FOREST FIRE, DEFORESTATION AND LANDCOVER CHANGE IN THE BRAZILIAN AMAZON

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ABSTRACT

Uncontrolled forest fires are a growing problem in the Amazon. Accidental fires burn thousands of square kilometers of forest each year in the Brazilian Amazon. These previously burned tropical forests are highly susceptible to recurrent fires which are significantly more severe in intensity and impact. Due to the positive feedback inherent in this process, fire has been predicted to pose a severe risk to the integrity of these forests (Cochrane and Schulze, 1998; Cochrane and Schulze 1999). This assertion was investigated using a multitemporal analysis of Landsat-TM imagery. A sub-pixel linear mixture modeling technique was used to detect and classify forested areas that had been subjected to surface fires in a series of images from two regions of the eastern Amazon. The results show that in the last several years, fire has affected approximately 50% of the standing forests in both study regions (3,920 km^2). In addition, accidental fire-induced deforestation increased deforestation estimates by 129% between 1993 and 1995. The current fire regime of both study regions, with fire-return intervals of less than 15 years, is capable of eradicating remaining forests from the landscape. Fire histories, constructed from landowner interviews, in several additional study areas indicate that this same fire dynamic may exist throughout an extensive portion of the Amazon (580,000 km^2). The current fire situation poses an extreme threat to the region's forests and the likelihood of globally significant emissions of CO_2.

Keywords: Amazon, tropical forest, fire regime, fire cycle, carbon emissions

METHODS

Multitemporal analyses of satellite imagery (Landsat TM), field studies and interviews of landholders were used to investigate the incidence and extent of forest fires in two regions of the eastern Amazon. Both regions have similar forests, pronounced dry seasons and receive average annual rainfall amounts of 1500 to 1800 mm (Silva, E. 1996). The methodology of Cochrane and Souza (1998) was applied to separate forest from non forest and classify burned forests in a series of images for 1,280 km^2 near Paragominas (1984, 1991, 1993, 1995) and 2,640 km^2 around Tailândia (1984, 1991, 1993, 1995, 1997) in Pará state (Figure 1). The location and forest area affected by fire were determined for the images of each region. Cross tabulation of the classified images provided a history of deforestation and forest burning throughout the study regions. Based on the imagery data, fire cycles for each study region were calculated. The fire cycle is the amount of time required to burn an area equivalent to the entire forested area with the understanding that some areas may not burn while others burn more than once during a cycle (Van Wagner, C. 1978).

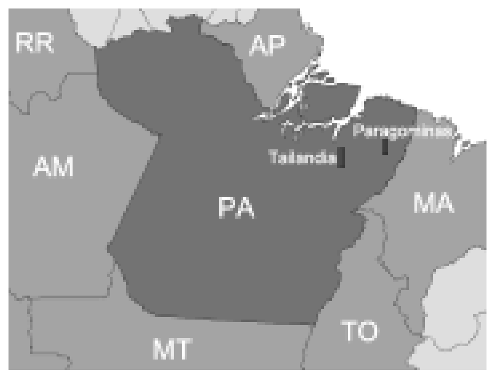

Figure 1. Study regions in Pará State (PA), Brazil. Roughly 2,640 km^2 around Tailândia and 1,280 km^2 around Paragominas.

RESULTS

Paragominas is an old frontier area which was minimally deforested until the Belém-Brasilia highway was built in the early 1960s (Veríssimo, A. et al. 1992). Analyses of the satellite imagery showed that the Paragominas study region was already 38% deforested in 1984 and 64% deforested by 1995. Second growth forest accumulation was minimal, less than 2% of the deforestation rate, due to the rapid rate of cutting and burning experienced by these forests. Tailândia, a new frontier area in the early 1990's (Uhl, C. et al. 1991), has developed rapidly since the paving of the main highway (PA-150) in 1985 (Cochrane, M. et al. 1999). The study region was less than 10% deforested in 1984 but had lost 44% of its forests by 1997. Second growth is insignificant in Tailândia. Deforestation rates for both sites are given in Table 1.

Years	Paragominas	Tailândia
Before 1984[a]	1.6%	1.6%
1984 - 1991	1.5%	2.5%
1991-1993	3.1%	2.7%
1993-1995	4.5%	4.0%
1995-1997	*	1.7%
Average rate	1.8%	2.3%
Since 1984	2.4%	2.8%

Table 1: Deforestation rates

a Deforestation since establishment, Paragominas (1960), Tailândia (1978)
* No data

The remaining forests of both study regions have been affected by fire since at least 1983 in Paragominas and 1991 in Tailândia (Figure 2 a, b). The amount of standing forest burned each year has varied widely from 1% to 45% (Table 2) with the largest fires occurring during the El Niño years 1983, 1992, and 1997. In Paragominas, burns detected in the imagery were compared with data from landowner questionnaires (n = 75) that described fire history from 1982 to 1995 (Nepstad, D. et al. 1999). Questionnaire data included 51.4% of the study region and showed 100% detection of reported fires that occurred within one year of the image date. Comparisons between the area reported burned by landowners with data from the imagery classifications showed that area burned was systematically underreported ($p < 0.001$; sign test) by an average of 43%, only small fires (<50 ha) were overestimated by landowners. Fire incidence throughout the Tailândia study region was corroborated by extensive field investigation in 1996 and 1997 (Cochrane and Schulze 1999; Cochrane, M. et al. 1999).

	Paragominas		Tailândia	
Year	Percentage [a] of forest burned	Burned [b] forests still standing	Percentage [a] of forest burned	Burned [b] forests still standing
1984[c]	9.6%	9.6%	?	?
1991[d]	4.7%	10.1%	1.0%	1.0%
1993	45.9%	48.9%	23.1%	23.4%
1995[e]	1.3%	44.7%	2.9%	23.9%
1997[f]	*	*	31.2%	46.6%

Table 2. Forest area burned by region

a) Percentage of standing forest classified as burned in the image.

b) Percentage of standing forest detected as burned with deforestation and reburning taken into account.

c) No detection of burned forest possible in Tailândia due to high levels of smoke.

d) Large gap in years between imagery precludes detection of fires for 1985, 1986, 1987, 1988, 1989. Numerous fires were documented in the Paragominas study area for 1987.

e) Large fire occurred in the center of the Tailândia region in October (Cochrane and Schulze 1999) 3 months after the 1995 image. Undetected in 1997 image.

f) Paragominas region cloud obscured so no analysis possible. Extensive fires throughout area in 1997 (personal observation). Another very large series of fires happened in the Tailândia study area in December 1997 (Cochrane et al. 1999) which do not appear in these statistics.

Many of the forest stands in the study areas are burning more than once. Recurrent fires are more likely due to changes in the microclimate of the forest interior (Cochrane and Schulze 1999) and more intense due to changes in fuel structure (Cochrane and Schulze 1998; Cochrane, M. et al. 1999). Large canopy trees have little or no survival advantage in these recurrent fires (Cochrane and Schulze 1999). The 1997 fires in Tailândia illustrate that burn history affects the probability of a forest stand burning (Table 3). Repeatedly burned forest stands are extensively thinned, having been reported to support as few as 18 live trees ha^{-1} (Cochrane and Schulze 1999). Such minimally forested areas are likely to appear deforested in satellite (e.g. Landsat TM, SPOT, AVHRR) imagery analyses. In this study crosstabulation showed that, in comparison to unburned forest, once-burned forests were twice as likely to be classified (Cochrane and Souza Jr. 1998) as having been deforested while twice and thrice-burned forests were 11 and 15 times more likely to appear deforested.

Status of forest before 1997	[a]Chance of burning in 1997	Amount burned (ha)	[b]Percentage of burn
Unburned	22.7%	30964	45.8%
Burned once	39.2%	33441	49.4%
Burned twice	47.8%	3196	4.7%
Burned thrice	68.8%	30	<1%

Table 3. Burn probabilities for 1997 Tailândia fire

a) Probability of burning based on percentage of existing forest type which burned in 1997. Therefore, 22.7% of all existing unburned forest burned etceteras.

b) Proportion of the total burn for 1997 from each forest class. Forests subjected to multiple burns were more likely to burn but make up a small percentage of the total landscape and therefore a small percentage of the total burned area. Forests burned multiple times are much more likely to be classified as having been deforested.

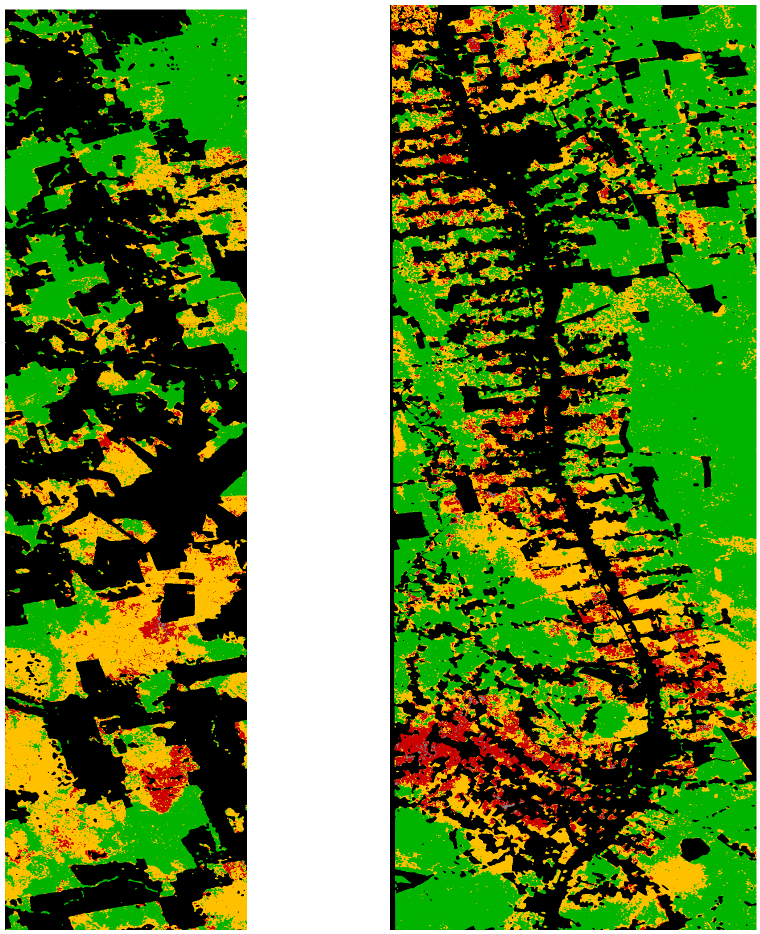

Figure 2a) **Figure 2b)**

Figure 2. Classified imagery of the Paragominas (Fig. 2a) and Tailândia (Fig. 2b) study regions. In the images, black represents nonforested land (e.g. pastures, roads, agricultural plots), green represents intact forest, yellow represents once-burned forest, red indicates twice-burned forest and grey indicates forests subjected to 3 or more fires. The Paragominas image (16.5 x 77.6 km) is from 1995 and represents the fire occurrence in existing forests detected in imagery from 1984, 1991, 1993, 1995. The Tailândia image (29.2 x 90.4 km) is from 1997 and represents the same thing for 1991, 1993, 1995, 1997.

Both Paragominas and Tailândia suffered severe fires (Table 2) in 1992/3 and showed a large jump in the rate of deforestation between 1993 and 1995 (Table 1). This change in deforestation mirrors the large jump in deforestation throughout the Brazilian Amazon from 1993 – 1995 (INPE 1996; INPE 1997). We conducted a detailed study of deforestation in burned forests of Paragominas for the 1993 to 1995 period to test whether deforestation of burned forests was intentional or accidentally induced by fire.

A supervised classification was used to separate pasture, recent slash and burn and degraded pasture (i.e. early second growth). Cross tabulation of land cover change between 1993 and 1995 was used to determine the fate of forests which burned in 1992/3. Forested areas that became either new slash and burn or pasture were classified as intentional deforestation. These areas were generally adjacent to existing forest edges and had regular shapes. Forests which became 'degraded pasture', an unlikely transition in just 2 years, were classified as accidental fire-induced deforestation. Fire-induced deforestation was generally irregular in shape and often occurred far from forest edges (Figure 3).

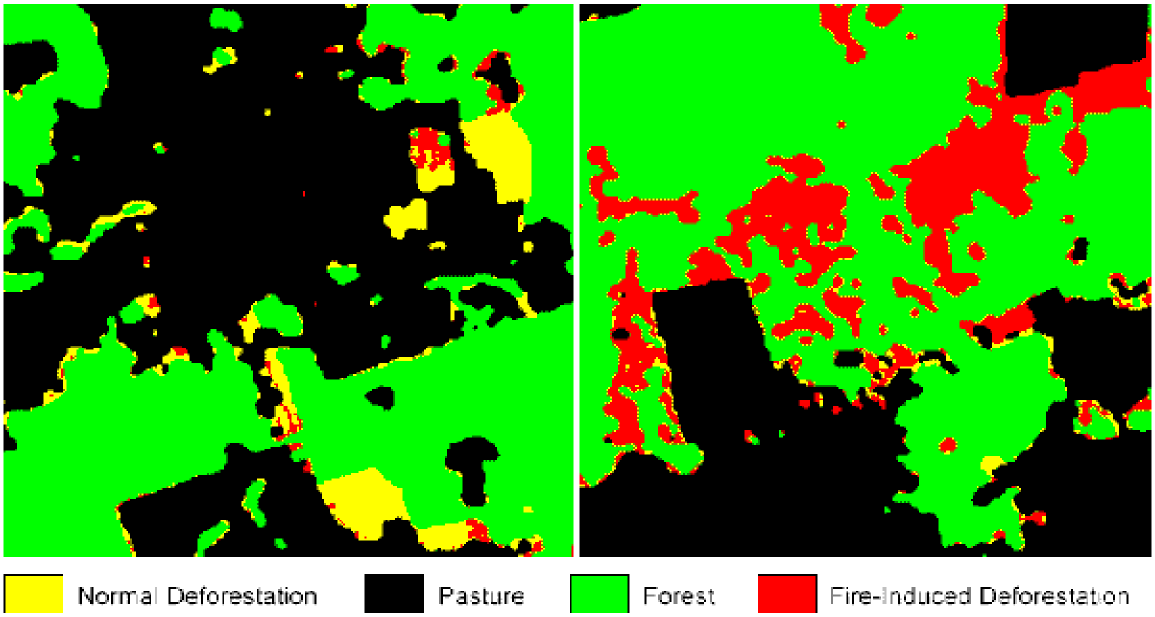

Figure 3. Two 64-km^2 imagery subsections illustrating the differences in location and form of normal deforestation (e.g. slash and burn for pasture or crops) and fire-induced deforestation, caused by accidental forest fires.

In the Paragominas region it is estimated that accidental fire-induced deforestation accounted for 62% of the recorded deforestation between 1993 and 1995. Correcting the deforestation estimates for this factor yields an intentional deforestation rate of 1.7% for 1993 –1995 which is in accord with deforestation rates prior to the El Niño induced fires of 1992/3 (Table 1). This surprising result implies that the basin wide jump in deforestation rates from 1993-1995 may have occurred in part due to the wide spread forest fires of 1992 and 1993.

Fire is now a major disturbance factor in Amazonian forests. Selectively logged forests, which are accumulating at 10,000 to 15,000 km^2 a year (Nepstad, D. et al. 1999), can burn during average weather conditions (Uhl and Buschbacher 1995; Uhl, C. et al. 1998, Uhl and Kauffman 1990; Holdsworth and Uhl 1997) and even undisturbed tropical forests are susceptible to fire during extensive droughts (Nepstad et al. 1994). The area burned varies greatly from year to year in the study regions but on average affects 3 times as much forest as slash and burn deforestation. Forest fire is a dynamic element of the disturbance regime in these regions and must be accounted for in any consideration of land-use or land cover change. The fire cycle concept (Van Wagner 1978) provides one measure of the importance of fire. The fire cycle is simply the reciprocal of the average proportion of the forested area that burns each year. Numbers of fires and fire size are unimportant.

Fire cycles were calculated using the average percentage of forest that burned in each study region. Cochrane and Souza's methodology (1998) can detect forest burns more than one year old but failed to detect a large series of fires in October 1995 in Tailândia (Cochrane and Schulze 1999) (21 months prior to the 1997 image). For this reason, fire cycle estimates are provided as a range which reflects the uncertainty that detected fires may be from 1 to 2 years old in each image. There have been no known analyses of the natural fire cycle in lowland tropical rainforests but the limited data from charcoal studies (Sanford et al. 1985; Saldarriaga and West 1986; Turcq et al. 1998) imply a fire cycle of hundreds or thousands of years. By contrast, the Paragominas and Tailândia forests have calculated fire cycles of between 7 and 14 years. Previously burned forests are even more prone to burning with a calculated fire cycle of less than 5 years in each study region. Fire-return-intervals of less than 90 years can eliminate rainforest species while intervals of less than 20 years may eradicate trees entirely (Jackson, W. 1968).

To determine if Paragominas and Tailândia might be representative of a larger portion of the Amazon Basin an additional study was conducted. Much of the deforestation and hence fire in the Brazilian Amazon occurs in an arc along the eastern and southern edges of the forest. We created a 260 kilometer wide swath to encompass this area of active deforestation (Figure 4). Forest cover remaining in this area, as of 1996, was estimated by using Stone et al.'s (1994) forest cover map as a base and then adjusting the forested area for each state using published deforestation rates (INPE 1992; INPE 1996; INPE 1997). Since the necessary fire data exist for only Pará, Mato Grosso, and Rondônia (Nepstad et al. in press), the fire cycle analysis was limited to the area intersecting these states (580,000 km^2).

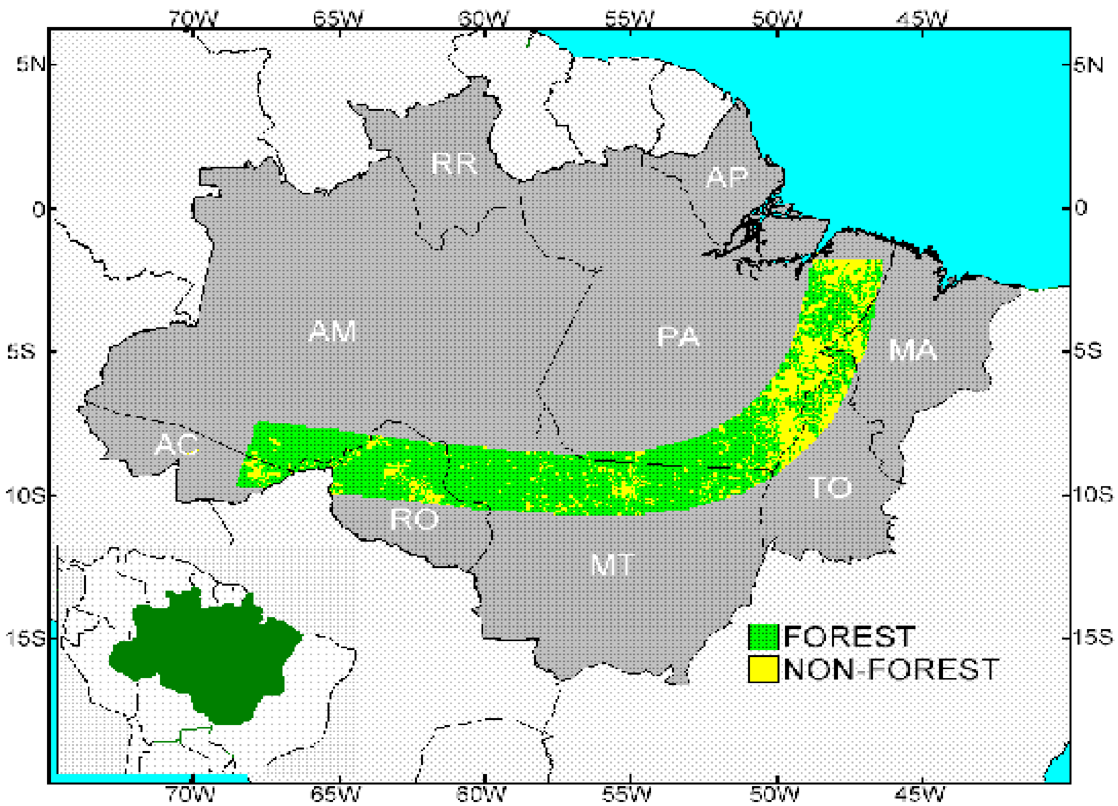

Figure 4. 'Arc of Deforestation.' Region of intensive deforestation and fire in the Brazilian Amazon. Fire studies from Paragominas and Tailândia were supplemented with landowner interviews in Pará (PA), Mato Grosso (MT), Rondonia (RO) and Acre (AC). Data indicate that the entire region from northern Pará to western Rondonia is experiencing a similar fire regime of very frequent fire return in much of the remaining forests. Interview data were for the non-El Niño years 1994 and 1995. No forest fires were reported in Acre.

Forest area burned in each state was rescaled to compensate for the calculated landowner underestimation (43%). The original estimates and the recalculated estimates were used to provide low and high range estimates of the forest area burned in each state. The calculated fire cycle ranges for each state were extremely similar (Table 4) indicating that the entire region is experiencing the same fire regime. The estimates of forest area burned (Nepstad et al. in press) were for non-El Niño years (1994 and 1995) and may therefore be overly conservative since this study's multitemporal analysis shows that 90% of forest burning occurred during El Niño years.

	[a]Area (km^2)	[b]Forested (km^2)	[c]Fire cycle (years)
Pará	237,087	120,563	18 - 32
Mato Grosso	239,326	180,488	19 - 34
Rondônia	105,264	75,981	19 - 33
Total	581,677	377,032	19 - 33

Table 4. Estimated fire cycles

a.) Area of study in each state.

b.) Estimated forest cover within study areas as of 1996.

c.) Fire cycle range based annual average area of forest burned in each state for 1994 and 1995 (Nepstad et al. in press). Lower fire cycle values based on corrected estimates of forest burning after accounting for landowner's underestimation.

The fire cycle that now exists across vast regions of the Amazon is at least an order of magnitude different than in the predevelopment era. The average rate and intensity of forest burning and deforestation can be expected to increase as previously burned forests accumulate (Cochrane et al. 1999). If left unchecked, the current fire regime, regardless of the high or low estimate of the fire cycle, will result in an inexorable transition of the entire area to either scrub or grassland (Jackson, W. 1968). Effects on the regional climate, biodiversity, and economy are likely to be extreme. Unless changes are made in current land management practices the entire 377,000 km^2 (1996 estimate) of forest remaining within this 260 kilometer wide band will be lost. Accounting for differences in forest biomass by state and the projected future landcover of deforested areas (Fearnside, P. 1997), this effectively equates to a net committed emission of 7.4 PgC. This is greater than the annual global emissions of carbon from fossil fuels and is equivalent to over 100 years worth of Brazil's current fossil fuel emissions (Marland et al. 1998a; Marland et al. 1998b). These fire-induced changes will take several years to occur but are likely to be irreversible (Mueller-Dombois, M. 1981; Shukla et al. 1990) under current climatic conditions.

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