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Synergistic Interactions between Habitat Fragmentation and Fire in Evergreen Tropical Forests

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Abstract: *The growing prevalence of fragmentation and fire in tropical forests makes it imperative to quantify changes in these disturbances and to understand the ways in which they interact across the landscape. I used a multitemporal series of Landsat images to study the incidence and coincidence of fire and fragmentation in two areas of Pará state in the eastern Brazilian Amazon: Tailândia and Paragominase. In both areas, deforestation and forest fires were quantified for time series of 6-10 years. The Tailândia study area typifies a landscape with the herringbone pattern of government-settled colonists, and the Paragominas area is dominated by large cattle ranches. In both areas, over 90% of the forests affected by fire were associated with forest edges. Although most burned forest occurred within 500 m of forest edges, some fires occurred in deep forest, several kilometers from any edge. The obvious synergism between forest fragmentation and fire poses serious risks to tropical ecosystems and has important implications for land management.*

Interacciones Sinérgicas entre la Fragmentación del Hábitat y los Incendios en Bosques Tropicales Perennes

Resumen: *La creciente prevalencia de la fragmentación y los incendios en bosques tropicales hacen imprescindible cuantificar los cambios en estas perturbaciones y entender las formas en las que estos interactúan a lo largo del paisaje. Utilicé series multitemporales de imágenes de Landsat para estudiar la incidencia de incendios y la coincidencia de estos con la fragmentación en dos áreas del Estado de Pará en la Amazonia Brasileña del Este: Tailậndia y Paragominase. En ambas áreas, la deforestación y los incendios forestales fueron cuantificados para series de tiempos de 6-10 años. El área de estudio de Tailậndia tipifica un paisaje con un patrón de 'hueso de arenque' poblado por colonizadores establecidos por el gobierno, mientras que el área de Paragominas está dominada por establecimientos ganaderos grandes. En ambas áreas, más del 90% de los bosques afectados por incendios estuvieron asociados con los bordes del bosque. Aunque la mayoría de los bosques quemados se encontraban a menos de 500 m de la orilla del borde, algunos incendios ocurrieron en la profundidad del bosque, a varios kilómetros adentro de cualquier borde. El sinergismo obvio entre la fragmentación del bosque y los incendios presenta serios riesgos para los ecosistemas tropicales y tiene implicaciones importantes para el manejo de la tierra.*

Introduction

The world's remaining evergreen tropical forests are being rapidly deforested. Globally, deforestation is proceeding at its highest rate in recorded history (Houghton 1991), with the largest areas being destroyed in the Amazon basin (Laurance et al. 2001). This deforestation has resulted in extensive fragmentation of the remaining forests. Fragmented forests have a relatively large ratio of perimeter to area, and the resultant forest edges may be different from interior forests in many ways. In the Amazon, the area of forest influenced by edge effects may actually exceed the total area deforested to date (Skole & Tucker 1993).

Fragmentation and the resulting increase in forest edge lead to changes of everything from microclimate to species composition (Margules & Pressey 2000) at various distances from the edge. Such changes may penetrate a few hundred meters (Laurance et al. 1997) or ex-

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tend as far as several kilometers into the forest (Curran et al. 1999). Fragmentation is known to cause structural changes near forest edges through increased tree mortality (Laurance et al. 1997), with a disproportionate effect on large trees (Laurance et al. 2000). Such structural changes are likely to mimic selective logging processes that fracture the forest canopy, increasing fuel loading and overall fire susceptibility (Holdsworth & Uhl 1997; Cochrane & Schulze 1999).

Fire is a growing problem in the tropics because of the frequent juxtaposition of fire-maintained land such as pastures with logged or otherwise damaged forests (Uhl & Buschbacher 1985). Recent large-scale fires in Indonesia (Brown 1998) and Brazil (Cochrane & Schulze 1998; Cochrane 2000*a*) illustrate the magnitude of this problem. Although resistant to fire propagation, tropical rainforests are extremely vulnerable to fire damage because their trees usually have thin bark (Uhl & Kauffman 1990). Once a forest does burn, fire susceptibility rises because of increased solar heating through the fractured canopy, and recurrent fires can become endemic (Cochrane & Schulze 1999). The new fire dynamic can become a runaway process as each fire increases on-site fuel loading and the severity of subsequent fires. This process results in catastrophic fires that can kill even the largest, thickest-barked trees (Cochrane et al. 1999). These altered fire regimes may be prevalent across vast expanses of the Amazon basin and may pose the risk of deflecting succession in these areas to scrub or savanna (Cochrane et al. 1999; Cochrane 2000*b*).

It has been suggested that fire might act as a large-scale edge effect (Laurance 2000) and pose a special risk to forest fragments (Gascon et al. 2000). I therefore hypothesized that the spatial distribution of forest fires is highly edge-related and that fire frequency varies as a function of distance from forest edge. I tested these predictions by comparing the locations of fire effects (Cochrane et al. 1999) in two fragmented landscapes of the eastern Amazon. Although my two study areas had different land-use histories, large-scale ranching and small-holder farming, fires were strongly associated with forest edges in both areas. The dramatic shift in the observed disturbance regime provides support for the notion that Amazonian forest fragments may "implode" over time (Gascon et al. 2000), with forest remnants being replaced by grasses and other fire-tolerant vegetation.

Methods

Multitemporal analyses of Landsat satellite imagery, field studies, and interviews with land owners were used to extend an earlier study of fire in space and time (Cochrane et al. 1999) in the Tailândia and Paragominas study areas (eastern Brasilian Amazon) (Fig. 1). These areas have similar tropical evergreen forests, pronounced dry seasons, and similar annual rainfall. I used a linear mixture-modeling methodology (Cochrane & Souza 1998) to separate forest from nonforest and to classify burned forests in a series of images of 1280 km^2 near Paragominas (1984, 1991, 1993, 1995) and of 2470 km^2 near Tailândia (1984, 1991, 1993, 1995, 1997). The methodology detects evidence of subcanopy surface fires for 1-2 years after a fire event (Cochrane et al. 1999). The forest location and area affected by fire were determined for each image and area. Cross-tabulation of the classified images provided a history of deforestation and forest burning throughout the study areas (Cochrane 2000*b*) by indicating both where and when these disturbances took place. I field-validated remotely detected information on fire damage to assess the accuracy of the method.

Field studies were concentrated in the Tailândia region (Fig. 1). Ten 0.5-ha plots (eight affected by fire and two control), spread over 100 km^2, were established in 1996 in a study of the effects of fire on forest structure, biomass, and species composition (Cochrane & Schulze 1999). These plots were recensused after the dry season of 1997, during which eight of the plots burned to various degrees. Fire recurrence, tree mortality, and biomass combustion levels within forests of different burn histories were quantified (Cochrane et al. 1999). In addition, combustible fuel mass was assessed by using the planar-intersect method (Brown 1974), as adapted by Uhl and Kauffman (1990).

Fire characteristics were recorded while fires were burning in four forest types (previously unburned, once-burned, twice-burned, more than two previous burns) in December 1997. Direct observations of fires were made at widely scattered locations within a 150-km^2 area south of Tailândia. For each observed fire, flame height and depth (width of the flaming front) were measured or estimated. Flame height was used as a conservative estimate of total flame length for the calculation of fireline intensity (Agee 1993) because there was minimal wind and slope (Rothermel 1983). The time the fireline took to move across a known distance was used to calculate the rate of spread and was combined with flame-depth data to calculate the average range of flame-residence times at any point (cf. Cochrane et al. 1999).

The classified imagery was used to determine the distance of each forested pixel from the nearest nonforested (i.e., deforested) edge with the cell-based modeling tools in the ArcInfo GIS 8.0.1 software package. Outputs were true Euclidean center distances of each forested pixel to the nearest nonforested edge pixel. Distance data were subsequently degraded to the scale of the input data (i.e., 30 m for Landsat imagery).

Distance data were used to relate the spatial placement of forests affected by fire to forest edges and to make interannual comparisons. Data on the average amount of

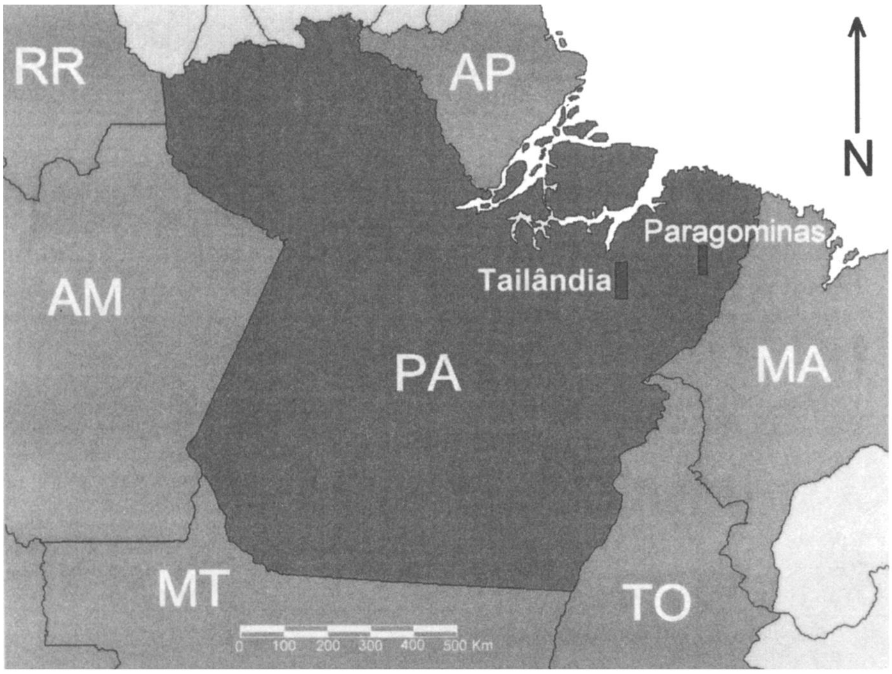

Figure 1. Study areas in Pará state (PA) in the eastern Brazilian Amazon (Tailândia, 2470 km^2; Paragominas, 1280 km^2).

annual forest burning at specific distances from the edge were used to calculate expected fire-rotation times as a function of edge distance. Fire-rotation intervals for these study sites have been discussed (Cochrane et al. 1999) but never expressed spatially. The fire rotation 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 and others may burn more than once during a cycle (Van Wagner 1978).

Results

Imagery Classification

In Paragominas, burns detected in the imagery were compared to data from landowner questionnaires (n = 75) that described fire history from 1982 to 1995 (Cochrane et al. 1999). Questionnaire data included 51.4% of the study region and showed 100% detection of reported fires that occurred within 1 year of the image date. Comparisons between the areas reported burned by landowners with 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 investigations in 1996 and 1997 (Cochrane & Schulze 1999; Cochrane et al. 1999), and no locations were classified erroneously as having been burned. On the contrary, several areas of burned forest were misclassified as having been deforested (Cochrane et al. 1999).

Deforestation

Paragominas is an older frontier area that was minimally deforested until the Belém-Brasilia highway was built in the early 1960s (Veríssimo 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. Tailândia, a new frontier in the early 1990s (Uhl et al. 1991), has developed rapidly since the paving of the main highway (PA-150) in 1985 (Cochrane et al. 1999). The study region was <10% deforested in 1984 but had lost more than 41% of its forests by 1997.

Fragmentation and Forest Edges

In both study areas the landscape was highly fragmented. Paragominas was dominated by cattle ranching, with several large (>1000 ha) forest fragments and many smaller fragments. Tailândia had small landholders along multiple roads, forming the herringbone pattern typical of planned forest-colonization projects. Most forest was contained in a few large, irregularly shaped fragments, with many smaller fragments that became isolated over time (Table 1).

The percentage of forest within 300 m of a forest edge has increased over time, growing to over 50% of the remaining forest in both study sites. About 84% and 90% of the remaining forest occurred within 1 km of the edge

Table 1. Number of forest fragments remaining over time, distributed by size class, at the Paragominas and Tailândia sites in the Brazilian Amazon.

Site and size (ha)	*Year*			
Paragominas	1984	1991	1993	1995
>10,000	4	2	3	2
>1,000 <10,000	4	9	5	5
>100 <1,000	6	20	16	21
>10 <100	40	41	48	53
>1 <10	147	157	149	156
<1	151	182	88	66
total	352	411	309	303
Tailândia	1991	1993	1995	1997
>10,000	3	2	4	4
>1,000 <10,000	2	3	1	1
>100 <1,000	8	11	23	23
>10 <100	64	66	94	94
>1 <10	107	168	193	193
<1	40	88	103	104
total	224	338	418	419

in Paragominas (1995) and Tailândia (1997), respectively (Table 2).

Forest Burning

At the time of the study, the forest remnants in both study areas had been affected by fires for several years, since at least 1983 in Paragominas and 1991 in Tailândia. The amount of standing forest burned each year has varied widely, from 1% to 45% (Table 3), with the largest fires occurring during the El Niño years of 1983, 1992, and 1997. Fire occurrence in both study areas and for all years was disproportionately concentrated near forest edges. The fact that disproportionate burning—more than that expected under random conditions—always occurred along edges and was contiguous with forest edges indicates an edge effect of variable intensity among different years. This edge effect was similar in both study regions, with an extent of 180 m and 270 m for both study regions in 1991 and 1995, respectively. In 1993 the effect was 450 m in Paragominas and 390 m in Tailândia. Roughly 75% of burned forests occurred in these regions of disproportionate burning for all years. Fire incursions occasionally penetrated >2.5 km from the nearest edge, and a limited number of isolated fires in forest interiors was also detected. Burned areas that had an edge component (i.e., those that contacted one or more forest edges) comprised >90% of the total area burned in both study areas, but the relative percentage of non-edge-related burns was >50% in some years (Table 3).

The spatial data on forest burning show that, in both study areas, the forests near edges are being altered dramatically by surface fires. In Paragominas the fire-return interval was similarly rapid throughout the entire study area, characterized by one to four fires every 20 years. In Tailândia, however, fire rotations increased with distance from forest edge, and there were at least three separate fire regions of different frequencies of fire occurrence, with mean fire-return intervals varying from 4 to >100 years (Table 2; Fig. 2).

Table 2. Distributions of forest, fires, and fire rotations as a function of distance from forest edges at two sites in the Brazilian Amazon.*

	1984		*1991*		*1993*		*1995*		*Fire rotation (years)*	
Site and distance (m)	*Forested (%)*	*Burned (%)*	*Forested (%)*	*Burned (%)*	*Forested (%)*	*Burned (%)*	*Forested (%)*	*Burned (%)*	*Low*	*High*
Paragominas										
≤300	38.7	17.2	51.4	7.8	47.1	50.9	55.6	1.7	5	10
>300 ≤1000	38.5	6.7	37.1	1.5	38.6	42.1	34.9	0.7	8	16
>1000 ≤2000	17.9	2.1	11.1	1.3	13.0	37.8	8.9	0.4	10	19
>2000	4.9	0.0	0.5	1.0	1.2	60.9	0.6	1.6	6	13
	1991		*1993*		*1995*		*1997*			
	Forested (%)	*Burned (%)*	*Forested (%)*	*Burned (%)*	*Forested (%)*	*Burned (%)*	*Forested (%)*	*Burned (%)*		
Tailândia										
≤300	46.0	1.7	49.1	36.3	51.8	4.0	52.1	38.2	5	10
>300 ≤1000	37.7	0.4	36.9	16.8	33.0	1.4	31.9	17.8	11	22
>1000 ≤2000	11.3	0.2	10.7	1.3	9.7	0.7	9.4	11.5	29	58
>2000	5.0	0.0	3.3	0.2	5.5	0.6	6.6	6.5	55	109

**For each edge-distance category, the "forested" column shows the percentage of remaining forest, whereas the "burned" column shows the percentage of remaining forest that burned. The detected fires are from 1-2 years of age and so the "fire rotation" data are presented as a range.*

Table 3. Length of existing forest edge, percentage of the total edge burned, total forested area burned, percentage of total forest burned, and percentage of burns in edge- versus non-edge-related categories at two site in the Brazilian Amazon.[a]

Site and year	*Length of forest edge (km)*	*Edge burned (%)*	*Area burned (km^2)*	*Forested area burned (%)*	*Edge-related burns (%)*	*Non-edge-related burns (%)*
Paragominas						
1984	1535	19.6	74	9.6	92.0	8.0
1991	1961	12.6	31	4.7	71.7	28.3
1993	1563	46.5	281	45.9	98.1	1.9
1995[b]	1599	2.0	6	1.3	46.3	53.7
Tailândia						
1991	3803	2.9	17	0.9	58.2	41.8
1993	3886	38.8	409	24.2	93.4	6.6
1995[c]	4490	3.2	45	2.6	44.6	55.4
1997[b]	4484	40.6	432	27.1	92.0	8.0

[a] *Edge-related burns are at least partially contiguous with the forest edge. Non-edge-related burns are isolated from the forest edge and may have been caused by hunters or loggers or by forest regrowth obscuring a previous linkage to a forest edge.*

[b] *The Paragominas region was obscured by clouds, so no analysis was possible, although extensive fires occurred throughout the area in 1997 (personal observation). Another large series of fires occurred in the Tailândia area in December 1997 (Cochrane et al. 1999), which does not appear in these statistics.*

[c] *A large fire occurred in the center of the Tailândia region in October (Cochrane & Schulze 1999) 3 months after the 1995 image; this was undetected in the 1997 image.*

Discussion

In both study areas, the synergism between fragmentation and fire was clear. As the forests became increasingly fragmented, more of the remaining forest was associated with nearby edges. Fire was used to clear forests and maintain cattle pastures, and forests near edges were obviously vulnerable to fire incursion. As edges proliferate so does the chance for the remaining forests to burn.

Most fires occurred within several hundred meters of the forest edge, although some fires that were contiguous with edges penetrated at least 2.5 km into forests. Additional isolated burns, which may have been caused by loggers or hunters, occurred as far as 5.5 km from any forest edge. In a sense, all of these burns could be considered a large-scale edge effect (cf. Laurance 2000), because they were probably much more common within the first 10 km of edges than farther into the forest.

There is evidence that the disturbance regime in the study areas has been altered dramatically. Although there are no definitive studies of the historic fire regimes for these forests, data from charcoal studies (Sanford et al. 1985; Saldarriaga & West 1986; Turcq et al. 1998) suggest a fire-return interval of at least 500–1000 years (Cochrane 2000*a*). At present, however, the existing fire rotations in both study areas imply that over half of the forest at each site will experience a fire every 5–10 years. This fire-return interval is more similar to that experienced by fire-associated ponderosa pine (*Pinus ponderosa*) forests (Agee 1993) than by tropical rainforests. Jackson (1968) found that rainforest vegetation could not persist with fire frequencies of <90 years. Fire frequency in most of these study areas is sufficient to prevent any significant regeneration of rainforest canopy trees. At both study sites, all forests up to 2100 m from forest edges had fire-return intervals that tropical forests cannot withstand. Forests >2100 m from edges may persist under the current fire regime but constitute <5% of the remaining forests. Because the study areas are typical of anthropogenic landscapes in this region, these re-

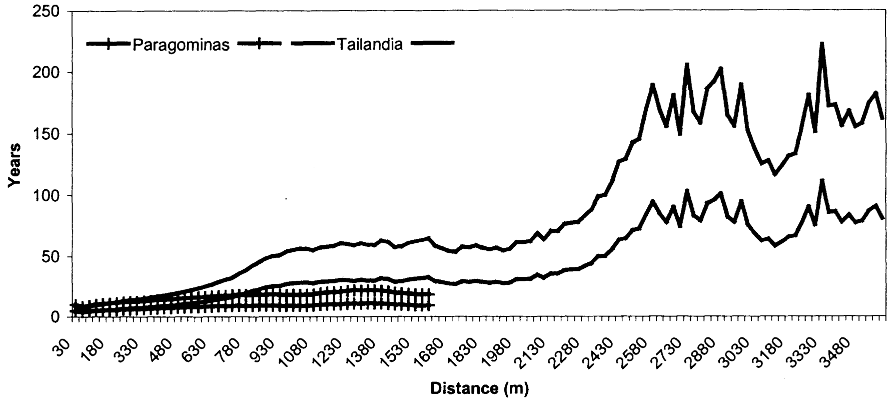

Figure 2. Fire rotations as a function of distance to edge for both study areas.

sults suggest that rainforests could be replaced by degraded, fire-resistant vegetation throughout much of the eastern Amazon. Regional climatic change could also contribute to the decline of Amazonian rainforests (Laurance & Williamson 2001 [this issue]).

Many forest stands in the study areas were burned more than once. Chances of recurring fires are increased by changes in the microclimate of the forest interior caused by the initial fires (Cochrane & Schulze 1999). Recurrent fires are more intense because the tree mortality induced by previous fires results in significantly increased fuel loads; counterintuitively, each fire creates more fuels than it consumes for the first several fire occurrences (Cochrane & Schulze 1998; Cochrane et al. 1999). Large canopy trees have little or no survival advantage in these recurrent fires (Cochrane & Schulze 1999). Although large trees typically have bark thick enough to survive the initial low-intensity fires, subsequent fires have more fuel and can be too severe for any trees to survive. Repeatedly burned forest stands are extensively thinned, having been reported to support as few as 18 live trees (>10 cm diameter at breast height) per hectare (Cochrane & Schulze 1999). Such minimally forested areas are likely to appear deforested in satellite imagery analyses. In this study, cross-tabulation of the imagery classifications showed that, in comparison to unburned forest, once-burned forests were twice as likely to be classified as having been deforested, whereas twice- and thrice-burned forests were 11 and 15 times more likely to appear deforested, respectively. This fire-induced deforestation is distinct from normal slash-and-burn deforestation and was responsible for >50% of the observed deforestation in Paragominas in 1995 (Cochrane et al. 1999).

Forest fires are becoming increasingly widespread in the tropics (Woods 1989; Cochrane & Schulze 1998, 1999; Stone & Lefebvre 1998; Cochrane et al. 1999; Peres 1999; Cochrane 2000*a*; Giri & Shrestha 2000). Land-use and climate change are interacting to create unprecedented stresses on Amazonian forests (Laurance & Williamson 2001 [this issue]), and the fire dynamics described here can be expected to worsen. Without fundamental changes in land-management practices, fire can be expected to affect vast expanses of tropical forest, degrading and eroding forest fragments (Gascon et al. 2000) and accelerating predicted levels of species extinctions (Pimm & Raven 2000). In terms of the total area affected each year, forest fires are quickly overtaking slash-and-burn deforestation as the primary cause of disturbance in tropical forests.

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