Selective Logging and Its Relation to Deforestation

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Selective logging is a major contributor to the social, economic, and ecological dynamics of Brazilian Amazonia. Logging activities have expanded from low-volume floodplain harvests in past centuries to high-volume operations today that take about 25 million m^3 of wood from the forest each year. The most common high-impact conventional and often illegal logging practices result in major collateral forest damage, with cascading effects on ecosystem processes. Initial carbon losses and forest recovery rates following timber harvest are tightly linked to initial logging intensity, which drives changes in forest gap fraction, fragmentation, and the light environment. Other ecological processes affected by selective logging include nutrient cycling, hydrological function, and postharvest disturbance such as fire. This chapter synthesizes the ecological impacts of selective logging, in the context of the recent socioeconomic conditions throughout Brazilian Amazonia, as determined from field-based and remote sensing studies carried out during the Large-Scale Biosphere-Atmosphere Experiment in Amazonia program.

1. INTRODUCTION

Selective logging is an important land use in Amazonia. The logging industry is an economic engine that generates revenue, provides jobs, and has the potential to be a renewable resource for the region. There is general consensus that selective logging is widespread and important to the economy; however, the industry has suffered from generally weak and inconsistent government oversight, low capital investment, and a lack of understanding of both forest ecology and management. This combination of conditions has prevented the development of a sustainable logging industry and has led to considerable ecological damage.

In the past decade, the ecological, social, and geographic sciences have made important but disparate strides to understand the dynamics of selective logging in Amazonia, with a focus on Brazil where most studies have been conducted. Our goal here is to synthesize the work from these studies and to clarify our understanding of the ecological role of timber production. We focus on the contributions from the Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA) program. We start with a brief history of the logging industry in Brazil, including the pertinent aspects of the social, economic, and policy drivers of logging practices. We then link this knowledge of the historical and contemporary conditions for the Amazon forest industry to recent scientific

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findings demonstrating the effects of logging on the ecology of the region. Throughout the chapter, we also highlight the contributions of remote sensing as a tool to understand and monitor the course and consequences of selective logging in Amazonia.

2. SOCIOECONOMIC CHARACTERIZATION OF SELECTIVE LOGGING

2.1. Development of Logging Frontiers in Amazonia

European settlers had begun logging the Amazon forest by the seventeenth century [*Rankin*, 1985]. For the first three centuries of settlement, logging was restricted to low-volume harvest of floodplain forests along the main Amazonian rivers and was of secondary importance to other extractive industries such as Brazil nuts and rubber. It was not until the 1950s that industrial mills, mainly subsidiaries of large international companies such as Georgia Pacific, sprang up in the Amazon estuary to produce high-value sawn wood and veneer for export. Among the earliest examples of selective logging were two floodplain tree species known as virola (*Virola surinamensis*) and andiroba (*Carapa guianensis*) [*Barros and Uhl*, 1995; *Pinedo-Vasquez et al.*, 2001; *Zarin et al.*, 2001].

In the 1960s and 1970s, government policies and investments in infrastructure throughout Amazonia opened access to extensive portions of upland forests [*Binswanger*, 1991; *Browder*, 1988; *Scholz*, 2000]. An extensive and migratory logging industry emerged based on a low-cost raw material in newly forming economic frontiers with minimal governance [*Uhl et al.*, 1997; *Veríssimo et al.*, 1998, 2002; *Stone*, 1998a]. The industry blossomed into a diverse sector with new products and extensive national markets, changing the nature of selective logging along the way. Instead of one or two key species destined for export, a domestic market based on rough-sawn wood and eventually plywood absorbed a greater variety of species. Notwithstanding the penetration of mahogany logging deep into the forest, the majority of selective logging operations followed the new roads to harvest high volumes. The new logging strategy created boom and bust economies, severe ecological damage, and a legacy of wasteful and marginally legal practices that still pervade the industry.

After 3 decades of deforestation and unplanned selective logging, timber stocks in the old frontiers became largely depleted. Old logging frontiers (Plate 1), which closely follow the arc of deforestation in the states of Pará, Mato Grosso, and Rondônia, still encompass 45% of the Amazonian logging centers, but they now generate only about 50% of the revenues and jobs of the timber industry [*Lentini et al.*, 2005]. The increasing scarcity of raw material stimulated the migration of firms to newer frontiers (intermediate and new frontiers in Plate 1). Roads that strike deep into the interior of Amazonia, mainly the BR-163 Cuiabá-Santarém Highway and, to a lesser extent, the BR-230 Transamazon Highway, have seen a dramatic surge in sawmills and logging.

Nepstad et al. [1999] used sawmill surveys conducted by the Brazilian nongovernmental organization Instituto do Homem e Meio Ambiente da Amazônia (IMAZON) and showed that, for the period 1995–1996, logging centers were busy in nearly all states of Brazilian Amazonia (Plate 2a). The pattern of logging centers is similar to the detailed geographic distribution of logged forest revealed in a remote sensing analysis for the years 1999–2002 (Plate 2b) [*Asner et al.*, 2005]. In 2004, IMAZON catalogued 82 Amazonian logging centers encompassing 3132 timber mills, which consumed 24.5 million m^3 of logs that produced 10.4 million m^3 of processed timber including sawn wood, veneers, plywood, and finished wood products (Table 1). This implies an average production yield of only 42% [*Lentini et al.*, 2005]. More than 90% of the production from Brazilian Amazonia is currently concentrated in the states of Pará, Mato Grosso and Rondônia. The total gross revenue of the timber industry in Brazilian Amazonia in 2004 was about \$2.3 billion U.S. dollars generating approximately 380,000 jobs, including 124,000 direct jobs (processing and logging) and 255,000 indirect jobs. Although there are cost and market share differences between the new, intermediate and old frontiers, this frontier migration has not been accompanied by notable improvements in forest management and timber processing [*Merry et al.*, 2006], as discussed in section 2.2.

2.2. Economics of Selective Logging

In their quest for high-quality raw materials, loggers seek new forest frontiers. The economics of the logging industry in Brazil directly influence the management approaches and therefore strongly affect ecological impacts and the long-term sustainability of forest timber production. As we mentioned in section 2.1, selective logging has evolved from a single- or few-species model, typical of floodplain logging and mahogany harvest, to a model that can remove up to 40 m^3 ha^{-1} and can comprise any variety of 50 or more species. This approach, called conventional logging, is widely used and is profitable. Spatial-economic models estimate the feasible extent of selective logging in Brazilian Amazonia, based on the expected costs for harvest timber and log transport and the prices for logs in the logging centers [*Stone*, 1998b; *Veríssimo et al.*, 1998, 2000]. Basically, these models (e.g., Plate 1) identify forests in which selective logging is economically viable and show widespread potential for

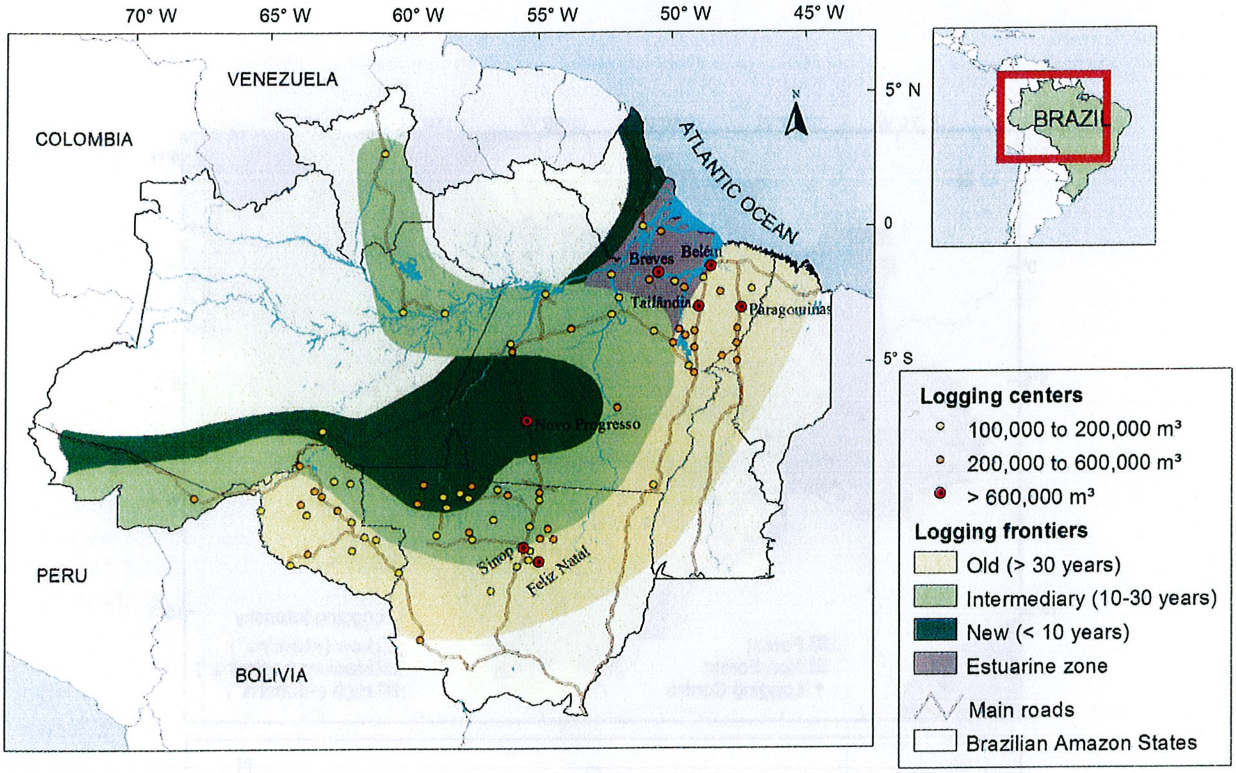

Plate 1. Geographic distribution of logging centers in 2004 and harvestable regions of the Brazilian Amazon [*Lentini et al.*, 2005].

the forest sector to play an important role in the development of emerging frontiers. Plates 1 and 2 demonstrate that logging centers have expanded sufficiently so that harvestable forests cover most of Brazilian Amazonia.

The growth of the logging industry in Brazil has not been determined by new harvesting and processing technologies that are available to logging companies. Instead, the high-damage, high-waste approaches involved in many conventional logging methods have persisted [*Pereira et al.*, 2002; *Holmes et al.*, 2002; *Asner et al.*, 2006]. Moreover, despite technological advances in forest management, whereby reduced-impact logging (RIL) methods can be employed to harvest wood while minimizing damage to the forest and maintaining economic returns [*Sist*, 2000], there has been poor adoption of good management practices. A brief list of reasons why RIL has not been widely adopted includes poorly defined property rights, high transaction costs associated with government bureaucracy, poor distribution of information on good forest management, and an entrenched rent-seeking bureaucracy [*Putz et al.*, 2000; *Boltz et al.*, 2001]. It is these influences on firm decision-making that continue to encourage the use of poor-quality selective logging practices over RIL. As discussed in section 3, this timber-harvesting environment results in ecological responses that have just recently been quantified during the LBA program.

While RIL logging has many ecological benefits, the economic benefits of RIL are less certain [*Putz et al.*, 2000]. Among the problems of RIL logging is, ironically, the preservation of a nearly intact canopy. For all of its biodiversity, microclimatic, and fire protection benefits, an intact canopy keeps potential regenerating trees in the dark and thereby limits postlogging growth. A potential solution to this problem is the selective elimination of competitors around future harvest trees, known as liberation [*Wadsworth and Zweede*, 2006]. *Dauber et al.* [2005] modeled tree growth based on field data from an extensive network of plots with growth rates measured on more than 10,000 trees in Bolivian Amazonia. Tree growth was modeled for no treatment and for a silvicultural treatment where surrounding competitive trees and vines are killed for a 25-year cutting cycle in four regions. While modeled first-harvest volumes were considerably larger than the second-harvest volumes for all four

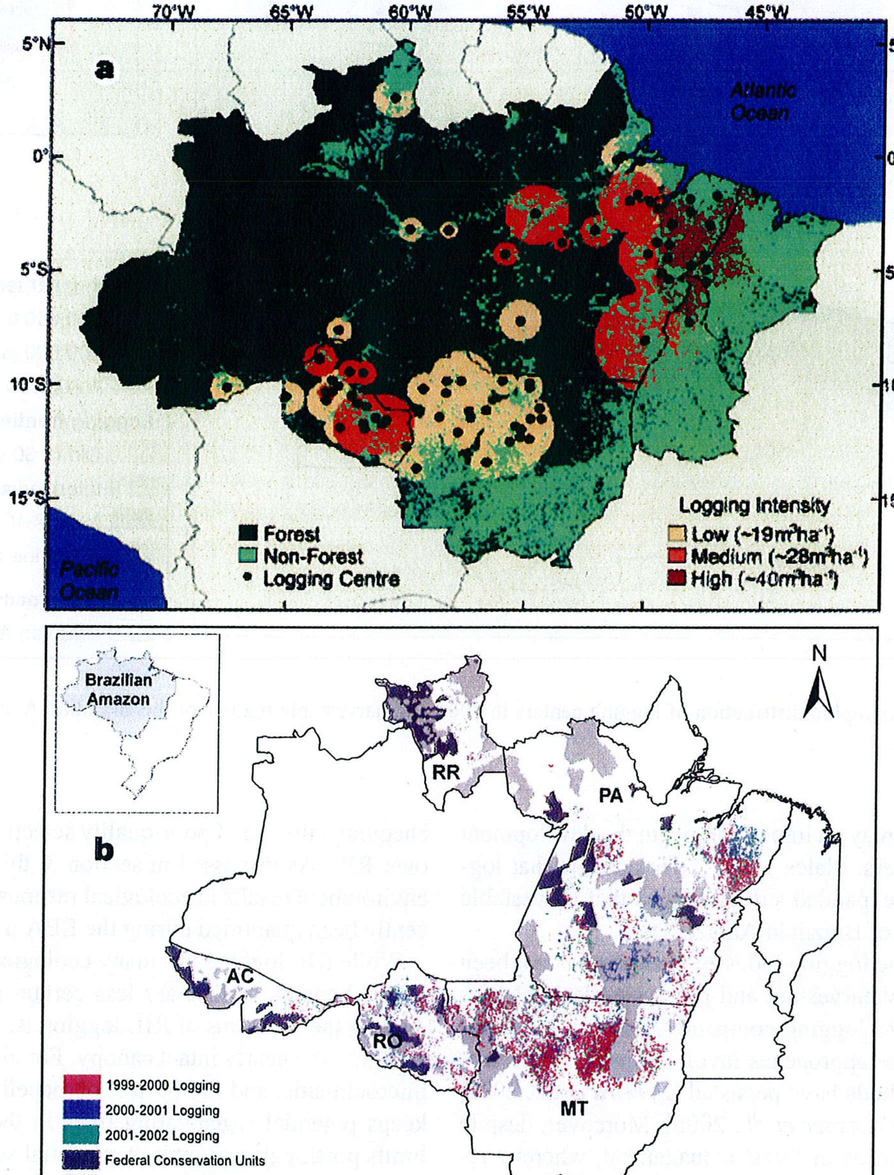

Plate 2. (a) Regional distribution of logging centers in the Brazilian Amazon, 1995–1996, derived from sawmill surveys [*Nepstad et al.*, 1999]. Reprinted by permission from Macmillan Publishers Ltd: *Nature*, copyright 1999. (b) Regional distribution of logging damage to forests from 1999 to 2002 in the states of Pará (PA), Roraima (RR), Rondônia (RO), Acre (AC), and northern Mato Grosso (MT) derived from satellite analysis [*Asner et al.*, 2005].

Table 1. Socioeconomic Data on Selective Logging in 2004 for Brazilian Amazonia[a]

State	Logging Centers (Timber Firms)	Logwood Consumption (× 1000 m^3 a^{-1})	Gross Income (million U.S. dollars)	Jobs Generated: Direct and Indirect	Market: Exportation (%)	Market: Regional (%)
Acre	1 (52)	420	41.6	5,729	83	12
Amapá	1 (73)	130	9.3	2,228	34	67
Amazonas	3 (48)	490	55.9	11,344	64	18
Maranhão	1 (45)	430	31.7	6,817	9	35
Mato Grosso	26 (872)	8,010	673.9	108,569	19	9
Pará	33 (1,592)	11,150	1,113.6	183,741	50	11
Rondônia	16 (422)	3,700	368.9	58,818	27	11
Roraima	1 (28)	130	15.9	2,375	79	21
Combined	82 (3,132)	24,460	2,310.7	379,621	36	11

[a]Data are retabulated from *Lentini et al.* [2005].

regions, in the best-case transitional (dry-to-moist forest) ecoregion, the second cut reached 64% of the volume of the first cut under silvicultural treatment compared to only 28% for untreated forest. Silvicultural treatments are costly and currently rarely implemented in Amazonia.

2.3. Role of Illegal Logging

Because it has been widespread, the practice of illegal logging requires some extra attention here. There are two legal mechanisms to gain permission to log forests in Brazilian Amazonia: forest management plans, regulated by specific policy instruments, and deforestation. Current Brazilian law allows the deforestation of 20% of the total area in rural Amazonian properties. In the past, both mechanisms were controlled by the federal environmental agency Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA). Currently, the enactment of a new forestry law (Lei 11284/2006) created the first directives to decentralize the control over forest management plans and to delegate authorizations for deforestation to state agencies in an attempt to increase the transparency of these processes [*Zarin et al.*, 2007]. The few available figures for the log wood volume generated through these mechanisms show that their sum was less than 15 million m^3 between 2000 and 2004. In contrast, surveys of the timber industry carried out in 1998 and 2004 [*Lentini et al.*, 2005] show that the total Amazonian production during this period was above 24 million m^3, a figure directly supported by satellite estimates of *Asner et al.* [2005]. Combining these estimates, it becomes clear that during these years, at least 40% of the log production in Amazonia was illegally generated.

In the last several years, government and civil society have taken measures against illegal logging. Hundreds of forest management plans were canceled by IBAMA in 2003–2004 in an attempt to halt illegal logging and decrease the deforestation rates, estimated by Instituto Nacional de Pesquisas Espaciais (INPE) (the National Space Agency) at 1.7 million ha in 2004 (PRODES: Assessment of deforestation in Brazilian Amazonia, 2005, see http://www.obt.inpe.br/prodes/index.html). In 2005, the Ministry of Environment, Federal Police, IBAMA, and several governmental organizations conducted three large-scale operations targeting illegality in the forest sector and corruption. Despite these recent efforts, the scale of illegal operations remains difficult to precisely estimate.

Illegal logging, conducted without government approved management plans and without permits, has especially deleterious economic, social, and ecological effects. Economic impacts can be measured by losses in governmental taxes and poor development of economic sectors related to logging. From a societal perspective, formally regulated employment is replaced by informality leading to the low quality of these jobs, higher risks for forest workers, lower benefits, and generation of conflicts between loggers and traditional communities over land use. Ecologically, while legal management plans limit logging entries for extended periods (often 30 years), illegal logging promotes multiple logging entries into an area as market conditions change. Multiple entries result in forest impoverishment, a dramatic loss of biodiversity, and increased susceptibility to fire [*Nepstad et al.*, 1999].

3. ECOLOGICAL IMPACTS OF CURRENT LOGGING PRACTICES

The ecological impacts of selective logging are directly related to harvest intensity, in terms of volume of wood removed per hectare and harvest method, which largely determines the level of collateral damage incurred during and after timber harvest. Harvest methods, ranging from large-scale conventional logging using crawler tractors and/or wheeled skidders to carefully planned and managed RIL, are tightly linked to both the initial forest damage and to the longer-term ecological responses ranging from canopy light environment to carbon cycling to fire regimes.

The effects of selective logging start with forest biophysical properties, where the forest canopy cover (measured by gap fraction or light availability) is immediately changed during harvest operations. Changes in the spatial pattern and extent of forest gaps then have cascading effects on rates of forest growth, hydrological processes, and the entire food web of a forest. These gaps can be arranged by forest-use stratum, including access roads, tree falls where logs are initially cut, skid trails used to remove logs from the forest, and log decks (commonly known as patios) used to load logs onto trucks (Plate 3). These four strata help to organize the ecological impacts as discussed below, and their pattern across the landscape, both in terms of number and density, exerts significant control over the rate of forest recovery for all organisms. Although roads, log decks, skids, and tree fall locations may be visible to satellites for a few years following timber harvest, the canopy rapidly closes (Plate 4), making the geography of logging difficult to track and misguiding the casual observer into thinking that forest recovery is rapid (Appendix A). In fact, while canopy closure is rapid, forest recovery, in terms of both carbon stocks and ecological processes, is far from rapid in upland rain forest areas of Amazonia. Selective logging alters forest ecological processes extending from changes in phenology to the way that carbon and nutrients are cycled and even to the emissions of trace gases such as nitrogen oxides and methane.

Although LBA did not focus on tropical forest wildlife, it is important to acknowledge the impacts of logging here because they can be highly variable and often substantial. Several studies have documented how selective logging can cause biotic impoverishment of species and communities or, alternatively, can stimulate population growth of some species [*Johns*, 1992; *Thiollay*, 1992; *Hill et al.*, 1995]. Both the magnitude and direction of ecological change following harvest depend heavily upon the initial logging intensity and the subsequent spatial and temporal dynamics of forest gap fraction (see *Fimbel et al.* [2001] for an extensive synthesis).

3.1. Light Environment

A major ecological constraint over plant establishment and regeneration in tropical forests is the low light intensity in the understory [*Johns et al.*, 1996]. In humid tropical forests, roughly 2–3% of photosynthetically active radiation (PAR) (400–700 nm) reaches the forest floor [*Lee*, 1987], and canopy gap fraction typically ranges from just 2 to 4% [e.g., *Chazdon and Fetcher*, 1984]. Plant productivity or carbon uptake by vegetation is tightly linked to PAR availability [*Monteith*, 1972; *Field et al.*, 1995]. Canopy gaps created by selective timber harvests have immediate effects on PAR interception, latent and sensible heat fluxes, water stress, and plant productivity in tropical forests [*Healey et al.*, 2000; *Pinard and Cropper*, 2000]. Rates of forest regeneration can thus be linked to the size, number, and spatial arrangement of canopy gaps following harvest [*Pereira et al.*, 2002].

The light environment following logging can be assessed in terms of ground damage resulting from timber harvest (e.g., skids, roads, and decks) and in terms of canopy gap fraction among these types of damage classes. Across a wide range of conventional and RIL harvest intensities (2.6–6.4 felled trees ha^{-1}) in the eastern Amazon, *Asner et al.* [2004b] found that the majority of ground damage occurred as skid trails (4–12%), whereas log decks and roads were only a small contributor to the total ground damage (<2%). *Feldpausch et al.* [2005] identified a similar pattern among RIL plots in Mato Grosso, Brazil. However, despite similar harvest intensities, conventional logging causes more canopy damage than does RIL, either from the initial harvest or from tree falls that occur in the years following the logging event [*Pereira et al.*, 2002; *Schulze and Zweede*, 2006]. Critically, neither the number of log decks nor their individual or total area is well correlated with the number of trees removed or intensity of tree harvesting (trees per hectare) [*Asner et al.*, 2004a]. In contrast, the area of skids is often well correlated with the ground area damaged (square meters) per tree felled, but these features are among the most difficult to map in the field or from satellite sensors (Appendix A).

In terms of light interception by the canopy following logging, field surveys across the damage classes show that gap fractions are highest in log decks and lowest in tree fall areas immediately following timber harvest [*Feldpausch et al.*, 2005]. However, the small surface area of log decks reduces their contribution to a very small fraction of the area-integrated effects of logging throughout a forest. In contrast, lower gap fractions from tree falls are spread throughout a harvested forest, resulting in a large contribution of these areas to the total stand-level canopy gap fraction [*Asner et al.*, 2006]. Canopy openings at tree fall locations are highest at the point where the crown is removed and then decrease with distance from each felled crown (Figure 1). Following harvests in the eastern Amazon, the area affected by the felling of each tree was approximately 100 m in radius for conventional logging but only 50 m for RIL [*Asner et al.*, 2004b]. The size and duration of the tree fall gaps have a significant impact on PAR interception and the resulting primary production following timber harvests [*Huang et al.*, 2008]. *Pereira et al.* [2002] demonstrated the advantages of RIL methods in the maintenance of canopy cover following timber harvest. *Feldpausch et al.* [2005] observed that RIL

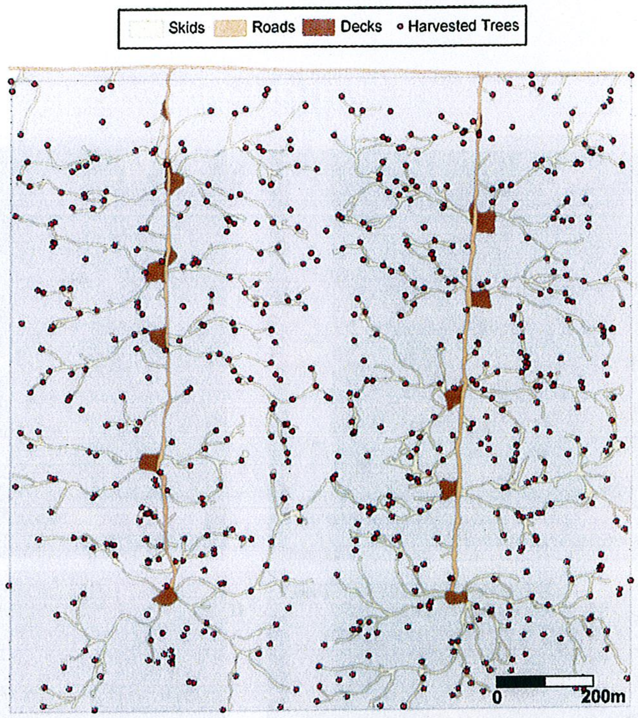

Plate 3. Plan view of an actual 100 ha logged area in the eastern Brazilian Amazon, harvested using conventional methods [*Pereira et al.*, 2002].

reduces canopy damage but only when harvest intensities, calculated in terms of wood volume, are relatively high. In sum, the positive effects of RIL practices on canopy cover are mostly realized at greater harvest volumes; otherwise, they converge on conventional logging damage levels when extraction rates are very low.

3.2. Carbon Cycling

The total carbon budget from logging depends upon a balance of the long-term storage of carbon in wood products, the losses resulting from inefficient milling and processing, the losses related to decomposition of wood resulting from logging damage to the forest, and the carbon gains over time from forest regrowth. Carbon lost as a result of the logging in the Amazon expressed on an areal basis is summarized in Table 2. Industrial logging in the Amazon region of Brazil removes about 19 to 40 m^3 ha^{-1} of roundwood from the forest. Compared to other losses, the carbon lost as a result of log processing is small (~12% of the total). Finished products account for only 42% of the roundwood removed from the forest [*Lentini et al.*, 2005]. While these products eventually decay, the lifetime of wood products from Amazon logging is unknown. The relevance of finished products to the overall carbon accounting is small. Most of the carbon contained in logs transported from forest to mills is rapidly cycled to the atmosphere because sawmill waste is generally burned.

Log harvesting operations in the Amazon are inefficient and create a great deal of collateral damage [*Veríssimo et al.*, 1992]. Table 2 shows that 6 times as much carbon is committed to waste in the forest (including fallen and standing coarse woody debris and belowground debris) as is exported as roundwood. In well-managed, low-impact operations, the ratio of debris creation to exported wood can be as low as 2.4 [*Feldpausch et al.*, 2005]. The waste includes the portions of harvested trees that are not trucked out of the forest, trees killed by felling operations, and especially trees killed by the operation of heavy equipment used to open forest roads and to skid logs out of the forest. Research indicates that skidding operations are responsible for a majority of the collateral damage and that improvements in skidding through the use of proper equipment and planning can cut the damage and carbon loss by half [*Pereira et al.*, 2002; *Keller et al.*, 2004b]. Most of the waste is generated immediately or within a year of logging. The loss of carbon from the ecosystem to the atmosphere is not instantaneous. However, under the hot and humid conditions of the Amazon, the av-

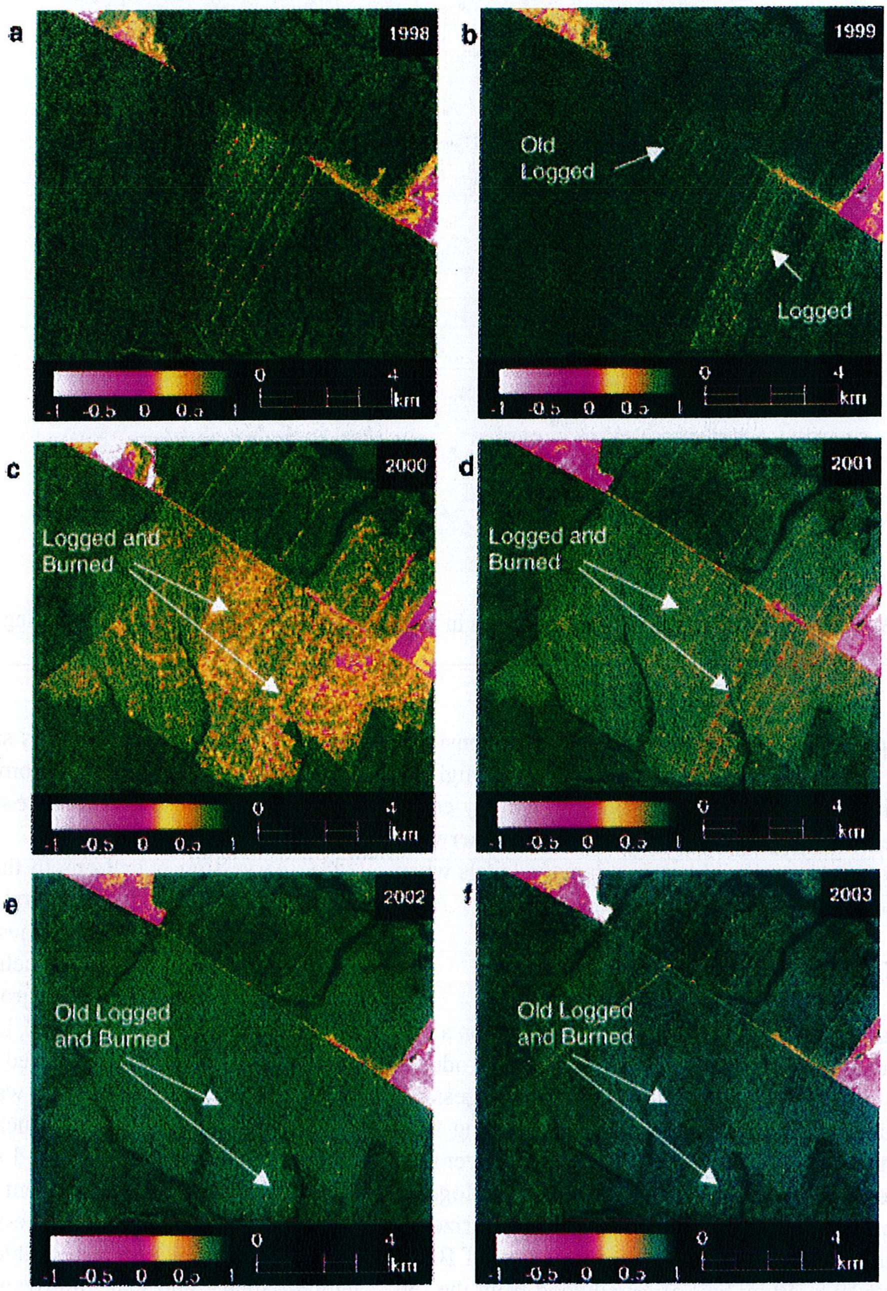

Plate 4. Sequence of Landsat images showing roads and log decks generated by selective logging in central Mato Grosso and the rapid apparent recovery of the canopy, even following fire [*Souza et al.*, 2005]. Colors indicate different normalized difference fraction index from high canopy cover in greens to low canopy cover in pinks and whites.

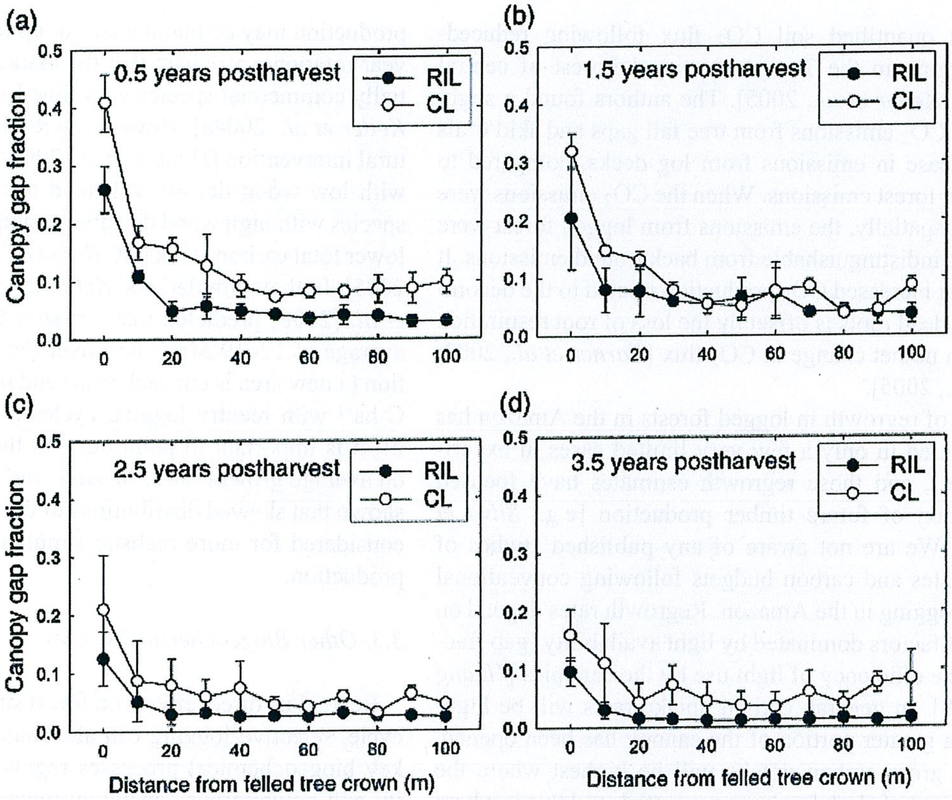

Figure 1. Mean (plus/minus standard deviation) forest canopy gap fraction at increasing distance from felled tree crowns in conventionally logged (CL) and reduced-impact logging (RIL) sites in the eastern Amazon at (a) 0.5, (b) 1.5, (c) 2.5, and (d) 3.5 years following timber harvest [*Asner et al.*, 2004b].

erage lifetime of coarse woody debris is about 5 to 7 years [*Chambers et al.*, 2000; *Palace et al.*, 2007]. Despite this basic understanding of carbon losses following timber harvest, the primary sources of data remain limited, and additional measurements are needed.

The belowground contribution to the carbon balance is especially uncertain because of the precarious knowledge of belowground carbon stocks in the Amazon [*Keller et al.*, 2001]. Root stocks are poorly quantified, and it is difficult to quantify small changes in soil carbon pools. In one study,

Table 2. Estimates of Carbon Loss From Logging[a]

	Mean ($Mg\ C\ ha^{-1}$)	Low ($Mg\ C\ ha^{-1}$)	High ($Mg\ C\ ha^{-1}$)
Roundwood	5	4	8
Aboveground woody debris	26	21	32
Belowground woody debris	6	5	8
Standing dead	5	4	6
Total	42	33	55

[a]Roundwood estimates for mean, high, and low harvest volumes are from *Asner et al.* [2005] and *Nepstad et al.* [1999]. Roundwood density is assumed to be 0.7 Mg m^3, and the conversion factor for wood mass to C is 0.5 [*Schlesinger*, 1997]. The roundwood loss is adjusted to account for 42% of the wood that becomes durable products [*Lentini et al.*, 2005]. Coarse woody debris estimates are based on the work of *Keller et al.* [2004b]. Belowground loss is calculated as 20% of aboveground coarse woody debris plus roundwood [*Keller et al.*, 2001]. Standing dead is 20% of aboveground coarse woody debris [*Palace et al.*, 2007].

researchers quantified soil CO_2 flux following reduced-impact logging in the Tapajós National Forest of central Pará State [*Keller et al.*, 2005]. The authors found a slight increase in CO_2 emissions from tree fall gaps and skid trails and a decrease in emissions from log decks, compared to background forest emissions. When the CO_2 emissions were aggregated spatially, the emissions from logged forest were statistically indistinguishable from background emissions. It is likely that increased CO_2 production related to the decomposition of dead roots is offset by the loss of root respiration resulting in no net change in CO_2 flux [*Varner et al.*, 2003; *Silver et al.*, 2005].

The rate of regrowth in logged forests in the Amazon has been measured in only a few very limited cases in experimental plots, and those regrowth estimates have focused on estimation of future timber production [e.g., *Silva et al.*, 1995]. We are not aware of any published studies of regrowth rates and carbon budgets following conventional industrial logging in the Amazon. Regrowth rates depend on a variety of factors dominated by light availability (gap fraction) and the efficiency of light use by the canopies [*Huang et al.*, 2008]. In general, carbon uptake rates will be highest where a greater portion of the canopy has been opened. Therefore, gross carbon uptake will be highest where the largest amount of slash has been generated, and this is where the largest gross carbon losses will be incurred from decomposition. Optimistic modeling scenarios suggest that timber production may be maintained for up to 200 years under 30-year rotations, provided that the market accepts new potentially commercial species with time [*Alder and Silva*, 2000; *Keller et al.*, 2004a]. However, without substantial silvicultural intervention [*Dauber et al.*, 2005], fast growing species with low wood density will tend to replace slow growing species with high wood density, leading to forest stands with lower total carbon stocks [*Keller et al.*, 2004a; *Bunker et al.*, 2005]. In their simulations, *Keller et al.* [2004a] and *Huang et al.* [2008] predicted that Amazon forests would lose an average of 12–19 Mg C ha^{-1} over the first 30 years of rotation (a new area is cut each year) and between 16 and 30 Mg C ha^{-1} with reentry logging cycles over 200 years (Figure 2). It is important to point out that these models are based on average growth rates. *Brienen and Zuidema* [2007] have shown that skewed distributions of the tree growth should be considered for more realistic simulations of tropical forest production.

3.3. Other Biogeochemical Cycles

Beyond its direct effects on forest structure and the carbon cycle, selective logging can alter nutrient cycles and other key biogeochemical processes regulating forest productivity and neighboring aquatic systems. For example, nitrate losses from logged areas in Guyana vary in proportion to the area of soil disturbance surrounding harvested trees [*Brou-*

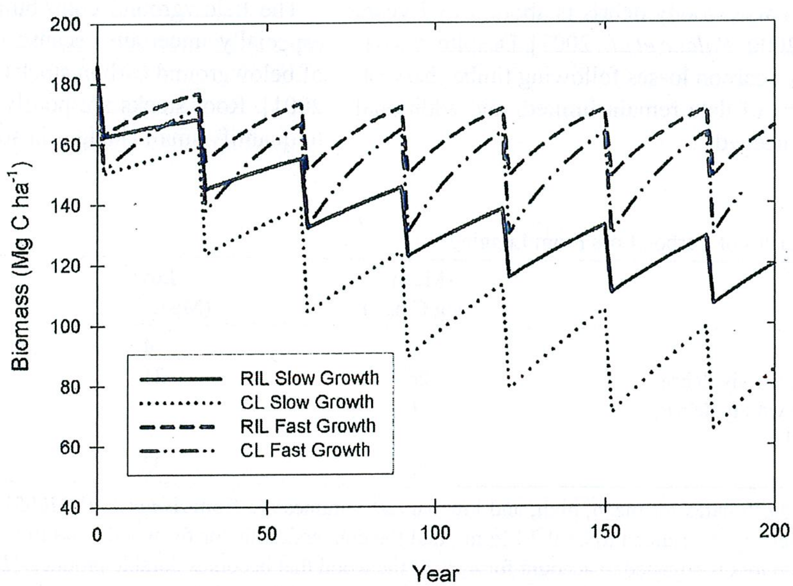

Figure 2. Simulated recovery of aboveground biomass in eastern Amazon forest sites under 30-year revisit scenarios using conventional logging (CL) and reduced-impact logging (RIL) extraction techniques [*Keller et al.*, 2004a].

wer, 1996]. Increases in nitrate availability in tropical forest soils stimulate denitrification and nitrogen oxide emissions [*Keller and Reiners*, 1994]. Logging often has its most obvious effect on soils via increased erosion and runoff, with concomitant losses of nutrients and organic matter [*McNabb et al.*, 1997; *Brouwer*, 1996; *Johns et al.*, 1996]. Both the magnitude and direction of ecological change following harvest depend heavily upon the initial logging intensity and the subsequent spatial and temporal dynamics of forest gap fraction.

Timber harvesting alters stocks and fluxes of plant nutrients in the landscape, with potential implications for short-term recovery and long-term sustainability of logging practices in tropical forests [*Brouwer*, 1996; *McNabb et al.*, 1997]. In particular, rock-derived nutrients such as phosphorus (P), calcium (Ca), and magnesium (Mg) are scarce in the most common soil types found in the eastern Amazon [*Sanchez*, 1976; *Silver et al.*, 2000]. Ultisols and oxisols contain little mobile inorganic P. Most P is found in organic pools or unavailable forms in the mineral soil, and both P and base cations (Ca, Mg, etc.) are recycled very efficiently in humid tropical forests [*Vitousek and Sanford*, 1986; *Stewart and Tiessen*, 1987]. Organic pools such as wood, foliage, fine roots, and soil organic matter are critical sources of these scarce nutrients.

Certain landscape features in selectively logged forests are more overtly impacted by harvest operations than others. Log decks and roads often undergo a complete removal of the surface root mat, litter layer, and soil organic matter, which are important nutrient storage pools for both rock-derived nutrients and nitrogen. Selective logging operations often result in soil compaction, which can enhance reducing conditions in the log deck soils, resulting in higher pH and Ca and Mg concentrations [*Olander et al.*, 2005]. These zones of changing redox can lead to changes in nitrogen oxide and methane production [*Keller et al.*, 2005; see also *Bustamante et al.*, this volume]. Under moderate logging intensities, no increases in soil nutrients are observed in the tree fall gaps despite the flush of nutrient-rich fresh foliage in the tree crown that is left behind after the bole wood is removed [*Olander et al.*, 2005]. Calculations suggest that nutrient inputs from crown foliage in tree fall gaps are probably too small to detect against the background level of nutrients in the topsoils [*Keller et al.*, 2004a]. The logging disturbances with the greatest spatial extent, skids and gaps, have the smallest immediate effect on soil nutrients, while those with the smallest spatial extent, roads and decks, have the largest impact. In the central Amazon, changes observed in soils 3–6 months after harvest were similar to those measured 16 years after logging, suggesting some interesting linkages between the mechanisms causing the immediate change and those maintaining these changes over time [*Olander et al.*, 2005]. The direct impacts on soil properties appear less important than the loss of nutrients in bole wood in determining the sustainability of selective logging.

4. LOGGING AND DEFORESTATION

4.1. Converting Logged Forest to Clearings

Selective logging is one of many land uses on the actively developing frontiers in Brazilian Amazonia. Capital formed through selective logging may be invested in other economic activities such as cattle ranching or intensive agriculture [*Schneider et al.*, 2000; *Merry et al.*, 2006]. Even for smallholders, revenues from logging may facilitate complete deforestation. This view of logging is juxtaposed with the view of selective logging as a potentially environmentally friendly land use alternative to deforestation. Along with capital formation, selective logging rapidly increases human access to the forests via logging roads [*Souza et al.*, 2005].

While the causal relations between logging and clearing are still uncertain, the spatial association has been clearly demonstrated by *Asner et al.* [2006] through the analysis of high-resolution satellite images covering five states of Brazilian Amazonia from 1999 to 2004. They combined selective logging maps derived from the Carnegie Landsat Analysis System (CLAS) with deforestation maps from the INPE PRODES program, as well as geographic information systems layers showing road networks. Over more than 2,000,000 km^2 of Amazonia, logging was most likely to occur within 10 km of paved roads (Figure 3). However, up to 30% of all mapped logging areas were 25–50 km from these arteries. Moreover, *Asner et al.* [2006] found that 16 ± 1% of selectively logged areas were deforested within 1 year of logging, with a subsequent annual deforestation rate of 5.4% for 4 years following timber harvests. The probability of deforestation for a logged forest was up to 4 times greater than for unlogged forests. During the early 2000s, selective logging was clearly a step toward full clear-cutting of the forest.

4.2. Forest Degradation and Fire Following Logging

Clear-cutting is not the only fate of selectively logged forests in Amazonia. As discussed, timber harvest operations result in a matrix of new roads throughout a forest, always leading back to more substantial paved road networks. These road networks increase general access to hunters, who may decrease faunal population densities, with cascading impacts on the forest food web [*Peres*, 2001; *Peres et al.*,

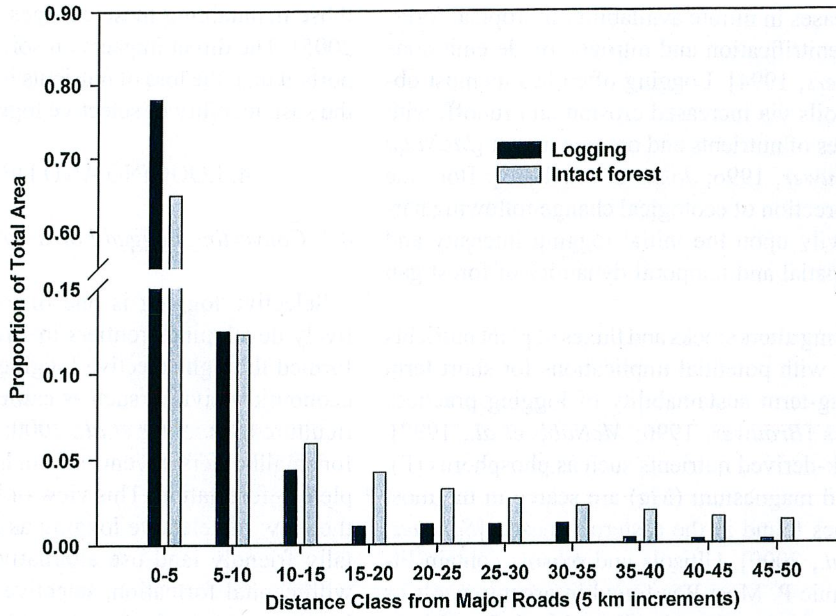

Figure 3. Proportion of total area of logging or intact forest with distance from major roads throughout the states of Pará, Mato Grosso, Rondônia, Acre, and Roraima in Brazilian Amazonia [*Asner et al.*, 2006].

2006]. Canopy openings can also result in forest desiccation [*Ray et al.*, 2005], leading to increased fire susceptibility, as documented at local to regional levels [*Cochrane et al.*, 1999; *Nepstad et al.*, 1999; *Gerwing*, 2002; *Souza et al.*, 2003, 2005].

The impacts of logging on forest fragmentation have recently been quantified over a four-state region of Brazilian Amazonia at a spatial resolution of 30 m [*Broadbent et al.*, 2008]. Annually from 1999 to 2002, deforestation and selective logging generated ~32,000 and 38,000 km of new forest edges, which equates to a growth rate in fragment edges of 0.8% and 3.1%, respectively, for clear-cutting and selective logging. On the basis of the average published distance in which forest edge effects persist (100 m), *Broadbent et al.* [2008] estimated that deforestation resulted in an additional ~3000 km^2 of "edge-affected" forest over the study period, whereas selective logging generated nearly 20,000 km^2 of edge-affected forest, often deep into intact forest areas. From a fragmentation perspective, the high-impact logging practices of the recent past in Brazil have been a major force of forest fragmentation and change.

In sum, a combination of logging, forest degradation, and deforestation is rendering Brazilian Amazonia as a new ecological landscape, with mosaics of cleared and forested land, the latter of which resides as a complex mosaic of secondary and logged primary forest [*Fearnside and Guimarães*, 1996; *Steininger*, 1996; *Cardille and Foley*, 2003]. Just a four-state area of forest affected by clearing and logging alone was enormous in 2000–2001 (Plate 5). Adding geographic detail on fires, degradation and hunting will be a challenging task, but advances in remote sensing are making it possible to map and monitor a range of changes in tropical forest environments (reviewed by *Chambers et al.* [2007]). Remote sensing research during LBA fueled many of the technique developments that make the mapping of selective logging more tractable today (Appendix A).

5. CONCLUDING REMARKS

Selective logging is clearly an important form of land use in Amazonia, with the potential for sustainable forest use if these more careful methods of extraction and planning can be more widely adopted and enforced. From 2000 to 2005, about half of the selective logging in Brazilian Amazonia was illegal and hence unregulated [*Barreto et al.*, 2006]. Moreover, at least through 2002, selective logging was regionally dominated by high-damage extraction operations that left the forest susceptible to drought and fire [*Nepstad et al.*, 1999; *Gerwing*, 2002]. Logging was often a precursor to deforestation [*Asner et al.*, 2006] via the increased access to the forest that unofficial logging roads provide to inhabitants [*Souza et al.*, 2005]. Furthermore, as of 2007, the total land under For-

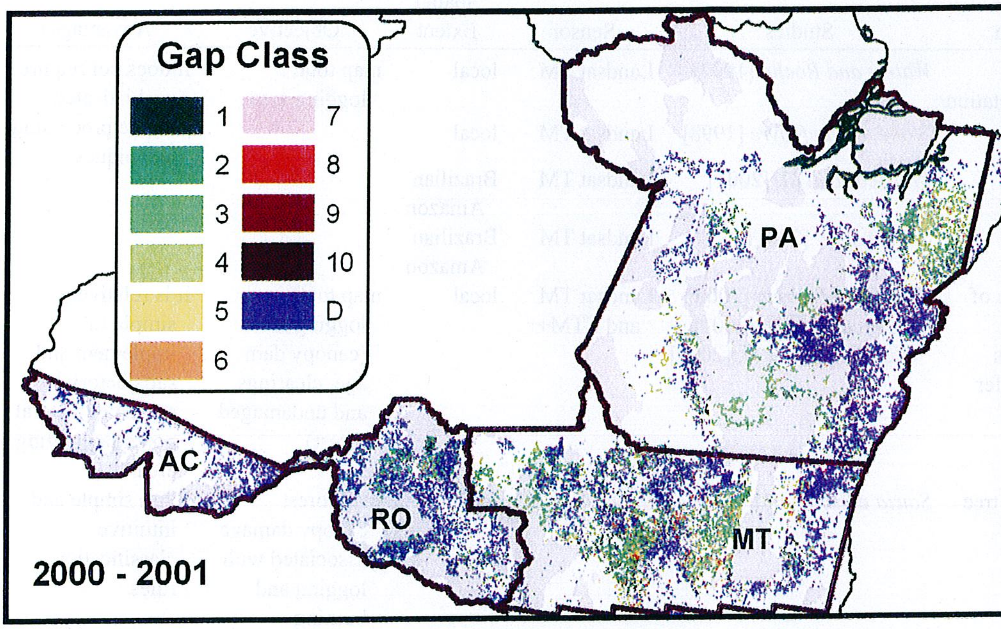

Plate 5. Mosaic of selective logging (gap classes 1–10) and deforestation (D, blue), compiled by *Asner et al.* [2006]. Both the logging and deforestation cover the period 2000–2001. Gap classes 1–10 for logging indicate the area-integrated loss of canopy cover at 1-km resolution. Class 1 is 0–10% canopy loss, class 2 is 11–20% canopy loss, etc. Gray polygons indicate federal conservation lands and indigenous reserves. This compilation was limited to the states of Pará (PA), northern Mato Grosso (MT), Rondônia (RO), and Acre (AC) as indicated.

est Stewardship Council green certification in Amazonia was merely 3.2 million ha (Forest Stewardship Council, Florestas Certificadas, 2005, available at http://www.fsc.org.br), which represents only 3% of total Amazonia timber production [*Barreto et al.*, 2006]. Thus, in recent years, selective logging was not dominated by the kind of well-managed, low-impact, green certification operations intended to preserve forest cover, structure, diversity, and function and to be an alternative to deforestation. Instead, it has been dominated by high-damage operations that leave the canopy in disarray, with cascading effects on the ecology of the region. This chapter has highlighted and synthesized much of what was learned about the ecological impacts of logging during the LBA program. Future studies will build upon these findings and hopefully will keep pace with the rapidly evolving timber industry policies in Brazil and other regions of the Amazon.

APPENDIX A: REMOTE SENSING OF SELECTIVE LOGGING

Detection of selective logging with moderate-resolution satellite imagery, such as Landsat thematic mapper (30-m pixel size), is challenged by the complex mixture of dead and live vegetation, shadowing, and soils found throughout forest environments. From the satellite vantage point, forest damage caused by logging seems to disappear within 3 years or less, making detection of previously logged forest (>1 year) very challenging [*Stone and Lefebvre*, 1998]. During LBA, remote sensing studies on logging in the Brazilian Amazon found that Landsat reflectance data have limited spectral resolution to detect logged forest from intact forest [*Asner et al.*, 2002a; *Souza et al.*, 2005]. Vegetation indices [*Stone and Lefebvre*, 1998; *Souza et al.*, 2005; *Broadbent et al.*, 2006] and texture filters [*Asner et al.*, 2002a] also showed a limited capability for detection of logging. Improving the spatial resolution of reflectance data can help; 1- to 4-m resolution IKONOS satellite data can readily detect forest canopy structure and canopy damage caused by selective logging [*Asner et al.*, 2002b; *Read et al.*, 2003; *Souza et al.*, 2003]. However, the high cost of these images and additional computational challenges of extracting information severely limit the operational use of IKONOS and similar imagery.

LBA research showed that the detection of logging at moderate spatial resolution is best accomplished at the subpixel scale using a technique called spectral mixture analysis

Table A1. Remote Sensing Techniques Applied to Selective Logging in the Brazilian Amazon[a]

Mapping Approach	Studies	Sensor	Spatial Extent	Objective	Advantages	Disadvantages
Visual interpretation	*Watrin and Rocha* [1992]	Landsat TM	local	map total logging area	It does not require sophisticated image processing techniques.	It is labor-intensive for large areas and may be user-biased to define the boundaries of logged forest.
	Stone and Lefebvre [1998]	Landsat TM	local			
	Matricardi et al. [2001]	Landsat TM	Brazilian Amazon			
	Santos et al. [2001]	Landsat TM	Brazilian Amazon			
Detection of logging landings and buffer	*Souza and Barreto* [2000], *Matricardi et al.* [2001], and *Monteiro et al.* [2003]	Landsat TM and ETM+	local	map total logging area (canopy dam age, clearings, and undamaged forest)	It is relatively simple to implement and satisfactory to estimate the total potential logging area.	Logging buffers vary across the landscape and do not reproduce the actual shape of the logged area.
Decision tree	*Souza et al.* [2003]	SPOT-4	local	map forest canopy damage associated with logging and burning	It has simple and intuitive classification rules.	It has not been tested in very large areas, and classification rules may vary across the landscape.
Change detection	*Souza et al.* [2003]	Landsat TM and ETM+	local	map forest canopy damage associated with logging and burning	It enhances forest canopy damaged areas.	It requires two pairs of images and does not separate natural and anthropogenic forest changes.
Image segmentation	*Graça et al.* [2005]	Landsat TM	local	map total logging area (canopy damage, clearings, and undamaged forest)	It is relatively simple to implement and satisfactorily estimate the total logging area. Free software is available.	It has not been tested in very large areas, and segmentation rules may vary across the landscape.
CLAS	*Asner et al.* [2005, 2006]	Landsat TM and ETM+	five states of the Brazilian Amazon	map total logging area (canopy damage, clearings, and undamaged forest)	It is highly automated and standardized to very large areas.	It requires high computation power and pairs of images to detect forest change.
CLASlite	http://claslite.ciw.edu	Landsat TM and ETM+, SPOT-4/5, ASTER, ALI, and MODIS	anywhere in the world	automated mapping of forest cover, deforestation, and forest degradation	It is highly automated, run on a standard desktop computer, requires minimal training.	It is limited to tropical forests.
NDFI and CCA	*Souza et al.* [2005]	Landsat TM and ETM+	local	map forest canopy damage associated with logging and burning	It enhances forest canopy damaged areas.	It has not been tested in very large areas and does not separate logging from burning damages.

[a]Abbreviations are TM, thematic mapper; ETM+, Enhanced Thematic Mapper Plus; CLAS, Carnegie Landsat Analysis System; NDFI, normalized difference fraction index; and CCA, Contextual Classification Algorithm.

(SMA). Images obtained with SMA that show detailed fractional cover of soils, nonphotosynthetic vegetation (NPV), and green vegetation enhance our ability to detect logging infrastructure and canopy damage. For example, soil fractional cover maps derived from SMA can enhance the detection of log decks and roads [*Souza and Barreto*, 2000]; maps of NPV fraction enhance the expression of damaged and dead vegetation [*Souza et al.*, 2003]; and the green vegetation fractional cover is sensitive to canopy openings [*Asner et al.*, 2004a].

Several mapping techniques were tested and applied in local to large regional-scale studies of selective logging in Brazil (Table A1). These techniques vary in terms of the mapping goals, the approach and geographic extent, and reported accuracies. In terms of mapping goals, some techniques were developed to map the total potentially logged area, which includes forest canopy damaged and forest clearings and undamaged forest islands, while others were focused only on the mapping of forest canopy damage. The former group of techniques included visual interpretation of Landsat images [e.g., *Stone and Lefebvre*, 1998; *Matricardi et al.*, 2001], manual and automated detections of log decks with an estimated timber-harvesting buffer around the decks [*Souza and Barreto*, 2000], and highly automated SMA approaches combined with pattern recognition methods [*Souza et al.*, 2005; *Asner et al.*, 2005, 2006]. Future studies will likely focus on techniques that balance issues of satellite image quality, availability and cost, processing time, and the level of expertise required to produce verifiable maps of selective logging. LBA research paved the way for these current and future developments.

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