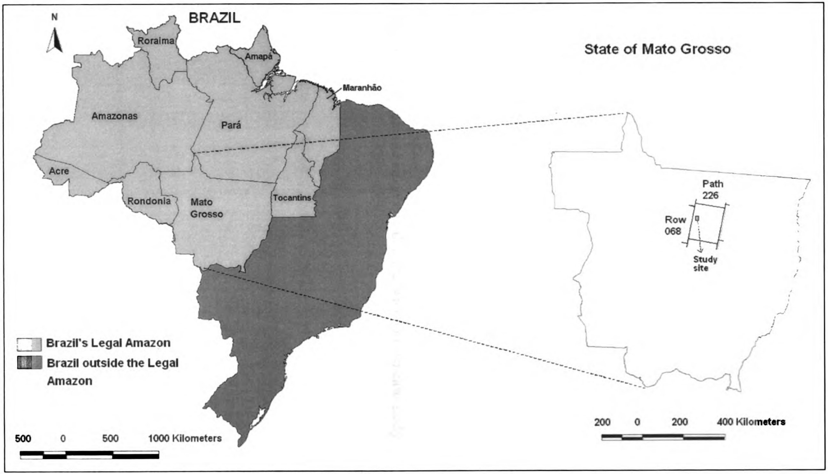
**Appendix A.1.** Timber production in Brazil's Amazonian states - 1990 to 2001

| Year | Round wood production ($m^3$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Acre | Amapá | Amazonas | Maranhão | Mato Grosso | Pará | Rondônia | Roraima | Tocantins |
| 1990 | 301,509 | 339,795 | 37,915,143 | 954,000 | 1,899,030 | 39,865,963 | 1,903,646 | 33,607 | 466,140 |
| 1991 | 304,722 | 353,192 | 180,852 | 931,135 | 2,874,701 | 28,369,671 | 1,027,302 | 35,897 | 483,380 |
| 1992 | 286,114 | 316,959 | 162,011 | 1,191,115 | 2,607,967 | 31,734,992 | 4,744,907 | 37,650 | 516,770 |
| 1993 | 357,604 | 332,648 | 493,323 | 1,180,853 | 2,729,971 | 44,177,956 | 1,353,456 | - | 437,497 |
| 1994 | 372,753 | 330,033 | 496,611 | 1,099,842 | 4,088,119 | 44,538,678 | 1,126,923 | 16,700 | 277,471 |
| 1995 | 321,308 | 352,104 | 530,603 | 1,048,170 | 4,256,770 | 43,919,777 | 1,457,132 | - | 247,580 |
| 1996 | 218,401 | 75,726 | 622,588 | 520,071 | 4,169,173 | 37,788,555 | 380,000 | 16,593 | 93,697 |
| 1997 | 213,887 | 57,349 | 735,166 | 457,688 | 2,997,959 | 15,648,375 | 380,000 | 17,096 | 92,444 |
| 1998 | 200,553 | 73,077 | 782,622 | 494,149 | 2,576,870 | 12,141,428 | 565,668 | 19,580 | 90,182 |
| 1999 | 210,046 | 82,782 | 792,731 | 540,825 | 2,636,544 | 11,325,056 | 750,464 | 26,500 | 99,526 |
| 2000 | 206,961 | 84,410 | 803,528 | 496,821 | 2,600,936 | 10,781,501 | 647,515 | 25,100 | 88,338 |
| 2001 | 242,845 | 71,367 | 851,946 | 487,149 | 2,725,512 | 10,645,334 | 567,330 | 25,100 | 87,652 |
| Total | 3,236,703 | 2,469,442 | 44,367,124 | 9,401,818 | 36,163,552 | 330,937,286 | 14,904,343 | 253,823 | 2,980,677 |

Source: IBGE(2003)

**Appendix A.1**

**Appendix B.1.** Study site location at Sinop municipality, State of Mato Grosso, Brazil.


N
BRAZIL
Roraima
Amapá
Maranhão
Amazonas
Pará
Acre
Rondonia
Mato
Grosso
Tocantins
Brazil's Legal Amazon
Brazil outside the Legal
Amazon
500 0 500 1000 Kilometers
State of Mato Grosso
Path
226
Row
068
Study
site
200 0 200 400 Kilometers

**Appendix B.1**

**Appendix B.2.** Satellite images used in the Mato Grosso case study.

| Satellite / Sensor | Scene | Band | Spatial resolution (m) | Acquisition date |
|---|---|---|---|---|
| Ikonos | PO_44060 | 1, 2, 3, 4 | 4 x 4 | 04/30/2000 |
| Ikonos | PO_44060 | Panchromatic | 1 x 1 | 04/30/2000 |
| Landsat ETM+ | WRS_226/068 | 1, 2, 3, 4, 5 | 30 x 30 | 06/18/2000 |
| Landsat ETM+ | WRS_226/068 | 1, 2, 3, 4, 5 | 30 x 30 | 08/19/1999 |
| Landsat TM | WRS_226/068 | 1, 2, 3, 4, 5 | 30 x 30 | 06/05/1998 |
| Landsat TM | WRS_226/068 | 1, 2, 3, 4, 5 | 30 x 30 | 08/05/1997 |
| Landsat TM | WRS_226/068 | 1, 2, 3, 4, 5 | 30 x 30 | 07/01/1996 |
| Landsat TM | WRS_226/068 | 1, 2, 3, 4, 5 | 30 x 30 | 06/29/1995 |
| Landsat TM | WRS_226/068 | 1, 2, 3, 4, 5 | 30 x 30 | 07/12/1994 |
| Landsat TM | WRS_226/068 | 1, 2, 3, 4, 5 | 30 x 30 | 08/26/1993 |
| Landsat TM | WRS_226/068 | 1, 2, 3, 4, 5 | 30 x 30 | 05/19/1992 |

**Appendix B.2**

**Appendix B.3.** Logged forests detected using Landsat and Ikonos images and different remote sensing techniques (automated and visual interpretation).

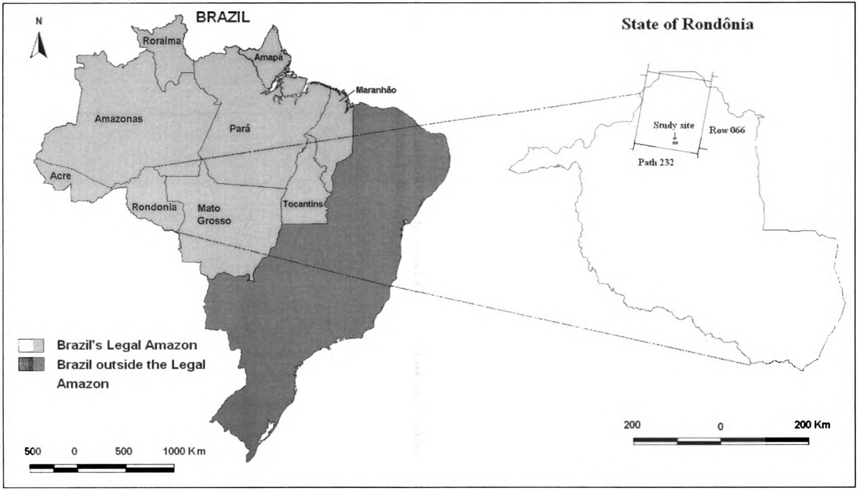
| Technique (Landsat ETM+) | Area (hectares) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Overlap (1) | % | Commission (2) | % | Omission (3) | % | Total | % |
| Visual only | 929.04 | 73.4 | 19.33 | 1.5 | 337.22 | 26.6 | 948.36 | 74.9 |
| Buffer 150 m | 936.50 | 74.0 | 179.17 | 14.1 | 329.75 | 26.0 | 1115.67 | 88.1 |
| Buffer 180 m | 1024.62 | 80.9 | 239.11 | 18.9 | 241.64 | 19.1 | 1263.72 | 99.8 |
| Buffer 210 m | 1091.56 | 86.2 | 298.36 | 23.6 | 174.70 | 13.8 | 1389.92 | 109.8 |
| Buffer 240 m | 1137.13 | 89.8 | 362.22 | 28.6 | 129.13 | 10.2 | 1499.34 | 118.4 |
| Buffer 270 m | 1170.73 | 92.5 | 651.16 | 51.4 | 95.52 | 7.5 | 1821.89 | 143.9 |
| Buffer 150 m + visual | 1119.80 | 88.4 | 186.69 | 14.7 | 146.46 | 11.6 | 1306.48 | 103.2 |
| Buffer 180 m + visual | 1155.32 | 91.2 | 246.09 | 19.4 | 110.94 | 8.8 | 1401.41 | 110.7 |
| Buffer 210 m + visual | 1186.90 | 93.7 | 305.23 | 24.1 | 79.36 | 6.3 | 1492.13 | 117.8 |
| Buffer 240 m + visual | 1211.74 | 95.7 | 369.06 | 29.1 | 54.52 | 4.3 | 1580.79 | 124.8 |
| Buffer 270 m + visual | 1229.34 | 97.1 | 658.63 | 52.0 | 36.91 | 2.9 | 1887.97 | 149.1 |

1. Overlap between the total area of logged forest mapped using Ikonos and Landsat imagery.
2. Commission areas of logged forest resulting from selective logging detection using Landsat imagery.
3. Omission areas of logged forest resulting from selective logging detection using Landsat imagery.

Note: The total of 1,266.5 hectares was assumed as 100% of logged forest within the study site. This area was mapped using a pansharpened Ikonos image and visual interpretation techniques.

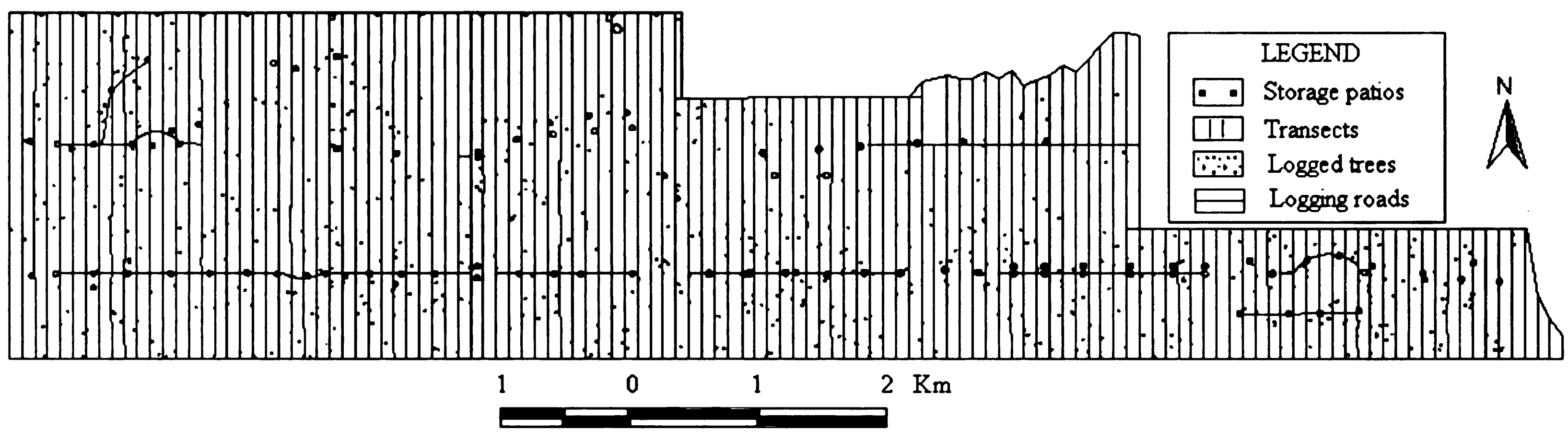
**Appendix B.3**

Appendix C.1. Study site location at Cujubim municipality in the State of Rondônia, Brazil.


BRAZIL
N
Roraima
Amapá
Maranhão
Amazonas
Pará
Acre
Rondonia
Mato Grosso
Tocantins
Brazil's Legal Amazon
Brazil outside the Legal Amazon
500 0 500 1000 Km
State of Rondônia
Study site
Row 066
Path 232
200 0 200 Km

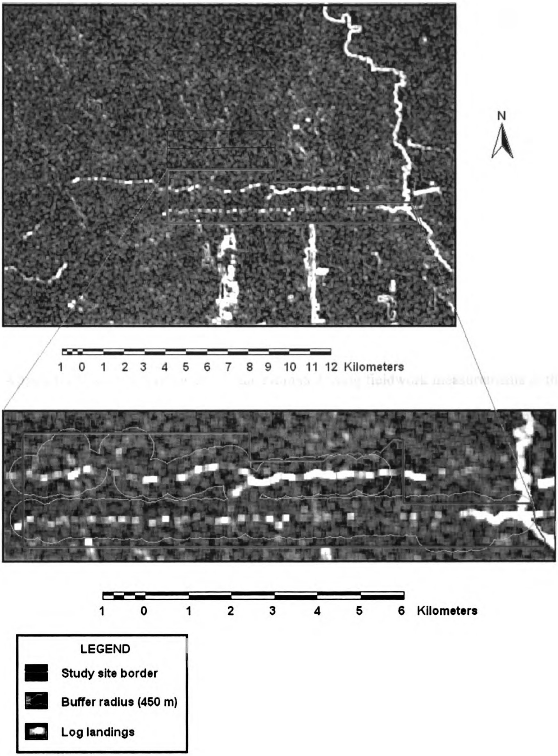
**Appendix C.1**

**Appendix C.2.** Forest inventory map (logged tree locations, and transects, patio and road locations in the field)


LEGEND
Storage patios
Transects
Logged trees
Logging roads
N
1 0 1 2 Km

**Appendix C.2**

**Appendix C.3.** Textural algorithm image and buffer radius of 450 meters around log landings captured using automated method. Path/row 232/066


N
1 0 1 2 3 4 5 6 7 8 9 10 11 12 Kilometers
1 0 1 2 3 4 5 6 Kilometers
LEGEND
Study site border
Buffer radius (450 m)
Log landings

**Appendix C.3.**

**Appendix C.4.** Selective logging areas estimated using fieldwork measurements in the study site at Manoa ranch, Cujubim municipality, State of Rondônia, Brazil.

| Buffer (m) | Trees | Total detected | | Total buffer | | Omission | | Commission | |
|---|---|---|---|---|---|---|---|---|---|
| | | Ha | % | Ha | % | Ha | % | Ha | % |
| 150 | 1147 | 557.80 | 27.72 | 557.83 | 22.67 | 1,903.06 | 77.33 | - | 0.00 |
| 180 | 1134 | 720.47 | 27.40 | 720.47 | 29.28 | 1,740.39 | 70.72 | - | 0.00 |
| 210 | 1736 | 880.19 | 41.95 | 880.19 | 35.77 | 1,580.67 | 64.23 | - | 0.00 |
| 240 | 2005 | 1,034.97 | 48.45 | 1,034.97 | 42.06 | 1,425.89 | 57.94 | - | 0.00 |
| 270 | 2250 | 1,189.71 | 54.37 | 1,189.71 | 48.35 | 1,271.14 | 51.65 | - | 0.00 |
| 300 | 2514 | 1,342.58 | 60.75 | 1,342.58 | 54.56 | 1,118.28 | 45.44 | - | 0.00 |
| 330 | 2777 | 1,495.16 | 67.11 | 1,495.16 | 60.76 | 965.70 | 39.24 | - | 0.00 |
| 360 | 2979 | 1,645.64 | 71.99 | 1,645.64 | 66.87 | 815.22 | 33.13 | - | 0.00 |
| 390 | 3175 | 1,793.82 | 76.73 | 1,793.82 | 72.89 | 667.04 | 27.11 | - | 0.00 |
| 420 | 3378 | 1,941.09 | 81.63 | 1,941.09 | 78.88 | 519.77 | 21.12 | - | 0.00 |
| 450 | 3549 | 1,954.19 | 85.77 | 2,083.16 | 79.41 | 506.67 | 20.59 | - | 0.00 |
| 480 | 3745 | 2,057.42 | 90.50 | 2,220.49 | 83.61 | 403.44 | 16.39 | - | 0.00 |
| 510 | 3829 | 2,135.36 | 92.53 | 2,335.26 | 86.77 | 325.50 | 13.23 | - | 0.00 |
| 540 | 3905 | 2,198.75 | 94.37 | 2,438.47 | 89.35 | 262.11 | 10.65 | - | 0.00 |
| 570 | 3963 | 2,253.76 | 95.77 | 2,537.06 | 91.58 | 207.10 | 8.42 | 76.20 | 3.10 |
| 600 | 4008 | 2,302.23 | 96.86 | 2,632.52 | 93.55 | 158.62 | 6.45 | 171.67 | 6.98 |
| 630 | 4068 | 2,344.17 | 98.31 | 2,724.98 | 95.26 | 116.68 | 4.74 | 264.12 | 10.73 |
| 660 | 4092 | 2,373.47 | 27.72 | 2,816.82 | 96.45 | 87.39 | 3.55 | 355.96 | 14.46 |
| 690 | 4112 | 2,393.02 | 27.40 | 2,908.42 | 97.24 | 67.84 | 2.76 | 447.56 | 18.19 |
| 720 | 4122 | 2,407.93 | 41.95 | 2,999.56 | 97.85 | 52.93 | 2.15 | 538.71 | 21.89 |

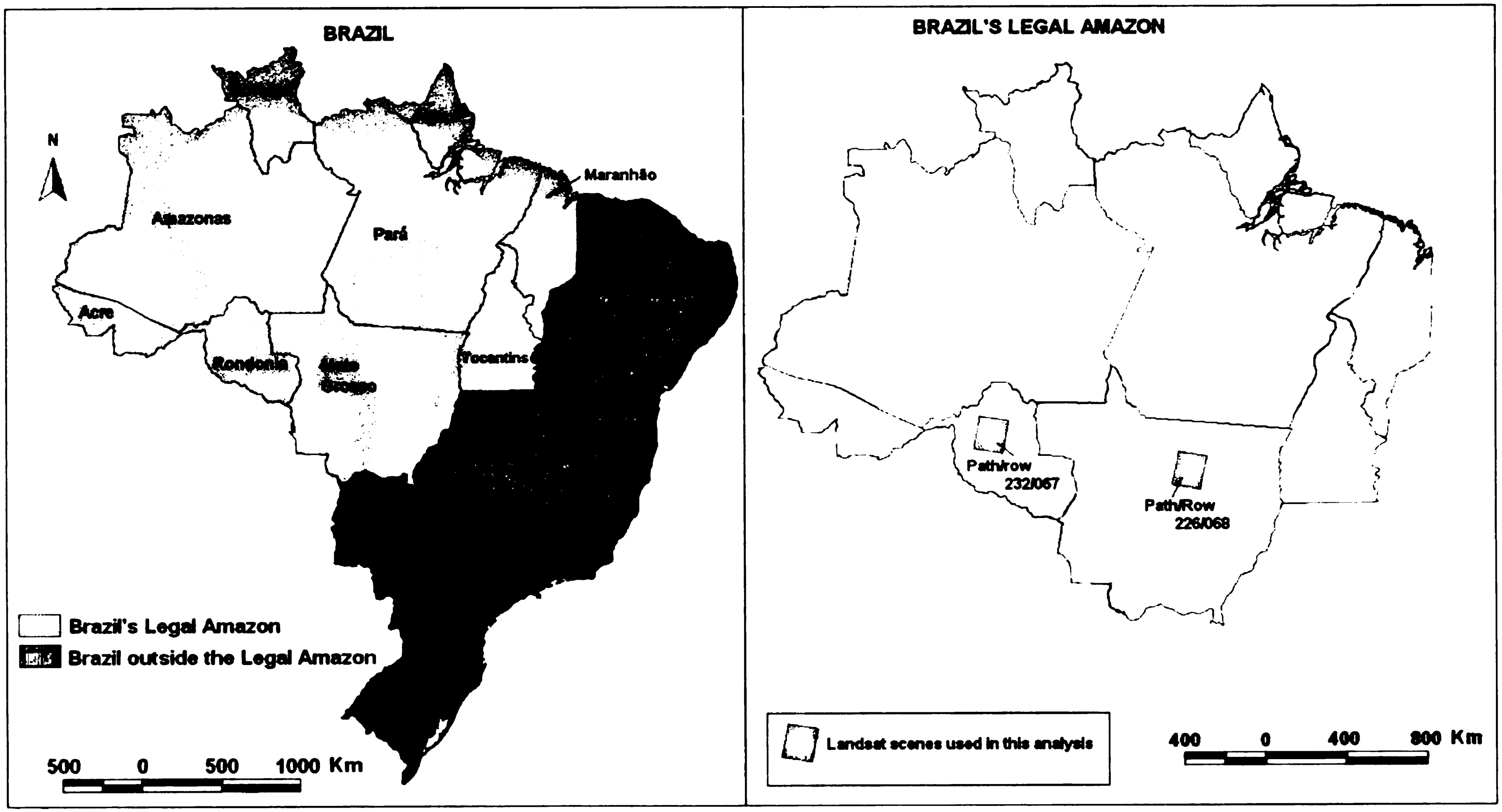
**Appendix C.4** **Note:** Total of logged area = 2,460.86 hectares (100%) from fieldwork.

**Appendix C.5.** Selective logging areas estimated using Textural algorithm and Landsat ETM+, band 5. Study case in the State of Rondônia, Brazil. Path/row 232/066 acquired in 08/05/2002.

| Buffer (m) | Trees | Total detected | | Total Buffer | | Omission | | Commission | |
|---|---|---|---|---|---|---|---|---|---|
| | | Ha | % | Ha | % | Ha | % | Ha | % |
| 150 | 1897 | 1,065.40 | 45.84 | 1,070.72 | 43.29 | 1,395.46 | 56.71 | - | 0.00 |
| 180 | 2165 | 1,212.67 | 52.32 | 1,222.28 | 49.28 | 1,248.19 | 50.72 | - | 0.00 |
| 210 | 2653 | 1,355.91 | 64.11 | 1,372.87 | 55.10 | 1,104.94 | 44.90 | - | 0.00 |
| 240 | 2858 | 1,489.37 | 69.07 | 1,518.07 | 60.52 | 971.49 | 39.48 | - | 0.00 |
| 270 | 3068 | 1,615.44 | 74.14 | 1,659.52 | 65.65 | 845.42 | 34.35 | - | 0.00 |
| 300 | 3230 | 1,731.03 | 78.06 | 1,794.42 | 70.34 | 729.83 | 29.66 | - | 0.00 |
| 330 | 3387 | 1,837.75 | 81.85 | 1,925.21 | 74.68 | 623.11 | 25.32 | - | 0.00 |
| 360 | 3512 | 1,937.18 | 84.87 | 2,052.38 | 78.72 | 523.68 | 21.28 | - | 0.00 |
| 390 | 3631 | 2,030.09 | 87.75 | 2,175.69 | 82.50 | 430.77 | 17.50 | - | 0.00 |
| 420 | 3728 | 2,108.23 | 90.09 | 2,287.83 | 85.67 | 352.63 | 14.33 | - | 0.00 |
| 450 | 3808 | 2,167.93 | 92.03 | 2,389.42 | 88.10 | 292.93 | 11.90 | - | 0.00 |
| 480 | 3875 | 2,218.55 | 93.64 | 2,487.33 | 90.15 | 242.31 | 9.85 | 26.47 | 1.08 |
| 510 | 3939 | 2,259.90 | 95.19 | 2,581.18 | 91.83 | 200.96 | 8.17 | 120.32 | 4.89 |
| 540 | 3975 | 2,294.64 | 96.06 | 2,673.58 | 93.25 | 166.22 | 6.75 | 212.72 | 8.64 |
| 570 | 4014 | 2,322.59 | 97.00 | 2,764.41 | 94.38 | 138.27 | 5.62 | 303.55 | 12.34 |
| 600 | 4043 | 2,347.09 | 97.70 | 2,855.20 | 95.38 | 113.77 | 4.62 | 394.34 | 16.02 |
| 630 | 4080 | 2,369.33 | 98.60 | 2,945.28 | 96.28 | 91.52 | 3.72 | 484.43 | 19.69 |
| 660 | 4099 | 2,389.06 | 99.06 | 3,036.16 | 97.08 | 71.79 | 2.92 | 575.30 | 23.38 |
| 690 | 4109 | 2,405.98 | 99.30 | 3,127.17 | 97.77 | 54.87 | 2.23 | 666.31 | 27.08 |
| 720 | 4115 | 2,418.89 | 99.44 | 3,218.12 | 98.29 | 41.97 | 1.71 | 757.26 | 30.77 |

**Appendix C.5** **Note:** Total logged forest = 2,460.86 hectares (100%) from fieldwork.

**Appendix D.1.** Landsat scenes used in this analysis (Path/row 232/062 and 226/068).


BRAZIL
N
Amazonas
Pará
Maranhão
Acre
Rondonia
Tocantins
Brazil's Legal Amazon
Brazil outside the Legal Amazon
500 0 500 1000 Km
BRAZIL'S LEGAL AMAZON
Path/row
232/067
Path/Row
226/068
Landsat scenes used in this analysis
400 0 400 800 Km

Appendix D.1

**Appendix D.2.** Landsat (TM and ETM+) images (path/row 232/067) used for the inter-annual analysis in the State of Rondônia, Brazil

**Path/Row 232/067**

| Year | Date | Sensor | Cloud/Shadow | Smoke |
|---|---|---|---|---|
| 1989 | August 08, 1989 | TM | 0% | 6% |
| 1990 | December 2, 1990 | TM | 0% | 0% |
| 1991 | June 01, 1991 | TM | 8% | 0% |
| 1992 | June 22, 1992 | TM | 0% | 0% |
| 1993 | October 07, 1993 | TM | 0% | 3% |
| 1994 | June 04, 1994 | TM | 1% | 0% |
| 1995 | July 25, 1995 | TM | 2% | 1% |
| 1996 | June 25, 1996 | TM | 0% | 0% |
| 1997 | June 28, 1997 | TM | 0% | 0% |
| 1998 | July 17, 1998 | TM | 0% | 0% |
| 1999 | December 16, 1999 | ETM+ | 3% | 0% |
| 2000 | June 28, 2000 | ETM+ | 0% | 0% |
| 2001 | August 11, 2001 | ETM+ | 6% | 1% |

**Appendix D.2.**

**Appendix D.3**. Landsat (TM and ETM+) images used for inter and intra-annual analysis in the State of Mato Grosso, Brazil.

**Path/Row 226/068 - Inter-annual analysis**

| Year | Date | Sensor | Cloud/Shadow | Smoke |
|---|---|---|---|---|
| 1992 | May 19, 1992 | TM | 0% | 0% |
| 1993 | August 26, 1993 | TM | 0% | 6% |
| 1994 | July 12, 1994 | TM | 0% | 0% |
| 1995 | June 29, 1995 | TM | 8% | 0% |
| 1996 | July 01, 1996 | TM | 0% | 0% |
| 1997 | August 5, 1997 | TM | 0% | 3% |
| 1998 | June 5, 1998 | TM | 1% | 0% |
| 1999 | August 19, 1999 | ETM+ | 2% | 1% |
| 2000 | June 18, 2000 | ETM+ | 0% | 0% |
| 2001 | August 8, 2001 | ETM+ | 0% | 0% |
| 2002 | April 21, 2002 | ETM+ | 0% | 0% |
| **Intra-annual analysis** | | | | |
| 2001 | May 4, 2001 | ETM+ | 3% | 0% |
| | August 8, 2001 | ETM+ | 0% | 0% |
| | October 27, 2001 | ETM+ | 6% | 1% |
| 2002 | April 21, 2002 | ETM+ | 0% | 0% |

**Appendix D.3**

**Appendix D.4.** Study case results of deforestation and selective logging for 2001 in the State of Mato Grosso.

| **Logging (date)** | **Deforestation Increment ($Km^2$)** | | | | **Deforestation of logged forests (2001 to 2002) ($Km^2$)** |
|---|---|---|---|---|---|
| | **May 2001** | **August 2001** | **October 2001** | **April 2002** | |
| May 2001 | - | 9.37 | 3.43 | 10.81 | 23.60 |
| August 2001 | - | - | 0.34 | 5.83 | 6.17 |
| October 2001 | - | - | - | 6.38 | 6.38 |
| April 2002 | - | - | - | - | - |
| **Total Deforested** | | 9.37 | 3.77 | 23.02 | 36.15 |

**Appendix D.4**

**Appendix E.1.** Landsat imagery used for the basin-wide logging analysis

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

* Not mapped in 1992 and 1996

**Appendix E.1**

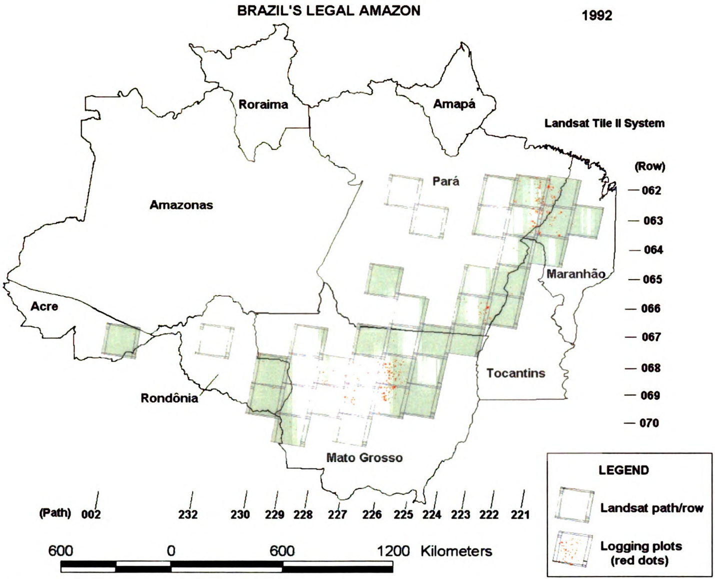
**Appendix E.2.** Basin-wide results of selective logging detection for 1992, 1996, and 1999.

| Path/Row | Logging Area Detected (Km²) 1992 | 1996 | 1999 | Average (1996+1999/7) (Km²) |
|---|---|---|---|---|
| 221/063 | 46.22 | 14.29 | 39.88 | 7.74 |
| 222/062 | 515.76 | 893.71 | 1,096.75 | 284.35 |
| 222/063 | 644.31 | 704.48 | 2,728.60 | 490.44 |
| 222/064(*) | - | - | 20.24 | 6.75 |
| 223/062 | 684.67 | 2,018.67 | 3,554.09 | 796.11 |
| 223/063 | 515.25 | 1,553.23 | 2,928.84 | 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 | 1,245.05 | 1,756.77 | 4,502.92 | 894.24 |
| 226/069 | 873.82 | 1,157.57 | 3,318.36 | 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 | 1,279.07 | 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 |
| | **5,979.80** | **10,064.10** | **26,085.40** | |

**Appendix E.2**

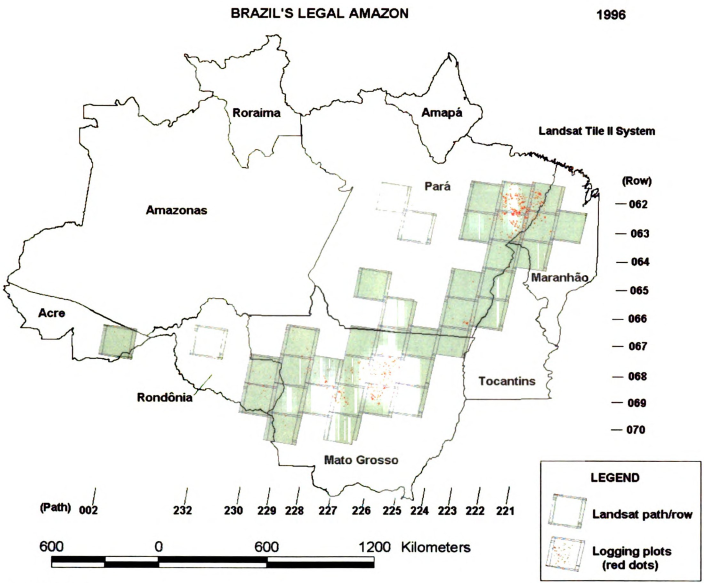
* Not mapped in 1992 and 1996

**Appendix E.3.** Basin-wide spatial distribution of selective logging detected in 1992.


BRAZIL'S LEGAL AMAZON
1992
Landsat Tile II System
Roraima
Amapá
Amazonas
Pará
Maranhão
Acre
Tocantins
Rondônia
Mato Grosso
(Row)
062
063
064
065
066
067
068
069
070
(Path) 002
232
230
229
228
227
226
225
224
223
222
221
600
0
600
1200 Kilometers
LEGEND
Landsat path/row
Logging plots
(red dots)

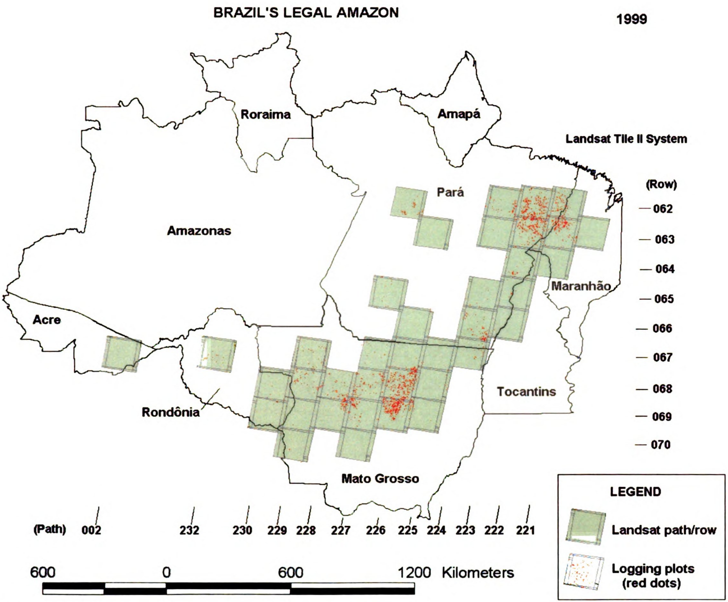
Appendx E.3

**Appendix E.4.** Basin-wide spatial distribution of selective logging detected in 1996.


BRAZIL'S LEGAL AMAZON
1996
Landsat Tile II System
Roraima
Amapá
Amazonas
Pará
Maranhão
Acre
Rondônia
Tocantins
Mato Grosso
(Row)
062
063
064
065
066
067
068
069
070
(Path) 002
232
230
229
228
227
226
225
224
223
222
221
600
0
600
1200 Kilometers
LEGEND
Landsat path/row
Logging plots (red dots)

Appendix E.4

**Appendix E.5.** Basin-wide spatial distribution of selective logging detected in 1999.


BRAZIL'S LEGAL AMAZON
1999
Roraima
Amapá
Landsat Tile II System
Pará
Amazonas
Maranhão
Acre
Tocantins
Rondônia
Mato Grosso
(Row)
062
063
064
065
066
067
068
069
070
(Path) 002 232 230 229 228 227 226 225 224 223 222 221
600 0 600 1200 Kilometers
LEGEND
Landsat path/row
Logging plots (red dots)

Appendix E.5