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The Changing Rates and Patterns of Deforestation and Land Use in Brazilian Amazonia

Diogenes S. Alves,[1] Douglas C. Morton,[2] Mateus Batistella,[3] Dar A. Roberts,[4] and Carlos Souza Jr.[5]

Investigating the rates and patterns of land cover and land use change (LCLUC) in Amazonia is a central issue for Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) research. LCLUC, along with climatic changes, affects the biological, chemical, and physical functions of Amazonia, thereby linking environmental change at the local, regional, and global scales. Considerable research has focused on estimating rates of forest conversion in Amazonia, mainly through the use of satellite remote sensing, and evaluating factors that influence these rates. Beyond the rates of forest loss, LCLUC research in Amazonia has also considered the variety of agricultural uses that replace forest cover, forest degradation from logging and fire, and secondary vegetation on previously cleared lands.

1. INTRODUCTION

Investigating the rates and patterns of land cover and land use change (LCLUC) in Amazonia is a central issue for Large-Scale Biosphere-Atmosphere (LBA) Experiment in Amazonia research [*Keller et al.*, 2004] (see the LBA Extended Science Plan at http://lba.cptec.inpe.br/lba/site/?p=plano_cientifico_estendido&t=1). LCLUC, along with climatic changes, affects the biological, chemical, and physical functions of Amazonia, thereby linking environmental change at the local, regional, and global scales [*Keller et al.*, 2004] (LBA Extended Science Plan at http://lba.cptec.inpe.br/lba/site/?p=plano_cientifico_estendido&t=1). Considerable research has focused on estimating rates of forest conversion in Amazonia, mainly through the use of satellite remote sensing and evaluating factors that influence these rates [e.g., *Tardin et al.*, 1980; *Fearnside et al.*, 1990; *Fearnside*, 1990; *Skole and Tucker*, 1993; *Alves*, 2002; *Margulis*, 2004; *Chambers et al.*, 2007]. Beyond the rates of forest loss, LCLUC research in Amazonia has also considered the variety of agricultural uses that replace forest cover, forest degradation from logging and fire, and secondary vegetation on previously cleared lands. LCLUC in Brazilian Amazonia is highly heterogeneous, both spatially and temporally, as are the varieties of agricultural uses that replace forest cover [e.g., *Becker*, 1997; *Machado*, 1998; *Faminow*, 1998; *Alves*, 2002, 2007a; *Morton et al.*, 2006]. To capture this heterogeneity, we develop a framework in which deforestation is one transition stage in a continuum of land use and land cover changes and their associated impacts on ecosystems and landscapes of Amazonia. We refer to the sequence of land cover changes, from mature forests to agricultural uses and abandonment, as a land use trajectory. Individual events within a trajectory are described as transitions.

The current Amazonian landscape is an integrated measure of the disturbance history from different development phases over the past 50 years. Numerous studies have provided

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[1] Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil.

[2] Goddard Space Flight Center, Greenbelt, Maryland, USA.

[3] Embrapa Satellite Monitoring, Campinas, Brazil.

[4] Department of Geography, University of California, Santa Barbara, California, USA.

[5] Instituto do Homem e Meio Ambiente da Amazônia, Belém, Brazil.

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a multifaceted history of the driving forces behind frontier expansion and deforestation in the region [e.g., *Velho*, 1976; *Sawyer*, 1984; *Schmink and Wood*, 1992; *Machado*, 1998; *Margulis*, 2004], and we will not duplicate those efforts here. Historically, variations in forest clearing rates were generally linked with changes in access to the region; thus, road building and migration were critical precursors to forest losses. During the 1980s and 1990s, large-scale colonization projects, credit incentives, and steady investment in the region led to annual forest losses of 1–3 million ha [*INPE*, 2001, 2007] (Figure 1). More recently, economic forces within and beyond Amazonia have exerted stronger controls over deforestation rates and postclearing land uses, including domestic and global demand for beef, soybeans, and wood products [*Faminow*, 1998; *Andersen et al.*, 2002; *Margulis*, 2004; *Veiga et al.*, 2004; *Morton et al.*, 2006].

LBA contributed to the development of remote sensing methods to map land cover and land use in Amazonia [*Roberts et al.*, 2002; *Hess et al.*, 2003; *Lu et al.*, 2004; *Anderson et al.*, 2005; *Morton et al.*, 2006] and to greater understanding of the patterns and processes of deforestation and the overall dynamics of LCLUC through field, remote sensing, modeling, and related studies [e.g., *Alves*, 2002; *Asner et al.*, 2005; *Soares Filho et al.*, 2004; *Alves*, 2007a]. LCLUC plays a central role in many elements of LBA research, since the sum of recent LCLUC defines the spatial patterns of land cover and the relative proportion of mature forest, secondary growth, or degraded forest of varying structural characteristics, wetlands, natural and planted pastures, and croplands in any Amazonian landscape.

In this chapter, we summarize recent LBA research focused on regional-scale patterns and processes of forest modification, conversion, postclearing land use, and the fate of deforested land over time. Rates and patterns of deforestation are influenced by a range of economic, social, and political factors, and where possible, we describe linkages between these controls and deforestation activity. We concentrate on the large-scale dynamics that link a variety of LCLUC processes; specific transitions such as logging, fire, and individual agricultural uses will also be addressed in more detail in the following chapters. We begin with a summary of deforestation mapping and monitoring approaches of both forest loss and postclearing land use. Basin-wide dynamics of forest loss, agricultural land uses, and rates of land abandonment are subsequently described to discuss recent spatial and temporal trends in LCLUC. Finally, we examine the deforestation and postclearing land use of Mato Grosso state in greater detail to highlight rapid changes over the past decade in this region and the development of grain production capacity.

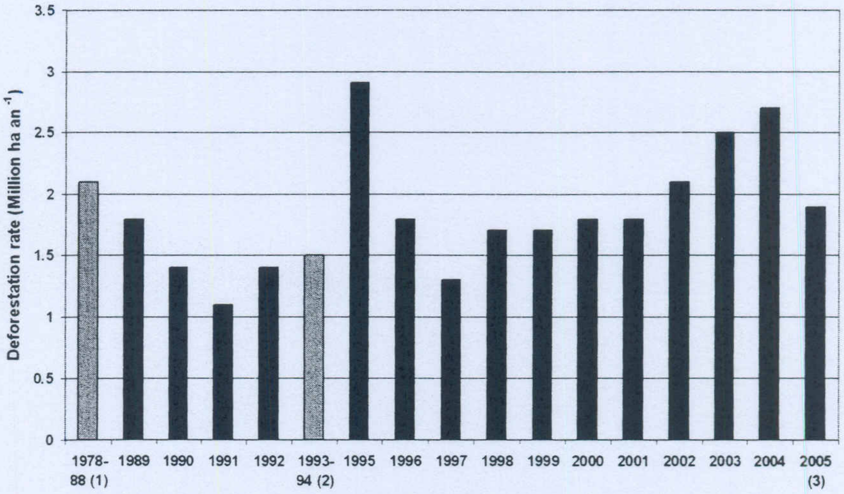

Figure 1. Interannual deforestation rates in Amazonia from Instituto Nacional de Pesquisas Espaciais (INPE) deforestation surveys [*INPE*, 2001, 2007; *Alves*, 2007b]. (1) Average annual rates for the 1978–1988 period; estimates for 1978 were produced after partial reanalysis of black-and-white Landsat MSS 1:500,000-scale images and maps by *Tardin et al.* [1980] to address inconsistencies between this study and later INPE surveys [*Fearnside et al.*, 1990]; (2) Average annual rates for the 1992–1994 period. Statistics for the 1987–2000 period are based on visual interpretation of color composites of Landsat TM red, near-infrared and mid-infrared channels at the 1:250,000-scale. Later statistics are derived from digital processing of Landsat TM images mapping forest clearings of 6.25 and larger.

2. CHARACTERIZING SPATIAL AND TEMPORAL VARIATIONS OF LAND COVER AND USE

Mapping or monitoring land cover changes in Amazonia is challenging. The region is very large, rapidly changing, and often covered by clouds. The study of deforestation and subsequent LCLUC has therefore relied on satellite remote sensing and periodic agricultural censuses to construct the spatial and temporal variations in deforestation and post-clearing land uses. Satellite remote sensing has also been an integral part of investigations of the forest modification by logging and fire that often precedes deforestation and to the characterization of the spatial and temporal distribution of anthropogenic fires in Amazonia.

Given the vast geographic extent of inundated forests and other wetlands, tropical forest, and savannas (Plate 1), methodological approaches to map or monitor LCLUC often require trade-offs in spatial or temporal resolution [*Chambers et al.*, 2007]. Thus, deforestation mapping based on high-resolution satellite data can only be completed once per year, since cloud-free satellite coverage is most reliable during the dry season months [*Fearnside*, 1990; *Asner*, 2001]. Monitoring changes in land management across Amazonia may only be possible at 5- or 10-year intervals from agricultural census data, given the amount of effort required to survey farmers across the basin. The required spatial and temporal resolution of any application will therefore influence the choice of a specific satellite sensor or data product.

Satellite remote sensing analyses have mapped the spatial extent of deforestation [e.g., *Fearnside et al.*, 1990; *Fearnside*, 1990; *INPE*, 2001; *Alves*, 2007b], selective logging [e.g., *Asner et al.*, 2005; *Souza et al.*, 2005], secondary forest [e.g., *Roberts et al.*, 2002; *Alves et al.*, 2003], and land use following clearing [e.g., *Moran and Brondízio*, 1998; *Morton et al.*, 2006; *Lu et al.*, 2008]. Region-wide deforestation in Brazilian Amazonia has been mapped with satellite data since the 1970s [e.g., *Tardin et al.*, 1980; *Fearnside et al.*, 1990; *Fearnside*, 1990; *Skole and Tucker*, 1993; *Shimabukuro et al.*, 2007; *Alves*, 2007b]. Annual Landsat-based surveys estimate total deforested area in Brazilian Amazonia to have reached nearly 70 million ha by 2005 [*INPE*, 2001, 2007] (Plate 1).

Information regarding the timing of forest clearing activities has emerged recently with the launch of new moderate resolution sensors SPOT-VEGETATION (1998, 1.1 km) and Moderate Resolution Imaging Spectroradiometer (MODIS; 2000, 2003, 250 m to 1 km). Near-daily coverage from these instruments can be combined to provide cloud-free data at weekly to monthly intervals to map land cover change [e.g., *Carreiras et al.*, 2002; *Souza et al.*, 2003; *Anderson et al.*,

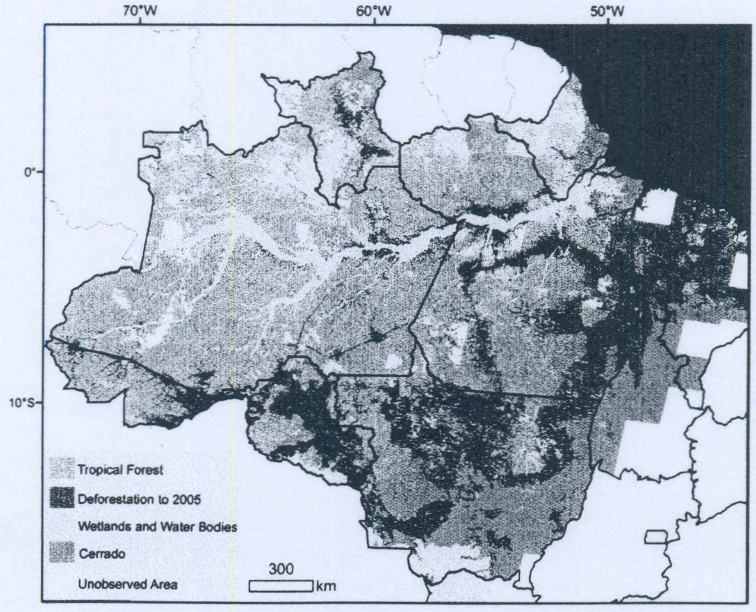

Plate 1. Brazilian Amazonia showing the areas of closed forest (58%), Cerrado woodland-savannas (14%), wetlands and water bodies (9%), and deforestation to 2005 (13%). Unobserved areas correspond to 2005 cloud cover (6%) or areas outside the limits of Brazilian Amazonia. Data sources: closed forest, woodland-savannas, and deforestation [*INPE*, 2007]; wetlands and water bodies [*Hess et al.*, 2003].

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2005; *Morton et al.*, 2005; *Lu et al.*, 2008]. Moderate resolution data are not ideal for quantifying fine-scale land cover changes; deforestation monitoring algorithms only consider forest losses larger than several moderate resolution pixels, or approximately 25 ha [*Morton et al.*, 2005; *Shimabukuro et al.*, 2007]. MODIS-based deforestation monitoring provided the first regional understanding of the timing of forest clearing activities [*Anderson et al.*, 2005; *Kay*, 2005; *Shimabukuro et al.*, 2007]. For recent deforestation in Mato Grosso state, clearing activity began in 93% of deforested areas prior to the onset of dry season conditions [*Kay*, 2005]. Clearings initiated in the wet season averaged three to five times the size of those areas cleared during the dry season, indicating that mechanized clearing may be less dependent on climate conditions than previously thought [*Kay*, 2005]. Data from DETER, an operational deforestation monitoring system developed by Instituto Nacional de Pesquisas Espaciais, Sao Paulo, Brazil [*Shimabukuro et al.*, 2007], show that deforestation timing differed markedly between 2005 and 2006. In 2005, forest clearing in Mato Grosso was almost equally split between September and April (47%) and May and August (53%), suggesting a strong wet season clearing component (November and April, 31%). In 2006, less than 20% of all clearing between was identified before May. Less wet season clearing in 2006 is consistent with reductions in large, mechanized clearing activities compared to other recent years.

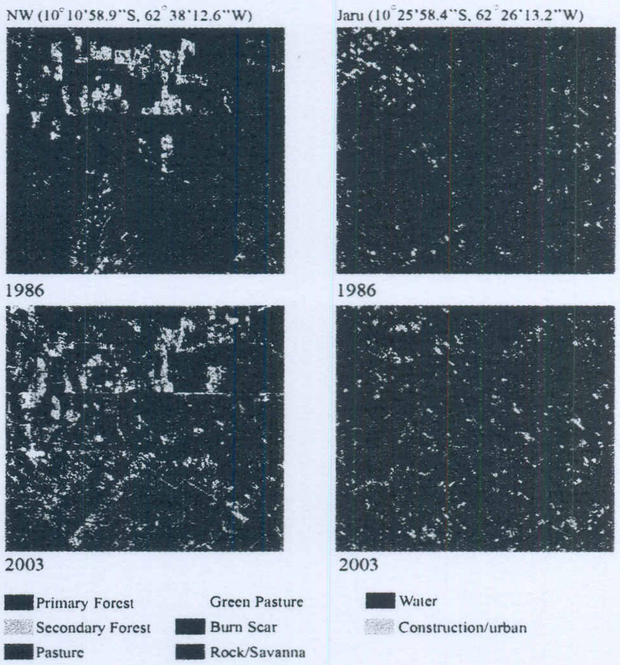

Plate 3. Contrasting patterns of forest fragmentation and land cover in two regions of Rondônia. Old secondary forest appears to be abundant in an area of the northwestern part of the state. Within a region of old settlement near the town of Jaru, deforestation eliminates most forest cover between 1986 and 2003. Each scene is 21 km across.

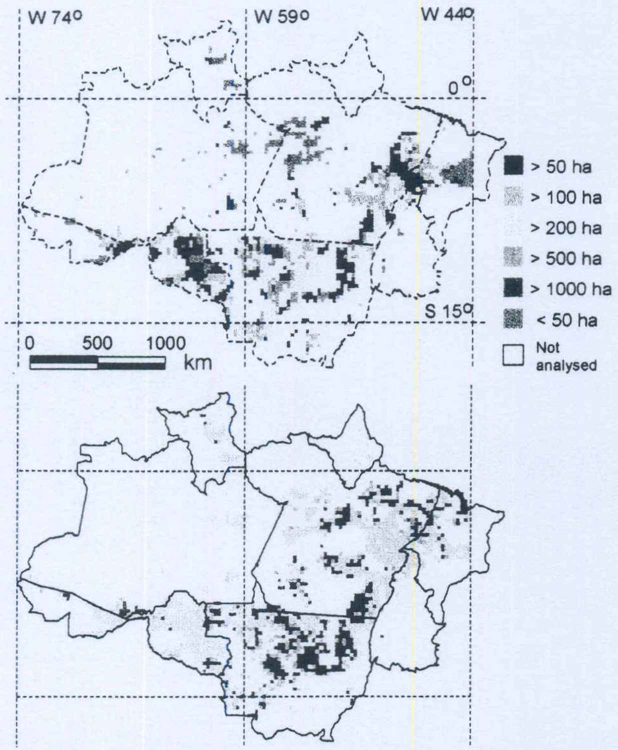

Plate 2. (a) Regions of predominance of forest clearings of various sizes during 1991–1997 [after *Alves*, 2002]. Categories represent the clearing size that accounted for 50% or more of the total cleared area in the period; area depicted comprises the ¼° cells that accumulated the first 95% in the Lorenz curve shown in Figure 3 [after *Alves*, 2002]. (b) Same as Plate 2a but for 2000–2005.

Agricultural census data are a rich archive of regional information on agricultural production, land management decisions, and related ecosystem and economic impacts. For 1970–1985, censuses were carried out every 5 years; after this period, a single survey was conducted (1995/1996), and a new census was underway in 2007. Census data are generally available at the municipal scale; however, due to frequent subdivisions of large municipalities, establishing a consistent unit of analysis to track changes over the entire 1970–1996 period would require very large, heterogeneous units, which, in some cases, would include entire states (see, for example, http://www.ipeadata.gov.br). Also, methodological issues from changes in the categories of data or the period of data collection, and difficulties related to the logistics of data collection in Amazonia further complicate comparisons between censuses. Despite these drawbacks, agricultural censuses constitute the most complete survey of agricultural production, including the area under different land use categories, crop production, and agricultural inputs, allowing for detailed analyses of social, economic, and environmental aspects of agriculture in Amazonia and comparison of the region with other parts of Brazil. During LBA, research based on data from the agricultural censuses evaluated the suite of positive and negative effects of deforestation in Amazonia [*Andersen et al.*, 2002] and the dynamics of land abandonment and land use intensification during this period [*Alves*, 2007a]. Methodological advances in fusing satellite and census data captured the corresponding spatial detail and management information in both data types for studies of land cover change and future landscape scenarios [*Cardille and Foley*, 2003; *Morton et al.*, 2009].

3. LAND COVER AND LAND USE CHANGE: PATTERNS AND TRAJECTORIES IN AMAZONIA

The same LCLUC trajectory can result from different suites of transitions, depending on the type of initial forest disturbance and the number of preceding land uses (Figure 2). For example, the forest to pasture trajectory can occur directly, if mature forest is clear-cut to plant grasses, or indirectly if pastures are established following logging or crop cultivation. The likely transition pathway from forest to other land uses depends on the stage of frontier occupation and the site conditions, such as distance to existing settlements and roads [*Alves*, 2002], soils and topography [e.g., *Machado*, 1998], land tenure, household assets, and market conditions for specific forest or agricultural products [*Batistella et al.*, 2003; *Batistella and Moran*, 2005]. These factors influence the probabilities for individual transitions within this diagram at a variety of spatial scales; the spatial extent of logging and deforestation were nearly equivalent during 2000–2002, yet logged forest within 25 km of major roads had a higher probability of being deforested than unlogged forest [*Asner et al.*, 2006].

Census data from 1970 to 1995 show several key trends in LCLUC trajectories during the expansion of the agricultural frontier. During this period, the majority of deforested land was converted to pasture for cattle ranching. The relative importance of temporary crops was relatively stable across much of Amazonia except Mato Grosso (Table 1). The contribution of Amazonian cattle to the total Brazilian herd increased from 8% to 23%, driven by both an increase in pasture area and a doubling of the average stocking rates per hectare.

The long-term land use trajectories in a given region may be linked to different land use processes and socioeconomic factors. For example, cycles of land abandonment can be linked to shifting cultivation or land rotation in established

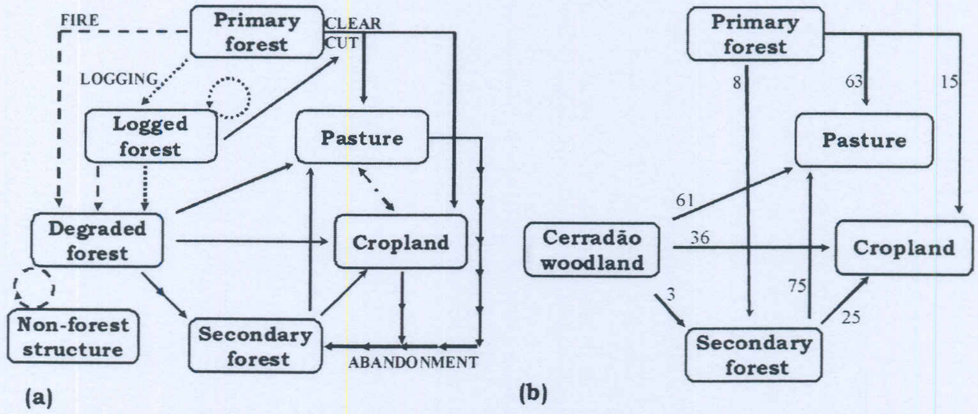

Figure 2. (a) Diagram showing the most common transitions among land cover/use classes studied during LBA. Initial forest disturbances occur through clear-cutting (solid), fire (dashed), and logging (dotted). Subsequent transitions among pasture, cropland, secondary forest, and degraded forest cover types show the diversity of pathways that are possible for any land use trajectory. (b) Transition probabilities for postclearing land uses in Mato Grosso state during 2000–2005 for forest, secondary forest, and cerradão woodland clearings >25 ha. Small deforestation events (<25 ha, not shown) in Mato Grosso account for 15% of all deforestation. Percentages refer to the fraction of cleared area converted to specific land uses [*Morton et al.*, 2006, 2007a].

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Table 1. Evolution of Aggregate Land Use Statistics According to Brazilian Agricultural Census[a]

	1970	1975	1980	1985	1995
			Land Category, % Total Farm Area		
Pasture	37.9	35.5	35.2	36.8	42.4
Crops, temporary	2.6	3.3	4.1	4.4	3.9
Crops, permanent	0.3	0.4	0.7	0.8	0.8
Forest	37.3	43.0	42.4	40.4	41.3
Abandoned land[b]	15.5	13.1	9.8	8.9	5.7
All other[c]	6.4	4.7	7.8	8.7	5.9
			Temporary Crops in MT and in All Other States, % Total Farm Area		
Mato Grosso state	1.4	2.1	4.1	5.3	5.6
All other states	3.0	3.8	4.0	4.0	2.8
			Cattle Head in Amazonia as a Fraction of National Herd, %		
	8.2	9.0	12.7	14.7	23.3
			Average Stocking Rate, head/ha		
	0.30	0.30	0.40	0.40	0.70

[a] Aggregate data for the nine states belonging to Legal Amazonia: Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins. Source: http://www.ipeadata.gov.br.

[b] Abandoned land is defined as land unused for more than 4 years.

[c] All other includes land in rotation, planted forest, and other categories like swamps.

farms; cropland can rotate with pasture when grain prices are low. Although not shown in Figure 2, agroforestry, reforestation, urban expansion, and other types of land use can also replace pastures or croplands. In addition, some land use trajectories can be influenced by a combination of factors, such as forest degradation from selective logging and fire [*Nepstad et al.*, 1999], which fundamentally alter forest structure and land value.

Particular LCLUC transitions generate unique patterns of forest loss. Different agrarian regimes, including farm size, the architecture of settlement projects, and different production and land management strategies can lead to diverse expressions of the same trajectory in landscape patterns. The composition and configuration of the landscapes produced have important consequences for the functioning of the biophysical systems in Amazonia and may help inform discussions of plausible development scenarios for the region. Within many older agricultural frontiers, concentrated deforestation activity in the vicinity of major roads and colonization projects [*Machado*, 1998; *Alves*, 2002] has led to landscapes dominated by pastures and cropland. The magnitude of forest clearing for agriculture in these areas often exceeds the limits prescribed by the Brazilian Forest Code [*Alves et al.*, 2003; *Alvez*, 2007b].

The following sections review advances in understanding the evolution of landscape patterns and the dominant long-term LCLUC trajectories in Amazonia.

3.1. Landscape Patterns of Forest Conversion

Deforestation in Amazonia has replaced the forest with a fragmented landscape of pasture and agricultural areas, leaving few forest remnants where deforestation has been most concentrated. The total extent of deforestation in Amazonia until 2005, depicted in Plate 1, provides a first approximation of important regional patterns in forest loss. Major road and river networks are buffered by the outlines of historic deforestation and older frontier areas of eastern Pará, Mato Grosso, and Rondônia states have greater forest loss than newer frontiers in central Pará, Acre, or Amazonas states. Specific site conditions, including soil quality or topography, further influence both the location of forest clearing and the postclearing land uses, such that patterns of deforestation and land use may be locally consistent.

The spatial patterns resulting from forest conversion may differ substantially across the basin as a function of clearing size (Plate 2). Deforestation between 1991 and 1997 occurred in very large clearings in central Mato Grosso and eastern Pará states and in smaller clearings in regions with higher densities of settlement projects in Pará and Rondônia. Overall, large clearings on larger farms contributed the greatest fraction of total deforestation (Figure 3) [*Alves*, 2002]. During 2000–2005, the patterns in deforestation size show a bimodal distribution, with regions either dominated by very large (>1000 ha, 25% of cells) or very small (<50 ha, 51% of cells) clearing sizes. Very large clearings in central Pará, southern Amazonas, and central Roraima states suggest that these regions were recently exposed to the same degree of capital and technology that was previously found only in older frontier areas.

Landscape patterns of forest conversion at the local scale reflect additional heterogeneity beyond clearing size (Plate 3). In 1986, central Rondônia near Jaru was already highly disturbed, consisting of nearly equal proportions of primary forest and pasture, with pasture concentrated along planned roads at 4-km intervals. By 2003, linear strips of forest from 1986 had been reduced to small forest fragments, many of which were less than 1 km across. Small patches of secondary forest mapped in 2003 occur exclusively along the margins of forest fragments that have never been cleared, suggesting that forest edges are taking on the spectral signature of secondary forest in the absence of any clearing. Patterns in a region of the nearby municipio of Ariquemes differ markedly with extensive tracts of mature forest in both 1986 and 2003, no "fishbone" pattern from evenly spaced roads, and some large patches of secondary forest as much as 18 years old. Differences in fragmentation patterns reflect differences in the architecture of settlement and colonization projects, whereas the persistence of secondary forest in the northwest is likely due to higher rainfall and poorer soils in this region.

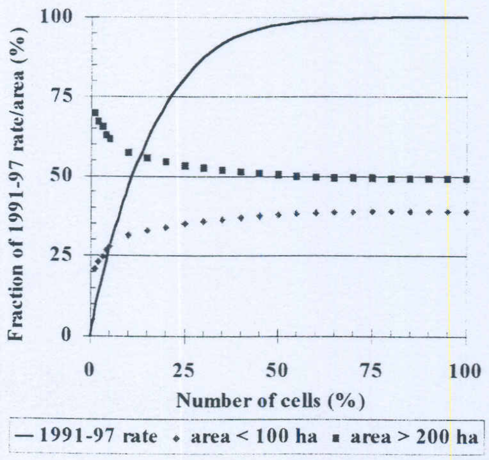

Figure 3. Lorenz curve of the 1991–1997 deforestation rate calculated for ¼° cells and accompanying cumulative curves of the area of forest clearings of two different sizes in the same period [after *Alves*, 2002].

3.2. Forest Degradation From Logging

Selective logging is one of the most important drivers of forest degradation and land cover change in Amazonia. Logging is rarely practiced in a sustainable fashion. In fact, only 1248 ha of mature forests were harvested following the Forest Stewardship Council (FSC) standards in Amazonia in 2003 [*Lentini et al.*, 2005].

The extensive network of secondary roads built by loggers and capital obtained by land owners selling timber help to accelerate the deforestation process near sawmill centers [*Uhl et al.*, 1991; *Verissimo et al.*, 1992]. Unmanaged logging practices lead to forest degradation through damage to forest structure and altered species composition [see *Asner et al.*, this volume]. Using remote sensing techniques, *Asner et al.* [2005] estimated that the annual area affected by logging was 12,000–19,000 km^2 between 2000 and 2002, equivalent to the average annual deforestation rate during this period of 18,000 ± 2900 km [*INPE*, 2007]. Logging and deforestation are not mutually exclusive; an average of 16% of logged forests are clear-cut in the first year following logging operations, with 33% deforested within 4 years of logging [*Asner et al.*, 2006]. Canopy damage and slash from logging operations increase the likelihood of fire damage in logged forests [*Nepstad et al.*, 1999], although the extent of logged and burned forest has not been estimated for the entire Amazon region.

3.3. Forest Conversion to Pasture

According to census data, pasture has been the most common land use in Amazonia (Table 1). Typical processes of pasture establishment in Amazonia include the direct conversion of forest to pasture or a longer conversion trajectory beginning with an initial phase of annual crops before pasture establishment after a number of years [e.g., *Millikan*, 1992]. After establishment, pasture productivity typically remains high for 5 to 7 years before declining due to changes in soil fertility and pH, resulting in a progressive decrease in forage quality and increased weed invasion [*Buschbacher*, 1986; *Serrão and Toledo*, 1990].

As pasture quality degrades, pastures can either be reinvigorated through repeated cycles of burning, reformed via fertilizer application and reseeding, or abandoned to secondary succession. The length of time a pasture remains productive is highly dependent on pasture management practices, local climate, and soil quality [*Serrão and Toledo*, 1990;

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Moran, 1993; *Dias Filho et al.*, 2000; *Numata et al.*, 2007]. For example, pastures established on Alfisols or Ultisols in Rondônia that receive moderate levels of precipitation can remain productive for well over 20 years, whereas pastures established on Oxisols or in more humid or arid conditions show earlier evidence of degradation and higher rates of abandonment [*Numata et al.*, 2007].

Cattle ranching remains the dominant land use in Amazonia (Table 1), following important changes during the last decades. *Faminow* [1998] argues that a fundamental cause for the growth of the cattle herd was the considerable expansion of regional demand associated with urban growth. *Andersen et al.* [2002] and *Margulis* [2004] reviewed the many motivations for cattle ranching and intensification of pasture use, concluding that ranching became profitable independent of subsidies due to the growth of urban demand and increased productivity. *Veiga et al.* [2004] observed a variety of market chains stimulated by local demands and markets outside Amazonia. Higher stocking rates are more commonly found in the most deforested areas, suggesting a transition to pasture use intensification [*Alves*, 2007a]. Taken together, these factors help to explain the continued predominance of pastures in land use trajectories in Amazonian landscapes.

3.4. Forest Conversion to Cropland

In the context of LCLUC, we classify forest conversion to cropland according to the most common land use trajectories in recent decades. Cropland may directly follow deforestation or arise as part of a rotation cycle with secondary forest or pasture. Direct conversion of forest to cropland occurs for both small-scale [e.g., *Moran and Brondizio*, 1998] and large-scale crop production [*Morton et al.*, 2006]. In addition to subsistence crops, small farmers may also invest in other crops for local or national markets [*Moran and Brondizio*, 1998; *Costa*, 2007]. Forest conversion for soybean, maize, or other grain production follows the recent development of crop varieties specifically adapted to the soils and climate of some Amazon regions [*Warnken*, 1999; *Jepson*, 2006]. The dynamics of forest conversion for mechanized crop production in Mato Grosso is discussed in more detail in section 4.1.

The nature of rotation systems between cropland and forest or pasture depend on both farm size and market conditions. For small farms, crop areas may be used until soil nutrients are depleted and then abandoned for several years to allow forest vegetation to accumulate nutrients. The length of fallow rotations in a "slash-and-burn" or "chop-and-mulch" system depends on the rate of forest recovery and farm size [*Denich et al.*, 2004]. On larger farms, market conditions for beef or grains may determine the interannual patterns of pasture and cropland use or the frequency of fallow cycles.

Cropland can be both a precursor to land consolidation for cattle ranching or an endpoint itself, independent of farm size. Census data suggest that in Amazonia, croplands established in the original phases of colonization were largely replaced by cattle ranching as more forest was converted [*Alves*, 2007a]. However, recent expansion of mechanized crop production was generated through new deforestation, savanna clearing, and transitions from pasture to cropland [*Morton et al.*, 2006]. The diversity of transition pathways, crop types, and farm sizes in Amazonia highlights the spatial and temporal variability of cropland on the landscape.

Deforestation dynamics in Mato Grosso state represents one case of particular interest because of specific sociodemographic, economic, and bioclimatic conditions, suggesting the establishment of a new land use system differing from those dominating in other parts of Amazonia. Mato Grosso had the highest deforestation rate during 1995–2005, accounting for 33–43% of the annual deforestation increment in the Brazilian Amazon [*INPE*, 2007]. High rates of forest loss were driven by large clearing sizes [*Alves*, 2002; *Morton et al.*, 2006; *Ferreira et al.*, 2007] (Plate 2 and Figure 3); large landholders (≥1000 ha) owned an estimated 84% and 82% of all land in private property statewide according to the 1985 and 1996 agricultural censuses, respectively [*IBGE*, 1996]. Although deforestation is associated with a variety of influences, economic factors have been largely linked with credit and economic opportunities for extensive cattle ranching operations and crop production such as soybeans, and with inter-regional differences in land prices [*Fearnside*, 2001; *Andersen et al.*, 2002; *Margulis*, 2004; *Morton et al.*, 2006].

Deforestation in Mato Grosso is highly mechanized in comparison with other states. Two tractors, linked by a strong chain, are used to pull down trees in the transitional forests. Even in taller-stature forests, heavy machinery is used to manage manually felled trees. Piling and re-burning forest vegetation can reduce standing forest to bare soil in a matter of months. Unlike previous estimates of carbon losses from deforestation, where 20% of biomass is combusted, and the remainder decomposes over 10–30 years [*Fearnside et al.*, 1993; *Houghton et al.*, 2000], mechanized forest clearing practices may result in near-complete combustion of aboveground woody biomass and woody roots [*Morton et al.*, 2008]. Mechanization has thereby increased the potential size of forest clearings and decreased the duration of the deforestation process.

Combined advances in deforestation mapping and tracking the fate of cleared land provide spatial and temporal details regarding land cover transitions statewide. Vegetation phenology, derived from time series of MODIS data, has proven useful for separating land cover types and following changes in land management over time [*Ratana et al.*, 2005; *Morton et al.*, 2006; *Brown et al.*, 2007]. Figure 2b highlights the dynamics of 2000–2005 transitions among major cover types in Mato Grosso state, showing the proportion of new deforestation, woodland savanna, and secondary forest conversions >25 ha as a function of postclearing land use. The main driver of forest loss in Mato Grosso is large-scale cattle production, yet direct conversion of forest to cropland contributed substantially to the number of large deforestation events and to woodland and secondary forest losses during this period [*Morton et al.*, 2006, 2007a, 2007b]. Secondary forest is not a large component of the landscape in Mato Grosso compared with estimates for other regions, comprising only 11–14% of historic deforestation [*Carreiras et al.*, 2006; *Morton et al.*, 2007a]. Detailed analysis of the source of secondary and degraded forests in Mato Grosso from abandonment, logging, and burning remains a research challenge.

Expansion of soybeans and other mechanized crop varieties in Amazonia has renewed the debate over extensive versus intensive land uses, and about the social and environmental outcomes of agricultural expansion. Climate, soils, and topography are suitable for soybean cultivation in forested regions of northern Mato Grosso and surrounding areas [*Jasinski et al.*, 2005], and some authors have argued that soybean cultivation can be a competitive, intensive agriculture alternative over extensive and low-productive cattle ranching [e.g., *Andersen et al.*, 2002; *Margulis*, 2004]. However, soybean production can contribute to pushing cattle ranching into new deforestation frontiers, as seen following its introduction in southern and west-central Brazil [*Andersen et al.*, 2002], even if a detailed assessment of the role of soybeans in concentration of land tenure and income, rural outmigration, and loss of biodiversity has not yet been completed [*Fearnside*, 2001].

3.5. Land Abandonment and Secondary Vegetation Growth

Considerable research has focused on mapping secondary forest at local and regional scales [*Lucas et al.*, 1993; *Moran et al.*, 1994; *Roberts et al.*, 2002; *Alves et al.*, 2003; *Carreiras et al.*, 2006]. Secondary forests are a potential carbon sink and can help recover hydrological and biogeochemical functioning after forest clearing [e.g., *Brown and Lugo*, 1990; *Moran et al.*, 1994]. Secondary succession can develop following different pathways, including land rotation during shifting cultivation and land abandonment after pasture degradation or immediately following forest clearing; species composition, vegetation structure, and rates of carbon uptake in secondary forests are highly dependent upon soil type and prior land use [*Alves et al.*, 1997; *Moran et al.*, 2000; *Lucas et al.*, 2002; *Zarin et al.*, 2005].

Census data and remote sensing analyses raise important questions about the long-term dynamics of secondary vegetation in Amazonia. The proportion of cleared land that was unused for more than 4 years as a percentage of farm area declined steadily, from 15.5% to 5.7%, during 1970–1995 (Table 1). This evidence is consistent with findings that rates of land abandonment were higher in newly established frontiers, while secondary vegetation tended to be re-cleared concurrently with the elimination of mature forest remnants in older settlement areas [*Alves et al.*, 2003; *Alves*, 2007a]. Time series of satellite data show that secondary forest is a dynamic component of the landscape in the Ariquemes and Ji-Paraná regions of Rondônia (Figure 4). In both regions, steady increases in pasture area resulted from more rapid re-clearing of secondary forest than pasture abandonment. Overall, the contribution of secondary forest remained stable or declined during 1986–2003, never exceeding 10% of the landscape. Declining rates of land abandonment in more intensively deforested areas indicate that over the long term, secondary forests may offset only a small fraction of the initial carbon emissions from deforestation [*Alves et al.*, 1997; *Alves*, 2007a].

4. CONCLUSIONS AND OUTLOOK

Brazilian Amazonia is one of most active regions of agricultural expansion in the world. Clearing tropical forest is the primary means to increase the area of cattle pasture and crops, while related processes such as logging, fire for land clearing and management, land abandonment, and land use intensification are also key elements of the LCLUC dynamics. The conceptual model of transitions between multiple land cover and use states illustrates the heterogeneity of LCLUC trajectories and their expression in landscape patterns across Amazonia. Characterizing the spatial patterns created by such processes represents an important methodological success in Amazonia, based on multiple data sources and a variety of analysis techniques, from which to investigate the role of LCLUC on the biophysical system.

Agriculture in the region is becoming increasingly intensive, conducted by large-scale operators with sufficient access to capital. These shifts in the spatial and temporal dynamics of LCLUC are present in both census data and satellite remote sensing as a decrease in secondary forests, increase in pasture stocking rates, and rapid expansion of the area under mechanized agriculture. The rise of intensive production and the influence of both national and international market forces on land use have led to the development of new ecologically oriented certification schemes for beef

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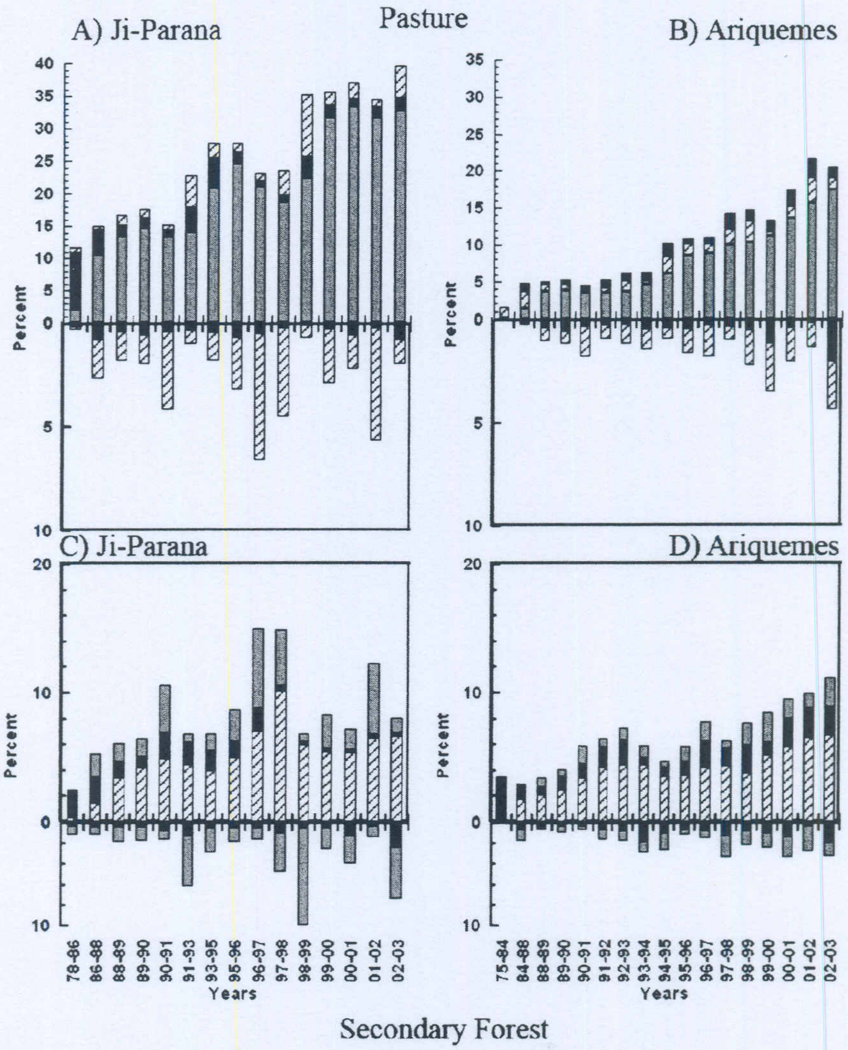

Figure 4. Transitions among pasture (gray), secondary forest (dashed), and primary forest (black) for the Ji-Paraná and Ariquemes regions of Rondônia state during 1986–2003. Dynamics for pasture in (a) Ji-Paraná and (b) Ariquemes. Values above the x axis represent a gain of a specific class as a percentage of the landscape, and values below the axis represent a loss. Changes in secondary forest over time in a similar manner for (c) Ji-Paraná and (d) Ariquemes. In Ji-Paraná, pasture shows a general increase over time, with most pasture originating from areas that were previously pasture. Pasture loss is primarily to secondary forest. Secondary forest shows no significant increase over time in Ji-Paraná, leading to a declining ratio of secondary forest to cleared lands. Large fluctuations between pasture and secondary forest in Ji-Paraná during 1997–1999 are most likely due to early dry season imagery in these years leading to overestimating secondary forest. Rates of pasture abandonment to secondary forest were more stable in Ariquemes than in Ji-Paraná. Both pasture and secondary forest show a general increase over time, resulting in a ratio of secondary forest to pasture of over 30% in Ariquemes.

and grain production in Amazonia. At the same time, high deforestation rates in older settlement areas, expansion of agricultural frontiers into new areas, and prevailingly low productivity of land show the recurrence of historical trends. Thus, a diversity of actors remain influential in both "old" and "new" frontiers presenting a challenge for delineating plausible future scenarios of LCLUC in Amazonia.

Advances in satellite remote sensing of deforestation and postclearing land use have led to high-quality data for both science and policy applications. Deforestation mapping in Brazilian Amazonia provides detailed estimates of forest loss on an annual basis. Advancement in near real-time monitoring of deforestation in cerrado and closed forest and mapping selective logging has generated essential data for environmental monitoring. Successes in remote sensing of deforestation in Amazonia serve as an important example of technical progress for other nations considering programs to reduce deforestation.

Future research will continue to focus on the economic, social, and environmental elements of each forest loss trajectory, highlighting spatial and temporal heterogeneity in the causes and consequences of Amazon deforestation. Recent advances in remote sensing pave the way for additional efforts to quantify the basin-wide impacts of forest degradation from fire, forest fragmentation, and land abandonment to secondary forest. Findings from LBA also lay the groundwork for related research on the influence of specific land use transitions and spatial patterns of land cover for climate, biogeochemistry, and long-term agricultural productivity, as reported in the following chapters of this book.

REFERENCES

Alves, D. S. (2002), Space-time dynamics of deforestation in Brazilian Amazônia, *Int. J. Remote Sens.*, *23*, 2903–2908.

Alves, D. S. (2007a), Cenários de cobertura e uso da terra e dimensões humanas no LBA, in *Dimensões Humanas da Biosfera-Atmosfera da Amazônia*, edited by W. M. da Costa, B. K. Becker, and D. S. Alves, pp. 39–63, EDUSP, São Paulo, Brazil.

Alves, D. S. (2007b), Science and technology and sustainable development in Brazilian Amazon, in *The Stability of Tropical Rainforest Margins*, edited by T. Tscharntke et al., pp. 493–512, Springer, Berlin, Germany.

Alves, D. S., J. V. Soares, S. Amaral, E. M. K. Mello, S. A. S. Almeida, O. F. da Silva, and A. M. Silveira (1997), Biomass of primary and secondary vegetation in Rondônia, Western Brazilian Amazon, *Global Change Biol.*, *3*, 451–461.

Alves, D. S., M. I. S. Escada, J. L. G. Pereira, and C. A. Linhares (2003), Land use intensification and abandonment in Rondônia, Brazilian Amazônia, *Int. J. Remote Sens.*, *24*, 899–903.

Andersen, L. E., C. W. J. Granger, E. J. Reis, D. Weinhold, and S. Wunder (2002), *The Economics of Deforestation: Dynamic Modeling of Amazonia*, Cambridge Univ. Press, Cambridge.

Anderson, L. O., Y. E. Shimabukuro, R. S. DeFries, and D. C. Morton (2005), Assessment of deforestation in near real time over the Brazilian Amazon using multitemporal fraction images derived from Terra MODIS, *IEEE Geosci. Remote Sens. Lett.*, *2*, 315–318.

Asner, G. P. (2001), Cloud cover in Landsat observations of the Brazilian Amazon, *Int. J. Remote Sens.*, *22*, 3855–3862.

Asner, G. P., D. E. Knapp, E. N. Broadbent, P. J. C. Oliveira, M. Keller, and J. N. Silva (2005), Selective logging in the Brazilian Amazon, *Science*, *310*, 480–482.

Asner, G. P., E. N. Broadbent, P. J. C. Oliveira, M. Keller, D. E. Knapp, and J. N. M. Silva (2006), Condition and fate of logged forests in the Brazilian Amazon, *Proc. Natl. Acad. Sci. U. S. A.*, *103*, 12,947–12,950, doi:10.1073/pnas.0604093103.

Asner, G. P., M. Keller, M. Lentini, F. Merry, and C. Souza Jr. (2009), Selective logging and its relation to deforestation, *Geophys. Monogr. Ser.*, doi:10.1029/2008GM000723, this volume.

Batistella, M., and E. F. Moran (2005), Dimensões humanas do uso e cobertura das terras na Amazônia: Uma contribuição do LBA, *Acta Amazonica*, *35*, 239–247.

Batistella, M., S. Robeson, and E. F. Moran (2003), Settlement design, forest fragmentation, and landscape change in Rondonia, Amazonia, *Photogramm. Eng. Remote Sens.*, *69*, 805–812.

Becker, B. K. (1997), *Amazônia*, 5th ed., ÁTICA, São Paulo.

Brown, J. C., W. E. Jepson, J. H. Kastens, B. D. Wardlow, J. M. Lomas, and K. P. Price (2007), Multitemporal, moderate-spatial resolution remote sensing of modern agricultural production and land modification in the Brazilian Amazon, *GIScience Remote Sens.*, *44*, 117–148.

Brown, S., and A. Lugo (1990), Tropical secondary forests, *J. Tropical Ecol.*, 6, 1–32.

Buschbacher, R. (1986), Tropical deforestation and pasture development, *Bioscience*, *36*, 22–28.

Cardille, J. A., and J. A. Foley (2003), Agricultural land-use change in Brazilian Amazônia between 1980 and 1995: Evidence from integrated satellite and census data, *Remote Sens. Environ.*, *87*, 551–562.

Carreiras, J. M. B., Y. E. Shimabukuro, and J. M. C. Pereira (2002), Fraction images derived from SPOT-4 VEGETATION data to assess land-cover change over the State of Mato Grosso, Brazil, *Int. J. Remote Sens.*, *23*, 4979–4983.

Carreiras, J. M. B., J. M. C. Pereira, M. L. Campagnolo, and Y. E. Shimabukuro (2006), Assessing the extent of agriculture/pasture and secondary succession forest in the Brazilian Legal Amazon using SPOT VEGETATION data, *Remote Sens. Environ.*, *101*, 283–298.

Chambers, J. Q., G. P. Asner, D. C. Morton, L. O. Anderson, S. S. Saatchi, F. d. B. Espírito-Santo, M. Palace, and C. Souza Jr. (2007), Regional ecosystem structure and function: Ecological insights from remote sensing of tropical forests, *Trends Ecol. Evol.*, *22*, 414–423.

Costa, W. M. (2007), Tendências recentes na Amazônia: Os sistemas produtivos emergentes, in *Dimensões Humanas da Biosfera–Atmosfera da Amazônia*, edited by W. M. da Costa, B. K. Becker, and D. S. Alves, pp. 81–11, EDUSP, São Paulo, Brazil.

Denich, M., K. Vielhauer, M. S. de A. Kato, A. Block, O. R. Kato, T. D. de Abreu Sá, W. Lücke, and P. L. G. Vlek (2004), Mechanized land preparation in forest-based fallow systems: The experience from eastern Amazonia, *Agroforestry Syst.*, *61*, 91–106.

Dias Filho, M. B., E. A. Davidson, and C. J. R. de Carvalho (2000), Linking biogeochemical cycles to cattle pasture management and sustainability in the Amazon Basin, in *The Biogeochemistry of the Amazon Basin*, edited by M. McClain, R. L. Victoria, and J. E. Ritchey, pp. 85–105, Oxford Univ. Press, New York.

Faminow, M. D. (1998), *Cattle Deforestation and Development in the Amazon*, CAB International, New York.

[redacted]

Fearnside, P. M. (1990), The rate and extent of deforestation in Brazilian Amazonia, *Environ. Conserv.*, *17*, 213–226.

Fearnside, P. M. (2001), Soybean cultivation as a threat to the environment in Brazil, *Environ. Conserv.*, *28*, 23–38.

Fearnside, P. M., A. T. Tardin, and L. G. Meira Filho (1990), Deforestation rate in Brazilian Amazonia, *Reprint*, Instituto de Pesquisas Espaciais, São José dos Campos, Brazil.

Fearnside, P. M., N. Leal Jr., and F. M. Fernandes (1993), Rainforest burning and the global carbon budget: Biomass, combustion efficiency, and charcoal formation in the Brazilian Amazon, *J. Geophys. Res.*, *98*(D9), 16,733–16,743.

Ferreira, N. C., L. G. Ferreira, and F. Miziara (2007), Deforestation hotspots in the Brazilian Amazon: Evidence and causes as assessed from remote sensing and census data, *Earth Interact.*, *11*(1), 1–16, doi:10.1175/EI201.1.

Hess, L. L., J. M. Melack, E. M. L. M. Novo, C. C. F. Barbosa, and M. Gastil (2003), Dual-season mapping of wetland inundation and vegetation for the central Amazon basin, *Remote Sens. Environ.*, *87*, 404–428.

Houghton, R. A., D. L. Skole, C. A. Nobre, J. L. Hackler, K. T. Lawrence, and W. H. Chomentowski (2000), Annual Fluxes of carbon from deforestation and regrowth in the Brazilian Amazon, *Nature*, *403*, 301–304.

INPE (2007), *Projeto PRODES*. (Available at http://www.obt.inpe.br/prodes).

Instituto Brasileiro de Geografia e Estatística (IBGE) (1996), *Dados do Censo Agropecuário*. (Available at http://www.ibge.gov.br).

Instituto Nacional de Pesquisas Espaciais (INPE) (2001), *Monitoring of the Brazilian Amazonian Forest by Satellite, Reprint*, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil.

Jasinski, E. W., D. C. Morton, R. S. DeFries, Y. E. Shimabukuro, L. O. Anderson, and M. C. Hansen (2005), Physical landscape correlates of the expansion of mechanized agriculture in Mato Grosso, Brazil, *Earth Interact.*, *9*(16), EI143, doi:10.1175/EI143.1.

Jepson, W. (2006), Producing a modern agricultural frontier: Firms and cooperatives in Eastern Mato Grosso, *Econ. Geogr.*, *82*, 289–316.

Kay, K. (2005), Estimating wet-season deforestation in the Brazilian Amazon using MOD13 250m data, Geography, M. S., 25, Univ. of Maryland, College Park.

Keller, M., M. A. Silva-Dias, D. C. Nepstad, and M. O. Andreae (2004), The large-scale biosphere-atmosphere experiment in Amazonia: Analyzing regional land use change effects, in *Ecosystems and Land Use Change*, edited by R. deFries, G. Asner, and R. Houghton, pp. 321–334, AGU, Boston, Mass.

Lentini, M., A. Verissimo, and L. Sobral (2005), *Forest Facts in the Brazilian Amazon 2003*, Imazon, Belém.

Lu, D., P. Mausel, M. Batistella, and E. F. Moran (2004), Comparison of land-cover classification methods in the Brazilian Amazon Basin, *Photogramm. Eng. Remote Sens.*, *70*, 723–731.

Lu, D., M. Batistella, and E. F. Moran (2008), Integration of Landsat TM and SPOT HRG images for vegetation change detection in the Brazilian Amazon, *Photogramm. Eng. Remote Sens.*, *73*, 421–430.

Lucas, R. M., M. Honzak, G. M. Foody, P. J. Curran, and C. Corves (1993), Characterising tropical secondary forests using multi-temporal Landsat sensor imagery, *Int. J. Remote Sens.*, *14*, 3061–3067.

Lucas, R. M., M. Honzak, I. do Amaral, P. J. Curran, and G. M. Foody (2002), Forest regeneration on abandoned clearances in Central Amazonia, *Int. J. Remote Sens.*, *23*, 965–988.

Machado, L. (1998), A fronteira agrícola na Amazônia, in *Geografia e Meio Ambiente no Brasil*, 2nd ed., edited by A. Christofoletti et al., pp 181–217, Hucitec, São Paulo, Brazil.

Margulis, S. (2004), *Causes of Deforestation in Brazilian Amazon*, World Bank, Washington. (Available at http://www-wds.worldbank.org).

Millikan, B. H. (1992), Tropical deforestation, land degradation, and society, lessons from Rondônia, Brazil, *Lat. Am. Perspect.*, *19*(1), 45–72.

Moran, E. F. (1993), Deforestation and land use in the Brazilian Amazon, *Human Ecol.*, *21*, 1–21.

Moran, E. F., and E. S. Brondizio (1998), Land-use change after deforestation in Amazônia, in *People and Pixels: Linking Remote Sensing and Social Science*, edited by D. Liverman et al., pp. 94–120, National Academy Press, Washington, D. C.

Moran, E. F., E. Brondizio, P. Mausel, and Y. Wu (1994), Integrating Amazonian vegetation, land-use and satellite data, *BioScience*, *44*, 329–338.

Moran, E. F., E. S. Brondizio, J. M. Tucker, M. C. da Silva-Forsberg, S. McCracken, and I. Falesi (2000), Effects of soil fertility and land-use on forest succession in Amazonia, *For. Ecol. Manage.*, *139*, 93–108.

Morton, D. C., R. S. DeFries, Y. E. Shimabukuro, L. O. Anderson, F. d. B. Espírito-Santo, M. C. Hansen, and M. Carroll (2005), Rapid assessment of annual deforestation in the Brazilian Amazon using MODIS data, *Earth Interact.*, *9*(8), EI139, doi:10.1175/EI139.1.

Morton, D. C., R. S. DeFries, Y. E. Shimabukuro, L. O. Anderson, E. Arai, F. d. B. Espirito-Santo, R. Freitas, and J. Morisette (2006), Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon, *Proc. Natl. Acad. Sci. U. S. A.*, *103*, 14,637–14,641, doi:10.1073/pnas.0606377103.

Morton, D. C., Y. E. Shimabukuro, R. Freitas, E. Arai, and R. S. DeFries (2007a), Secondary forest dynamics and Cerradão loss in Mato Grosso during 2001–2005 from MODIS phenology time series, paper presented at XIII Simp. Bras. Sens. Remoto, Florianópolis, Sta Catar, Brazil, 21–26 Apr 2007. (Available at http://www.dsr.inpe.br/sbsr2007/biblioteca/).

Morton, D. C., Y. E. Shimabukuro, B. F. T. Rudorff, A. Lima, R. Freitas, and R. S. DeFries (2007b), Challenge for conservation at the agricultural frontier: Deforestation, fire, and land use dynamics in Mato Grosso, *Agua Ambiente*, *2*, 5–20.

Morton, D. C., R. S. DeFries, J. T. Randerson, L. Giglio, W. Schroeder, and G. R. van der Werf (2008), Agricultural intensification increases deforestation fire activity in Amazonia, *Global Change Biol.*, *14*, 2262–2275.

Morton, D. C., R. S. DeFries, and Y. E. Shimabukuro (2009), Cropland expansion in cerrado and transition forest ecosystems: Quantifying habitat loss from satellite-based vegetation phenology, in *Cerrado Land-Use and Conservation: Assessing Trade-offs Between Human and Ecological Needs*, edited by C. Klink, R. S. DeFries, and R. Cavalcanti, Conservation Int., Washington, D. C., in press.

Nepstad, D. C., et al. (1999), Large-scale impoverishment of Amazonian forests by logging and fire, *Nature*, *398*, 505–508.

Numata, I., O. A. Chadwick, D. A. Roberts., J. P. Schimel, F. F. Sampaio, F. C. Leonidas, and J. V. Soares (2007), Temporal function of soil order, pasture age, and management, Rondônia, Brazil, *Agric. Ecosyst. Environ.*, *118*, 159–172.

Ratana, P., A. R. Huete, and L. G. Ferreira (2005), Analysis of Cerrado physiognomies and conversion in the MODIS seasonal-temporal domain, *Earth Interact.*, *9*, EI119, doi:10.1175/1087-3562(2005)009<0001:AOCPAC>2.0.CO;2.

Roberts, D. A., I. Numata, K. Holmes, G. Batista, T. Krug, A. Monteiro, B. Powell, and O. A. Chadwick (2002), Large area mapping of land-cover change in Rondônia using multitemporal spectral mixture analysis and decision tree classifiers, *J. Geophys. Res.*, *107*(D20), 8073, doi:10.1029/2001JD000374.

Sawyer, D. (1984), Frontier expansion and retraction in Brazil, in *Frontier Expansion in Amazônia*, edited by M. Schmink, and C. H. Wood, pp. 180–203, Univ. of Florida Press, Gainesville.

Schmink, M., and C. H. Wood (1992), *Contested Frontiers in Amazonia*, Columbia Univ. Press, New York.

Serrão, E. A. S., and J. M. Toledo (1990), The search for sustainability in Amazonian pastures, in *Alternatives to Deforestation: Steps Toward Sustainable Use of the Amazon Rain Forest*, edited by A. B. Anderson, pp. 195–214, Columbia Univ. Press, New York.

Shimabukuro, Y. E., V. Duarte, M. A. Moreira, E. Arai, D. M. Valeriano, L. O. Anderson, and F. d. B. Espírito-Santo (2007), Desflorestamento na Amazônia—Sistema DETER, in *Sensor MODIS e Suas Aplicações Ambientais no Brasil*, edited by B. F. T. Rudorff, Y. E. Shimabukuro, and J. C. Ceballos, pp. 389–401, Editora Parêntese, São José dos Campos, Brazil.

Skole, D., and C. Tucker (1993), Tropical deforestation and habitat fragmentation in the Amazon - Satellite data from 1978 to 1988, *Science*, *260*, 1905–1910.

Soares-Filho, B., A. Alencar, D. Nesptad, M. Cerqueira, M. C. V. Diaz, S. Rivero, L. Solórzano, and E. Voll (2004), Simulating the response of land-cover changes to road paving and governance along a major Amazon highway: The Santarém-Cuiabá corridor, *Global Change Biol.*, *10*, 745–764.

Souza, C., Jr., L. Firestone, L. M. Silva, and D. Roberts (2003), Mapping forest degradation in the Eastern Amazon from SPOT 4 through spectral mixture models, *Remote Sens. Environ.*, *87*, 494–506.

Souza, C., Jr., D. A. Roberts, and M. A. Cochrane (2005), Combining spectral and spatial information to map canopy damages from selective logging and forest fires, *Remote Sens. Environ.*, *98*, 329–343.

Tardin, A. T., D. C. L. Lee, R. J. R. Santos, O. R. Assis, M. P. S. Barbosa, M. L. Moreira, M. T. Pereira, D. Silva, and C. P. Santos Filho (1980), *Subprojeto Desmatamento: Convênio IBDF/CNPq–INPE*, *Technical Report INPE-1649-RPE/103*, Instituto de Pesquisas Espaciais, São José dos Campos, Brazil.

Uhl, C., A. Verissimo, M. M. Mattos, Z. Brandino, and I. C. G. Vieira (1991), Social, economic, and ecological consequences of selective logging in an Amazon frontier—The case of Tailandia, *For. Ecol. Manage.*, *46*, 243–273.

Veiga, J. B., J. F. Tourrand, M. G. Piketty, R. Poccard-Chapuis, A. M. Alves, and M. C. Thales (2004), *Expansão e Trajetórias da Pecuária na Amazônia: Pará, Brasil*, Editora Universidade de Brasília, Brasília, Brazil.

Velho, O. G. (1976), *Capitalismo Autoritário e Campesinato*, DIFEL, São Paulo, Brazil.

Verissimo, A., P. Barreto, M. Mattos, R. Tarifa, and C. Uhl (1992), Logging impacts and prospects for sustainable forest management in an old Amazonian frontier—The case of Paragominas, *For. Ecol. Manage.*, *55*, 169–199.

Warnken, P. F. (1999), *The Development and Growth of the Soybean Industry in Brazil*, Iowa State Univ., Ames.

Zarin, D. J., et al. (2005), Legacy of fire slows carbon accumulation in Amazonian forest regrowth, *Front. Ecol. Environ.*, *3*, 365–369.

D. S. Alves, Instituto Nacional de Pesquisas Espaciais (INPE), DPI (SRE 2), Avenida dos Astronautas 1758, CEP 12227-010, São José dos Campos SP, Brazil. (dalves@dpi.inpe.br)

M. Batistella, Embrapa Satellite Monitoring, Avenida Soldado Passarinho, 303 CEP 13070-15, Campinas SP, Brazil. (mb@cnpm.embrapa.br)

D. C. Morton, Goddard Space Flight Center, 8800 Greenbelt Road, Code 614.4, Greenbelt, MD 20771, USA. (douglas.morton@nasa.gov, douglas.morton@gmail.com)

D. A. Roberts, Department of Geography, EH 1832, University of California Santa Barbara, Santa Barbara, CA 93117, USA. (dar@geog.ucsb.edu)

C. Souza Jr., Instituto do Homem e Meio Ambiente da Amazônia (Imazon), Rua Domingos Marreiros 2020, CEP 66060-160, Belém PA, Brazil. (souzajr@imazon.org.br)

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