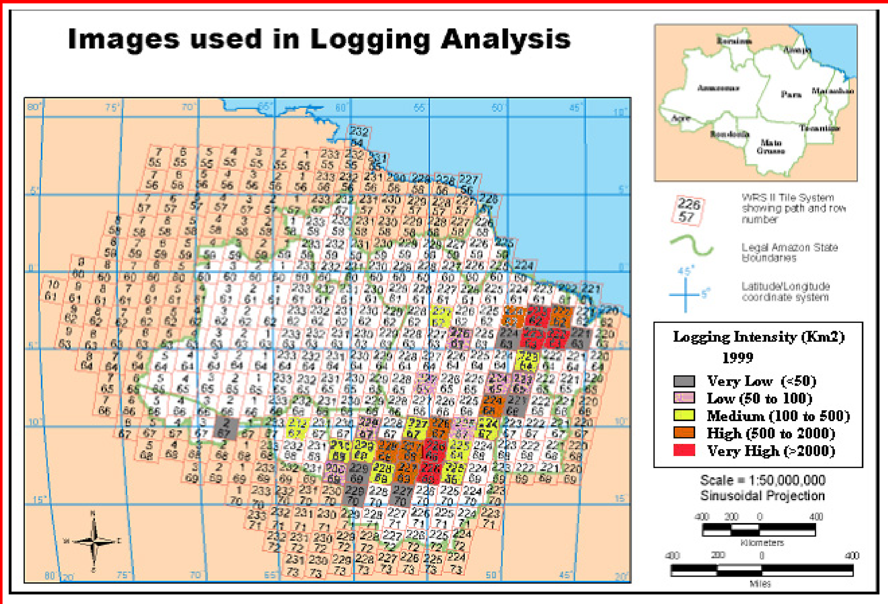
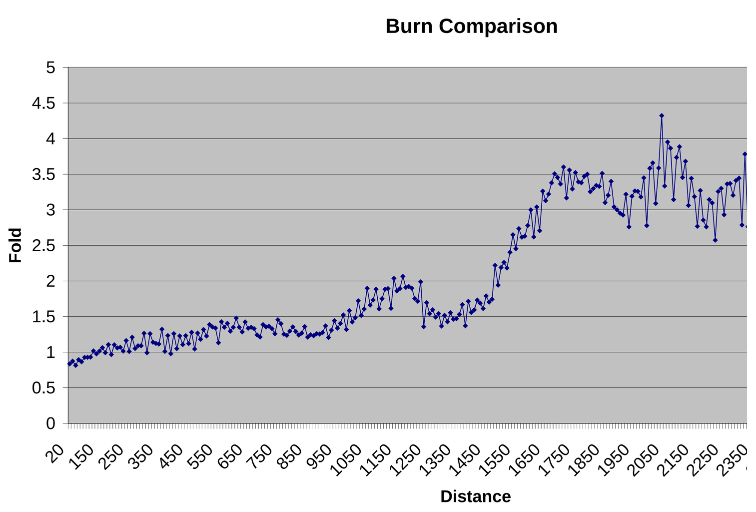


Logging in the Amazon >2.3 million hectares (1999) (Matricardi et al. 2001).



Selective logging (the removal of a few valuable trees), increases the probability (fold) of a forest burning. Data below show that even 7 years after logging, affected forests are more likely to burn.

Synergism between Fire, Forest Fragmentation and Selective Logging in Tropical Forests

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Abstract

Tropical forests are increasingly impacted by degrading activities as well as outright deforestation. Landscapes have been transformed from continuous tracts of unbroken forest into mosaics of pastures, agricultural plots and forest fragments that have often been subjected to varying degrees of increased disturbance from sun, wind, fire and logging operations. Multitemporal case studies from within the Brazilian Amazon are used to illustrate the linkages and synergy between forest fragmentation, selective logging and forest fire. A geographic information system is then used to quantitatively and spatially relate disturbance across the landscape so that spatially articulated disturbance regimes can be mapped. These maps provide both knowledge of the current state of existing forests as well as the likely future of given parcels of forest. Preliminary results have shown that forest fragmentation and forest fire are directly linked with fires becoming edge effects that penetrate kilometers into standing forests. Selective logging also exacerbates fire probability but with larger effects at larger distances from forest edges. In typical anthropogenic landscapes, fragmentation effects, fire and logging can involve nearly all of the remaining forests and pose special challenges for sustainable management of these resources.

Introduction

Deforestation is a continual process in the world's remaining tropical forests. Globally, deforestation is proceeding at its highest rate in recorded history (Houghton et al. 1991) with the largest quantities being destroyed in the Amazon Basin (Laurance et al., 2001). This process of deforestation has resulted in extensive fragmentation of the remaining forests. The area of forest subject to modification from edge effects may now exceed the total area deforested to date in the Amazon (Skole and Tucker 1993).

Fragmentation and the resulting increase in forest edge lead to changes of everything from microclimate to species composition (Margules and Pressey 2000) at varying distances from the edge. Such change may occur at distances of a few hundred meters (Laurance et al. 1997) or extend several kilometers into the forest (Curran et al. 1999). Fragmentation is known to cause structural changes along the forest edge 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 which fracture the forest canopy, increasing fuel loading and overall fire susceptibility (Holdsworth and Uhl 1997, Cochrane and Schulze 1999).

Fire has been recognized as a growing problem in the tropics due to the synergistic nature of fire-maintained land cover such as pastures in close proximity to logged or otherwise damaged forest (Uhl and Buschbacher 1985). Large-scale fires in both Indonesia and Brazil (Cochrane and Schulze 1998, Cochrane 2000) have illustrated the magnitude of the problem that fire presents for standing tropical forests. Tropical rainforests, though resistant to fire propagation, are extremely vulnerable to fire damage because of the thin bark that is characteristic of its trees (Uhl and Kauffman 1990). Once a forest does burn, fire susceptibility increases and recurrent fires can become endemic (Cochrane and Schulze 1999). The new fire dynamic can become a runaway process as each fire increases on-site fuel loading and the subsequent fire's severity. This process results in catastrophic fires that can kill even the largest, thickest barked trees (Cochrane et al 1999). These modified fire regimes may be prevalent across vast expanses of the Amazon and pose the risk of deflecting succession in these areas to scrub or savanna (Cochrane et al. 1999, Cochrane 2001). Such fires can act as a large-scale edge effect (Cochrane and Laurance in press) and pose a special risk to forest fragments (Gascon et al. 2000).

Logging operations frequently result in the death of 6 trees for every tree extracted (Uhl et al 1997)

Fragments become progressively smaller

Fragment number and size distribution.

Paragominas	1984	1991	1993	1995
Size (ha)	#	#	#	#
>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
Size (ha)	#	#	#	#
>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

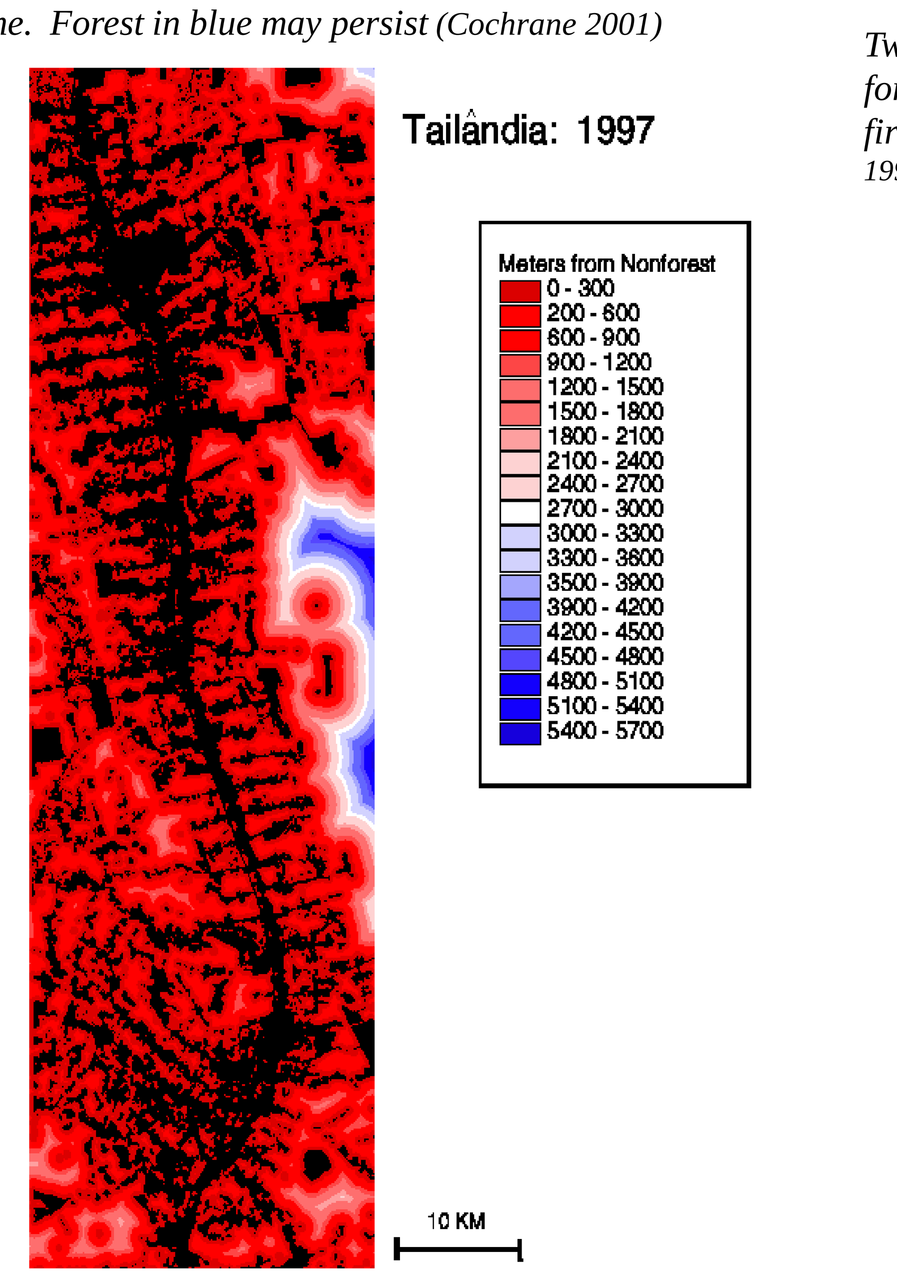
Disproportionate representation of fires along forest edges. Table gives the distance from the forest edge where fire was disproportionately experienced in each year and at each site. The percentage of all burning represented by the given distance and year is also presented.

	Paragominas		Tailândia	
	Distance (m)	% of total	Distance (m)	% of total
1984	360	75%	?	?
1991	180	75%	180	73%
1993	450	65%	390	85%
1995	270	73%	270	76%
1997	?	?	300	74%

Distance distribution of forest, fires and fire rotations. Data are presented as the percentage of the total forest and percentage that burned for each given year and study site. The fire rotation values are those implied by the observed forest burning. The detected fires are from 1-2 years and so the data are presented as a range.

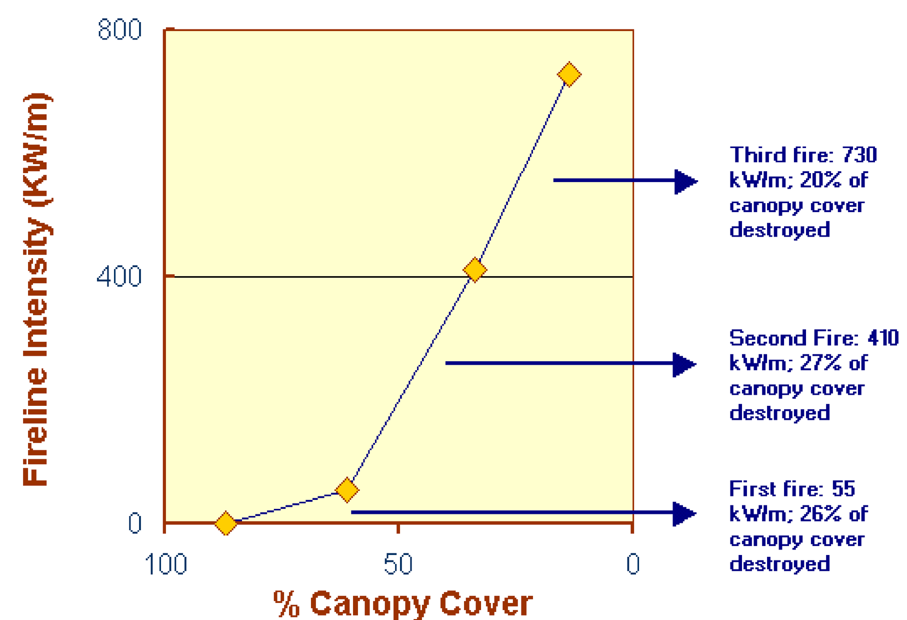
Paragominas										
	1984		1991		1993		1995		Fire Rotation (Years)	
Distance (m)	Forested	Burned	Forested	Burned	Forested	Burned	Forested	Burned	Low	High
≤ 300	38.7%	17.2%	51.4%	7.8%	47.1%	50.9%	55.6%	1.7%	5	10
>300 ≤ 1,000	38.5%	6.7%	37.1%	1.5%	38.6%	42.1%	34.9%	0.7%	8	16
>1,000 ≤ 2,000	17.9%	2.1%	11.1%	1.3%	13.0%	37.8%	8.9%	0.4%	10	19
>2,000	4.9%	0.0%	0.5%	1.0%	1.2%	60.9%	0.6%	1.6%	6	13
Tailândia										
	1991		1993		1995		1997		Fire Rotation (Years)	
Distance (m)	Forested	Burned	Forested	Burned	Forested	Burned	Forested	Burned	Low	High
≤ 300	46.0%	1.7%	49.1%	36.3%	51.8%	4.0%	52.1%	38.2%	5	10
>300 ≤ 1,000	37.7%	0.4%	36.9%	16.8%	33.0%	1.4%	31.9%	17.8%	11	22
>1,000 ≤ 2,000	11.3%	0.2%	10.7%	1.3%	9.7%	0.7%	9.4%	11.5%	29	58
>2,000	5.0%	0.0%	3.3%	0.2%	5.5%	0.6%	6.6%	6.5%	55	109

Forests as a function of distance from deforested (black) edges. Forests in red can not survive the current fire regime. Forest in blue may persist (Cochrane 2001)



Amazonian forest fire: The first fire may be of very low intensity (<50 kw/m) but is slow moving and kills 40% of the trees (Cochrane and Schulze 1999)

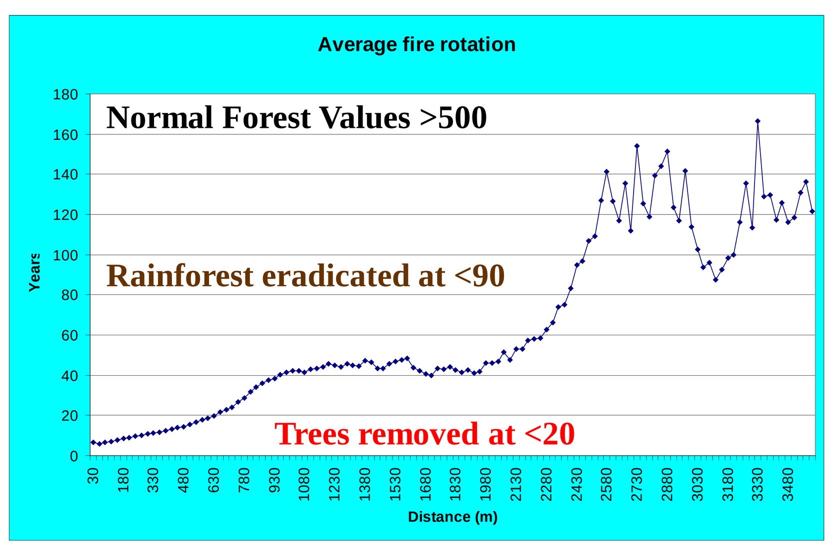
Burning Sumauma tree (2m diameter): Subsequent fires can be much more extreme and exceed the capabilities of manual firefighting (Cochrane et al. 1999)



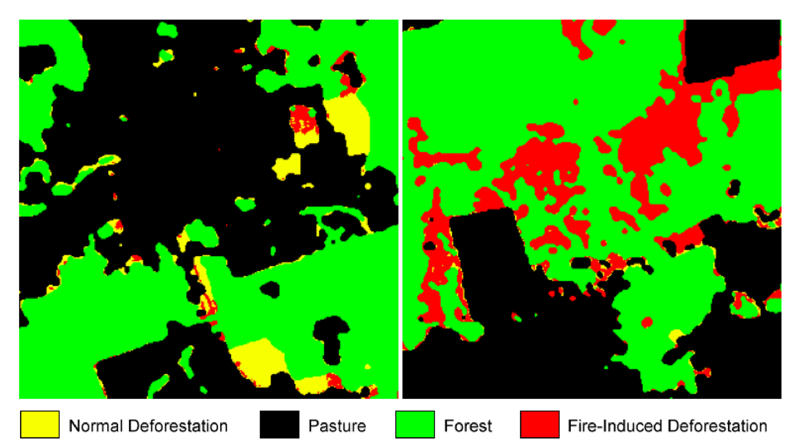
http://www.globalchange.msu.edu/images/centerlogoserif2.jpg

The cumulative capacity of recurrent tropical forest fires (Cochrane 2000)

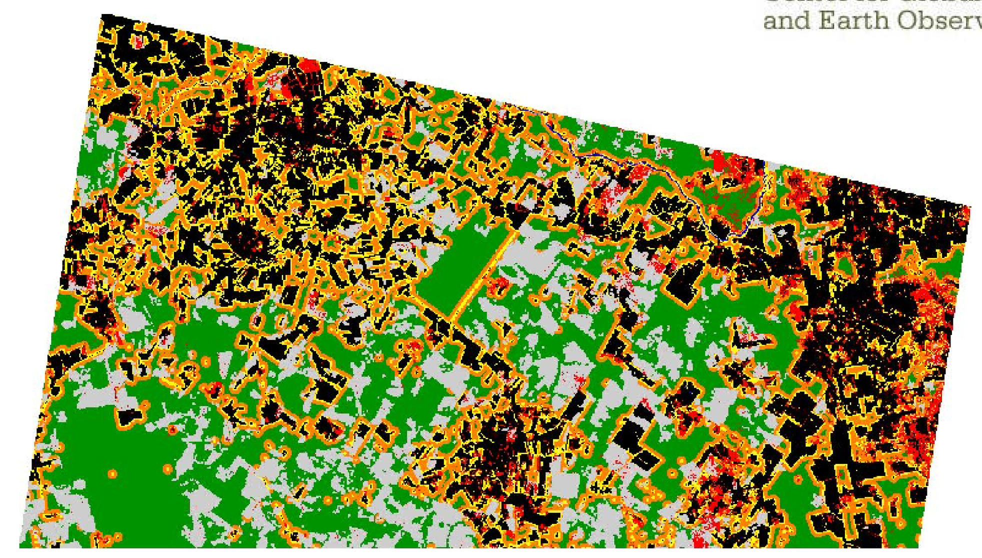
Spatially articulated fire regime: Fire rotation values by distance for a 250,000 hectare study region. Indications are that forests within 2 km of current edges can not persist under the current disturbance regime and will be replaced with grass or scrub vegetation (Cochrane 2001)



Two 64-km² 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 (Cochrane et al. 1999)



An example of fire-induced deforestation. The white lines are the ashes from trees which were completely consumed by fire.



16,800 km² sample landscape showing combined effects of deforestation (black), fragmentation (yellow/orange), fire in 1999(red) and selective logging 1992-1999 (gray).

Discussion

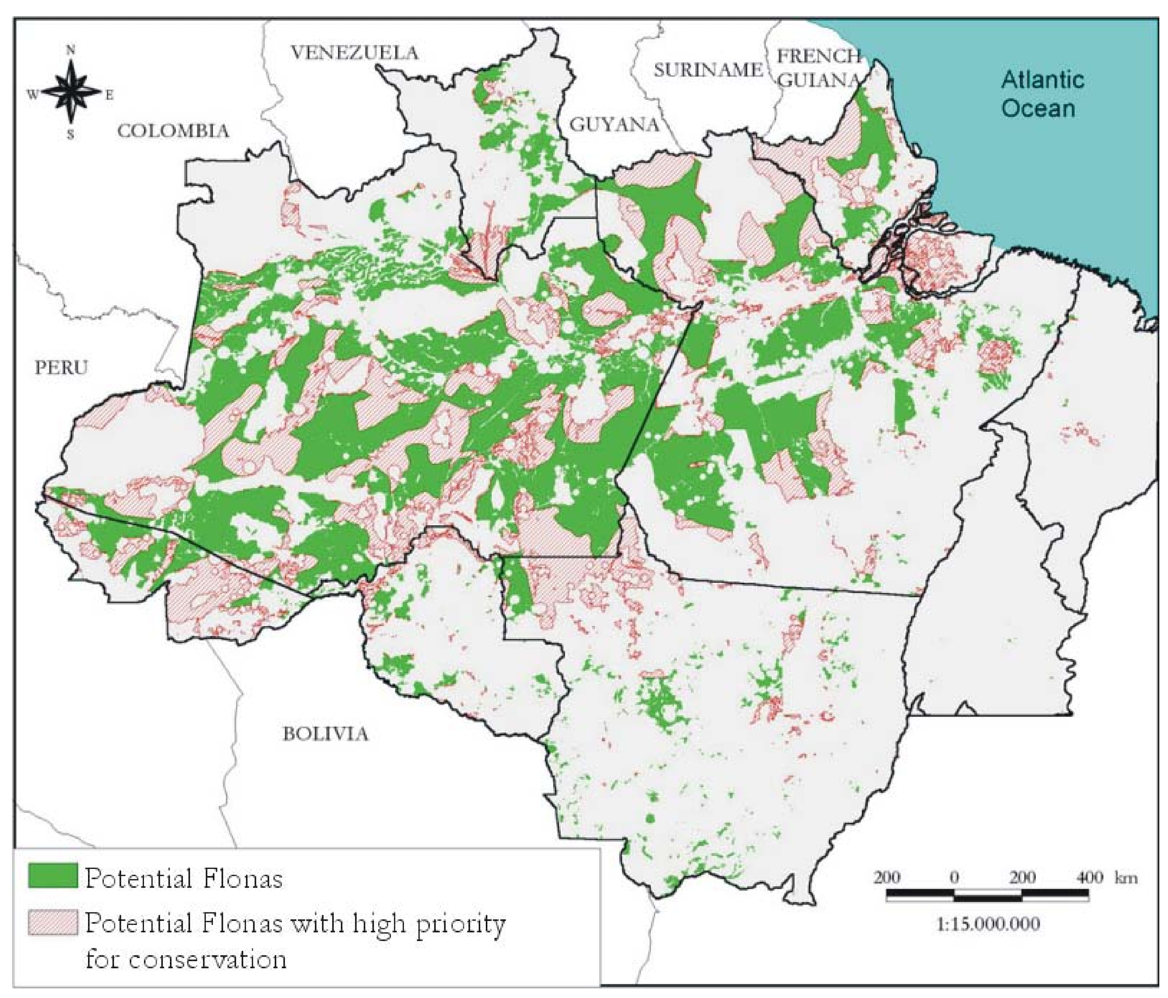
The connection between fragmentation, selective logging and fire is clear. As the forests are increasingly fragmented, more and more of the remaining forest is associated with nearby edges. Fire use is prevalent along forest edges and adjoining pastures, and edge forests are obviously vulnerable to fire incursion. Logging disturbs the forest and makes them more susceptible to fire. As forest edges and distrubance proliferate so does the chance for forest burning.

Although most fires are strongly associated with edges they also occurred deep within the forest interior. While the data do not definitively indicate either the cause or origin of these fires, it is clear that most burning is occurring within several hundred meters of the forest edge. 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 a forest edge. In a sense, these additional burns can be considered a large-scale edge effect (Cochrane and Laurance, in press), as they are probably much more common within the first 10 km of edges than further into the forest.

There is clear evidence that the disturbance regime at these sites has been changed dramatically. Although there are no definitive studies of the historic fire regimes for these forests, data from charcoal studies (Sanford et al. 1985, Saldarraiga and West 1986, Turcq et al. 1998) suggest a fire-return interval of at least 500-1000 years (Cochrane 2000). At present, however, the existing fire rotations in sudy areas suggest that over half of the forest at each site will experience a fire every 5-10 years. This fire-return interval is much more similar to the fire frequency experienced by fire-associated ponderosa pine (*Pinus ponderosa*) forests (Agee 1993) than that of tropical rain forests. Jackson (1968) found that rainforest vegetation could not persist with fire frequencies of <90 years. The current fire frequency being experienced throughout the majority of the studied forests is sufficient to prevent any significant regeneration of current canopy trees from occurring. Because these study areas are typical of anthropogenic landscapes in the region, these results 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 closed-canopy forests in the Amazon (Laurance and Williamson 2001).

Many forest stands in the study areas were burned more than once. The chances of recurring fires are increased by changes in the microclimate of the forest interior caused by the initial fires (Cochrane and Schulze 1999). Recurrent fires are more intense because the mortality induced by previous fires results in significantly increased fuel loads, counter-intuitively, each fire creates more fuels than it consumes (Cochrane and Schulze 1998, Cochrane et al. 1999). Large canopy trees have little or no survival advantage in these recurrent fires (Cochrane and Schulze 1999). Though large trees typically have thick enough bark to survive the initial low intensity fires, subsequent fires have more fuels 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 DBH) ha^{-1} (Cochrane and 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 while 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, Stone and Lefebrvre 1998, Cochrane and Schulze, 1998, 1999, Peres 1999, Cochrane et al. 1999, Cochrane 2000, Giri and Shrestha 2000). Land-use and climate change are interacting to create unprecedented stresses on Amazonian forests, and the fire dynamics described here can be expected to worsen. Without fundamental changes in land management practices, fire can be expected to impact vast reaches of tropical forest, degrading and eroding forest fragments (Gascon et al 2000) as well as accelerating predicted levels of species extinctions (Pimm and Raven 2000). In terms of total annual area affected, forest fires are quickly overtaking slash-and-burn deforestation as the primary disturbance factor in tropical forests.



***Hope for the future**: To sustainably supply the demand for timber, approximately 700,000 km² of the Amazon forest needs to be brought into well managed production. Our results indicate that 1.15 million km² of forests (23% of the Brazilian Amazon) could be established as National Forests in a manner that will promote sustainable forest management while acting as buffer zones for fully protected areas (Parks and Reserves) (Veríssimo et al. 2002). The Brazilian government is beginning to implement this plan (400,000 km²).*