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MODELING FOREST UNDERSTORY FIRES IN AN EASTERN AMAZONIAN LANDSCAPE

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Abstract. Forest understory fires are an increasingly important cause of forest impoverishment in Amazonia, but little is known of the landscape characteristics and climatic phenomena that determine their occurrence. We developed empirical functions relating the occurrence of understory forest fires to landscape features near Paragominas, a 35-yr-old ranching and logging center in eastern Amazonia. An historical sequence of maps of forest understory fire was created based on field interviews with local farmers and Landsat TM images. Several landscape features that might explain spatial variation in the occurrence of understory fires were also mapped and co-registered for each of the sample dates, including: forest fragment size and shape, forest impoverishment through logging and understory fire, sources of ignition (settlements and charcoal pits), roads, forest edges, and others. The spatial relationship between forest understory fire and each landscape characteristic was tested by regression analyses. Fire probability models were then developed for various combinations of landscape characteristics. The analyses were conducted separately for years of the El Niño Southern Oscillation (ENSO), which are associated with severe drought in eastern Amazonia, and non-ENSO years.

Most (91%) of the forest area that burned during the 10-yr sequence caught fire during ENSO years, when severe drought may have increased both forest flammability and the escape of agricultural management fires. Forest understory fires were associated with forest edges, as reported in previous studies from Amazonia. But the strongest predictor of forest fire was the percentage of the forest fragment that had been previously logged or burned. Forest fragment size, distance to charcoal pits, distance to agricultural settlements, proximity to forest edge, and distance to roads were also correlated with forest understory fire. Logistic regression models using information on fragment degradation and distance to ignition sources accurately predicted the location of >80% of the forest fires observed during the ENSO event of 1997–1998. In this Amazon landscape, forest understory fire is a complex function of several variables that influence both the flammability and ignition exposure of the forest.

Key words: agricultural frontiers; deforestation; ENSO; forest fire; fragmentation; landscape structure; tropical forest.

Introduction

Fire is an increasingly important agent of ecological change in the upland (terra firme) forests of Amazonia. During pre-Columbian times, fires burned large areas of Amazon forest at intervals of ~400–700 yr, perhaps in association with severe droughts (Sanford et al. 1985, Meggers 1994). But in recent years, the rate of forest burning has increased greatly in the settlement frontiers in eastern and southern Amazonia through the synergistic influence of selective logging, forest fragmentation, and severe drought (Uhl and Buschbacher 1985, Uhl and Kauffman 1990, Cochrane et al. 1999, Nepstad et al. 1999*b*, Gascon et al. 2000). As much as one-third of the Amazon forest may have become vulnerable to fire during the severe ENSO event of 1997–1998 (Nepstad et al. 2001); 13 000 km² of mature forest burned in the northern Amazonian state of Roraima in 1998 (Barbosa and Fearnside 2000) while more than 20 000 km² of forest burned in southeastern Amazonia during this same year (Diaz et al. 2002). Unlike the ''deforestation'' fires that are set by farmers and ranchers to deliberately burn 11 000 to 30 000 km²/yr of felled forest in preparation for crops and pasture formation (Instituto Nacional de Pesquisas Espaciais [INPE] 2000), releasing 2–3 × 10^{14} g of carbon to the atmosphere (Fearnside 1997, Houghton et al. 2000), the fires that inadvertently burn the understory of standing forests are poorly understood. We studied the landscape features that are associated with forest understory fires, described by Nepstad et al. (1999*b*) as surface fires, to develop a quantitative model of forest fire risk in an ageing Amazon frontier.

High, dense, primary forests in Amazonia are resistant to fire incursion even during prolonged dry seasons partly because of their remarkable capacity to maintain

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dense leaf canopies during rainless periods by tapping deep soil water supplies (Nepstad et al. 1994, 1995). This resistance is lost, however, when the canopy thins, the forest floor fuel layer increases, and the forest interior grows warmer and drier. Canopy thinning occurs when soil moisture depletion provokes drought-induced leaf abscission (Nepstad et al. 1999*a*, 2001), when selective logging opens large gaps in the canopy (Uhl and Buschbacher 1985, Uhl and Kaufmann 1990), and when understory fire kills trees, perpetuating the formation of gaps as they fall to the forest floor in subsequent years (Nepstad et al. 1995, Cochrane and Schulze 1999). Amazon forest fires are more common along forest edges (Cochrane 2001, Cochrane and Laurance 2002) perhaps because of warm, dry air from neighboring pastures (Kapos et al. 1993, Gascon et al. 2000) and higher ignition probability. Some Amazon forests have low resistance to fire incursion because their canopies are sparse because of soil infertility (Kauffman et al. 1988, Uhl et al. 1988), or because of chronic drought.

Forest flammability only results in forest fire in the presence of ignition sources. Lightning events in Amazonia are usually associated with rain showers, and rarely cause forest fires. The agricultural frontier, however, provides abundant dry season ignition sources. Fires frequently escape beyond their intended boundaries and ignite adjacent forests when farmers and ranchers burn felled vegetation in preparation for crops and pasture formation, or set pastures on fire to kill the tops of forage-invading shrubs and trees (Nepstad et al. 1999*b*). Other rural economic activities, such as charcoal production, may also provide sources of ignition to flammable forests.

In sum, forest flammability can increase through severe drought, logging, and understory fire, and flammable forests are likely to be ignited in close proximity to fire-dependent production systems, such as cattle ranching, slash-and-burn agriculture, and charcoal production pits. But the interaction of these factors within Amazon landscapes, or moist tropical forest landscapes generally, has not been analyzed. We investigated the landscape characteristics that are associated with forest understory fire in an eastern Amazon frontier with the objective of quantifying the contribution of each landscape feature to forest fire occurrence for years of severe and mild drought. Such information could help in the design of rainforest settlement policies that attempt to avoid forest impoverishment through understory fire.

The contribution of landscape attributes to the spatial distribution of forest understory fire was measured through regression analysis of co-registered maps of understory fire, land cover, roads, settlements, and charcoal pits. Analyses were conducted separately for ENSO and non-ENSO years to test for drought effects on these spatial relationships. Predictive models of forest understory fire occurrence were then developed using logistic regression analysis employing the landscape features that explained most of the variation in understory fire. These models were tested using forest fire maps for 1998 and 2000.

Methods

Study area

We studied a 62 × 56 km (338 000-ha) landscape centered on Paragominas, an eastern Amazonian ranching and logging center first settled in the late 1960s (Fig. 1). Deforestation and forest impoverishment through logging and understory fire is more advanced in the Paragominas region than in most of Amazonia, but it represents the possible future trajectory of other younger frontiers. Although 51% of this landscape supported forest cover in 1996, 23% of this residual forest suffered understory fire from 1983 to 1995. The deeply weathered, acid-infertile Oxisols that dominate the Paragominas region are found in approximately one third of Amazonia (Richter and Babaar 1991). The seasonal rainfall pattern, with four to five months per year with $<$50 mm of rain, and average annual totals of 1800 mm (Jipp et al. 1998) are typical of three-fourths of Amazonia's frontier landscapes, which are concentrated along the eastern and southern margins of the region (Nobre et al. 1991, Skole and Tucker 1993, Nepstad et al. 1994). Rainfall declines during ENSO years (Fig. 2).

Fire scar maps

Maps of forest impoverishment through understory fire (i.e., surface fire) were made for the entire region. A major impediment to mapping forest fire scars is the speed with which the detectable signal in Landsat TM imagery disappears as vegetation regrows. Therefore, we combined Landsat TM image analysis with interviews of 145 landholders and field visits to burned forests to develop a 10-yr sequence of forest fire scars within the study landscape. Ranchers and farmers identified and dated burned areas in printed Landsat TM images from June 1991 and 1996. Half of the burned areas were visited and georeferenced using a Global Positioning System and used as training sites for supervised classifications in a time series of Landsat TM images that included 1984, 1988, 1991, 1993, 1995, and 1996. Burned forest areas were classified with a maximum likelihood algorithm (Environment for Visualizing Images [ENVI] 3.2; Research Systems, Inc., Boulder, Colorado, USA) and aggregated across the time series to develop a binary, burned vs. unburned, forest cover map for the entire landscape. This map was done separately for ENSO and non-ENSO years. Maps of forest fire scars from 1998 and 2000 were used to test the predictive equations of understory fires in ENSO and non-ENSO years, respectively. These maps were created using Landsat TM and ETM images from August 1999 and 2001.

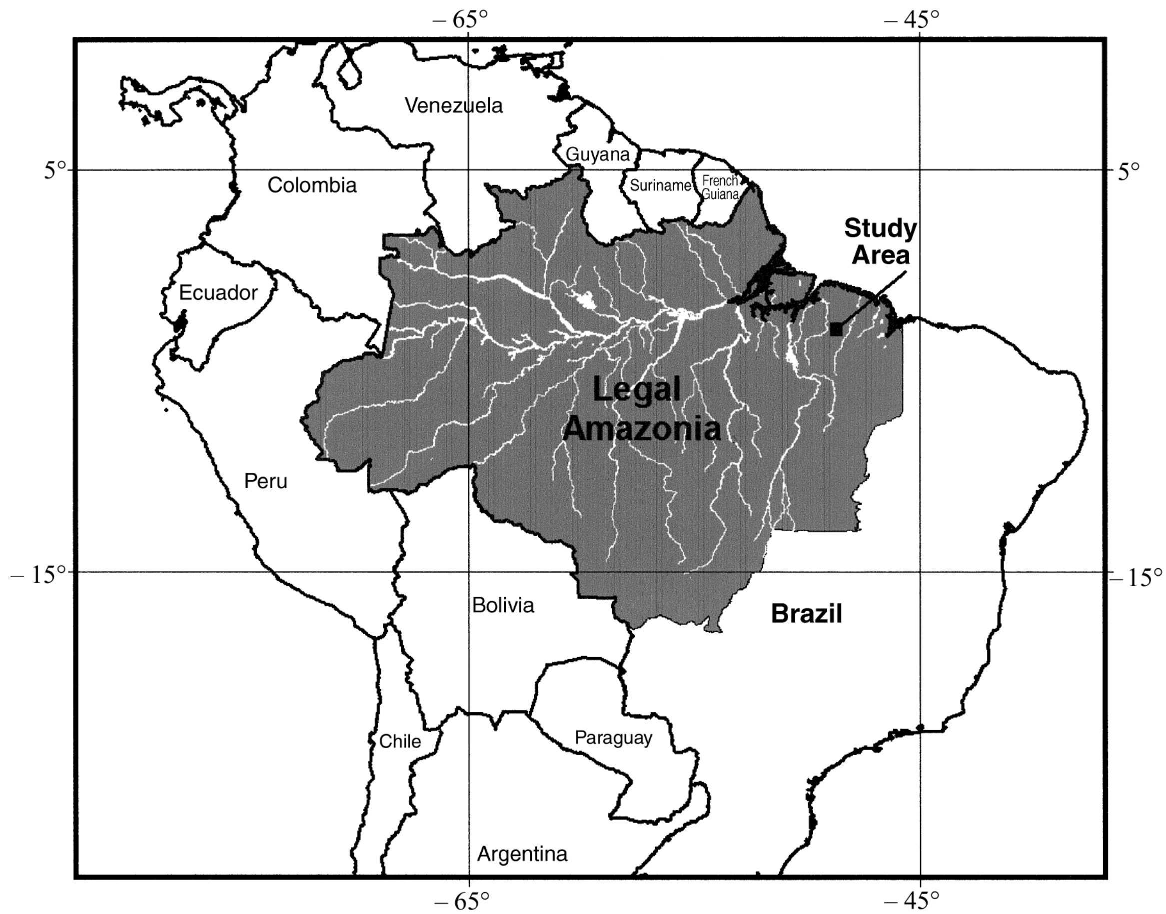

FIG. 1. Location of the study area.

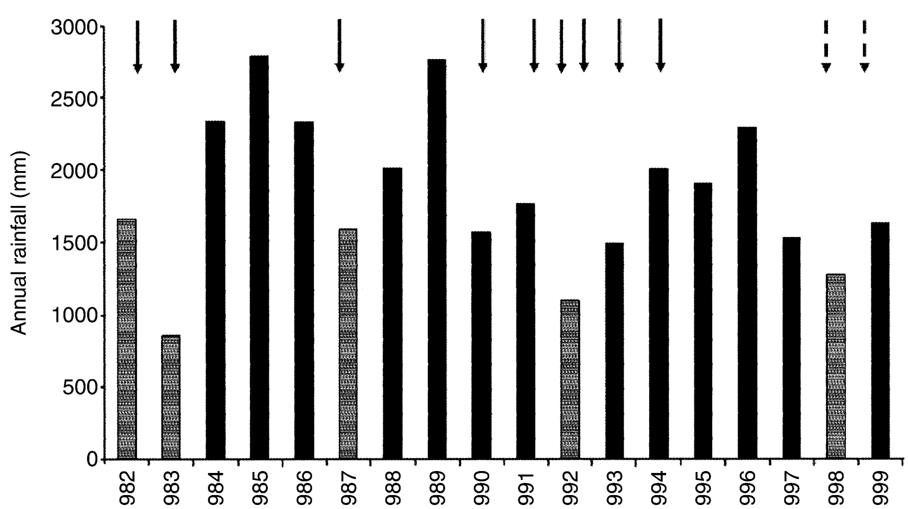

FIG. 2. Annual precipitation registered in the Paragominas Region during the years analyzed for this study. Black bars represent non-ENSO years, and gray bars show years when ENSO occurred. The arrows on top point at the dates of the Landsat images employed for this study. Continuous arrows designate images used for model development and validation within the same time interval. Dashed arrows point to images used for model validation into the future.

Land-cover map

Degradation.—The variable DEGRADATION was defined as the percentage of the forest fragment that was disturbed through selective logging or past understory fires. This percentage was then multiplied by the number of years during which the fragment had experienced understory fires or logging events. This frequency of disturbance was calculated on a scale from 0 to 1 with the maximum number of events receiving one. Landsat TM images (years 1984, 1988, 1991, 1993, 1995, and 1996) and field surveys were used to classify and map forest logging scars. Logging operations in this region create log decks in the forest for storing logs and these decks appear in satellite images as large gaps in the forest canopy, thus providing a basis for remote detection of logging. A supervised classification was used to separate three main vegetation types (forest, burned forest, and non-forest), and a masking routine using a Closing Filter algorithm (ENVI 3.2) was used in each image to identify the nonforest isolated pixels inside the forest fragments. These pixels were reclassified as log decks. On-screen visual interpretation was also done to identify the log decks that were not recognized by the masking routine.

Type of land-use neighborhood.—This variable accounts for neighborhood effects on forest fire occurrence that are associated with the fire regime of adjacent land-use types (Keeley et al. 1999). The variable ''neighborhood'' was calculated as the percentage of the forest fragment perimeter that intersected cattle pasture.

Distance variables

Roads.—Roads are a key landscape element for fire prediction because they are strongly associated with human settlement and fire-based land use activities (Nepstad et al. 2001; Alves 2002). The variable MAINROAD is the distance of each forest cell (30 × 30 m) to the nearest federal, state, or municipal road (from 1:100 000 digital maps provided by the Instituto Brasileiro de Geografia e Estatistica); ''road'' includes fragment distance to smaller private roads digitized from the Landsat TM images.

Ignition sources.—The main source of ignition in the Amazonia region is agricultural fire and other activities related to biomass burning. Active fires are monitored from space with the NOAA/AVHRR satellite sensor, but the spatial resolution and accuracy of these data are inadequate for our fire model. We therefore analyzed the distance from forest fragments to agricultural settlements (variable SETTLEMENT) and to charcoal pits (variable CHARCOAL) as proxy variables for describing ignition risk in the Paragominas landscape. Agricultural settlements are planned agricultural colonies in which subsistence farming provides abundant ignition sources through slash-and-burn agriculture and pasture management fires. Charcoal pits are used to make charcoal with wood from nearby forests in pits excavated in the soil and represents an important economic activity in Paragominas. Charcoal pits are a source of ignition both directly, through the sparks and flaming embers that they produce, and indirectly because of their association with slash-and-burn agriculture in this region. In supplying charcoal pits with fuel wood, the surrounding forests are often thinned, increasing their flammability. The locations of settlements were identified through government colonization agency (INCRA) maps and the charcoal pits were identified and georeferenced through field surveys and interviews with the charcoal merchant in Paragominas.

Edges.—The probability of forests catching fire may also change with distance to the forest fragment edge (Cochrane 2001, Cochrane and Laurance 2002), a variable that we call ''edge.'' Forest edges are drier (Kapos et al. 1993) and have higher tree mortality (Ferreira and Laurance 1997, Laurance et al. 1997) than the core of a forest fragment. They are also closer to sources of ignition. EDGE was estimated for each cell (30 × 30 m) in each forest fragment.

Landscape indices

Fragment size.—The SIZE variable is estimated for the forest fragments as the ratio of each forest fragment's area to the largest forest fragment area in the landscape. Small fragments are expected to be more susceptible to fires than larger ones because a larger percentage of the forest area is subject to more flammable land covers as pastures.

Fragment shape.—Each fragment's shape is given by the ratio of the fragment perimeter to the fragment area. This ''shape'' index (from the FRAGSTATS program)[4] is one when the forest fragment is regular (i.e., a circle) and increases without limit as the fragment's shape becomes more irregular. The irregularity of the fragment shape increases the area of the fragment that is exposed to the ''edge effect'' (Laurance et al. 1997), possibly influencing the probability of a fragment burning.

The spatial distribution of understory fires

The spatial correlates of forest understory fires were identified initially by determining the percentage of forest cells that burned as a function of each of the independent variables described above. This analysis permitted us to assess the influence of individual variables on forest understory fire, and test their statistic significance. For variables represented by distance, a buffer analysis was conducted and the percentage of a burned forest was calculated for each buffer segment (buffers were 100 m in width). The relationship of forest fires with the forest fragment size index and the

[4] ⟨www.umass.edu/landeco/research/fragstats/fragstats.html⟩

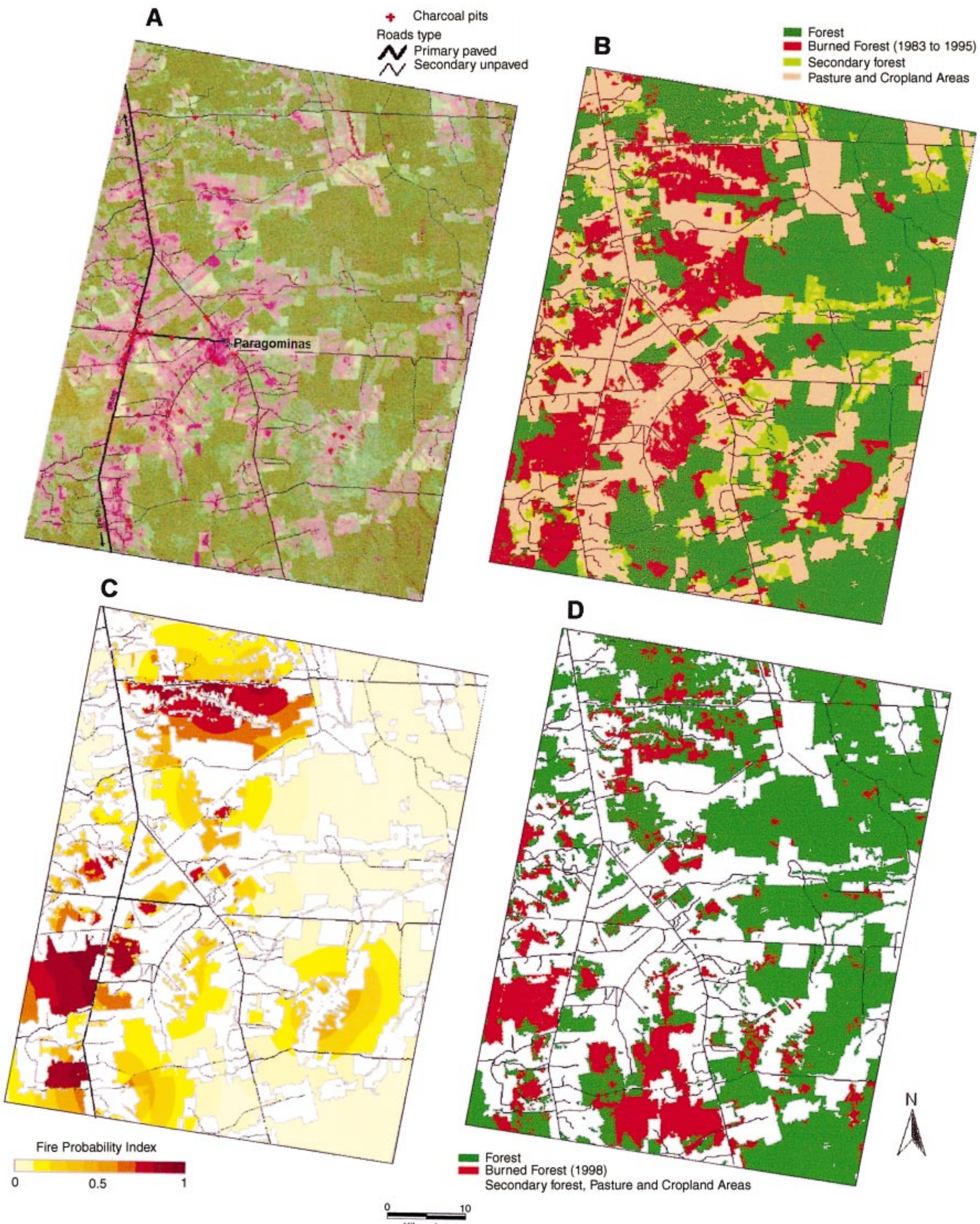

FIG. 3. (A) Landsat TM 5 satellite image from July 1996 from the study area showing charcoal pit locations and road type distribution. (B) Aggregated forest fire scars from 1983 to 1995 overlaid on a forest mask of 1996 image classification. (C) Forest fire probability map created through logistic regression based on distance to ignition sources and forest fragment degradation. (D) The 1998 forest fire scars classified from Landsat 7 ETM+ satellite image from 1999.

degradation index were calculated by separating forest fragments into ten uniform classes of each index. These spatial relationships were tested using linear regression for ENSO and non-ENSO years.

Probability models

Logistical regression techniques were used to model the probability of forest understory fire as a function of landscape characteristics. Initially, the contribution of each variable to fire occurrence was determined using stepwise forward logistic regression (Chou 1992). Each forest cell in the study area was assigned a value of either zero (no fire) or one (fire) as the dependent variable. Ten samples of 1000 cells each were randomly distributed among forest cells and their respective values for the dependent and independent variables were extracted for the regression. Samples for each variable were tested for spatial autocorrelation using the Moran's I first lag statistic (Eastman 2001), and its value always showed low spatial autocorrelation ($I < 0.001$; $P < 0.0001$) except for SETTLEMENT and CHARCOAL, which had similar distributions. We therefore present results only for the latter. Those variables that explained a significant amount of the variation in understory forest fire occurrence were then used in various combinations to develop fire probability models using the logistic function (Chou 1992).

Validation

We validated the logistic models by comparing their probability designations with fire maps that were not employed in model development. The models for ENSO years were validated using a fire map for 1998, while the models for non-ENSO years were validated using the fire map for 2000. These fire maps were developed based on land-holder interviews and Landsat TM images from 1999 and 2001, respectively.

In addition to the standard Kappa statistic and Moran's I statistic for validation, the relative operating characteristic (ROC; Pontius and Schneider 2001) was employed to assess the effectiveness of the model in predicting the occurrence of the forest understory fire. The ROC is a validation method that measures the accuracy of a logistic model by comparing the map of predicted fire probabilities with the binary, burned vs. unburned map of subsequent observed fires. The ROC aggregates errors due to quantity and location of the predicted response into a single index (Egan 1975, Eastman 2001, Pontius and Schneider 2001).

Results

Forest understory fires were closely associated with ENSO. Most (91%) of the forest understory fires mapped in the study landscape during the 10-yr study period (Fig. 3A, B) occurred during the three years in which the ENSO provoked drought in the Paragominas region (1983, 1987, 1992; Figs. 2 and 4). A cumulative total of 24% of the forest area suffered understory fire from 1983 to 1995 (Fig. 3B), climbing to half by 1999 (Fig. 3D).

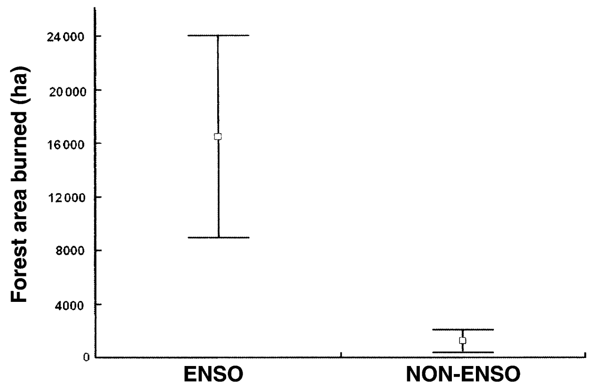

FIG. 4. Difference in burned area between ENSO and non-ENSO years (Mann-Whitney test two-tailed $P = 0.031$). Plotted values are mean ± 1 SE.

The spatial distribution of understory fires was a complex function of several landscape characteristics. The percentage of the forest that burned was highest near the forest edge, but it was highest near the forest edge only during ENSO years (Fig. 5C and 5H). Distance to charcoal ovens, forest degradation by logging and fire, distance to main roads and forest fragment size were also strongly correlated with understory fire during ENSO years (Fig. 5A–E). During non-ENSO years, only distance to charcoal ovens, distance to main roads, and previous degradation showed strong spatial correlations with understory fire (Fig. 5F–J). The percent of forest that burned within these buffer areas was much higher in ENSO years than in non-ENSO years, reaching maximum values of 80% and 8%, respectively (Fig. 5A–J).

The variables that were significantly correlated with the binary forest fire variable during ENSO years were, in decreasing order of importance: previous disturbance through logging and fire, distance to charcoal pits, distance to main roads, distance to the forest edge, and fragment size (Table 1). Only DEGRADATION and CHARCOAL explained a significant amount of variation in understory fires during all ten sample sets in ENSO years. Distance to main road and forest edge were the best predictors of forest fire during non-ENSO years, ranked in five and four of the 10 sample sets, respectively, as the most significant predictors.

To facilitate application of these results to other tropical landscapes, the 20 two-variable models that best predicted forest understory fire are presented in Table 2. Although DEGRADATION and CHARCOAL were the only variables that were significant in all 10 sample sets, the logistic model with these two variables ranked third in explaining the spatial variation of understory fire (Table 2, Fig. 6A). However, when CHARCOAL was substituted with distance to agricultural settle-

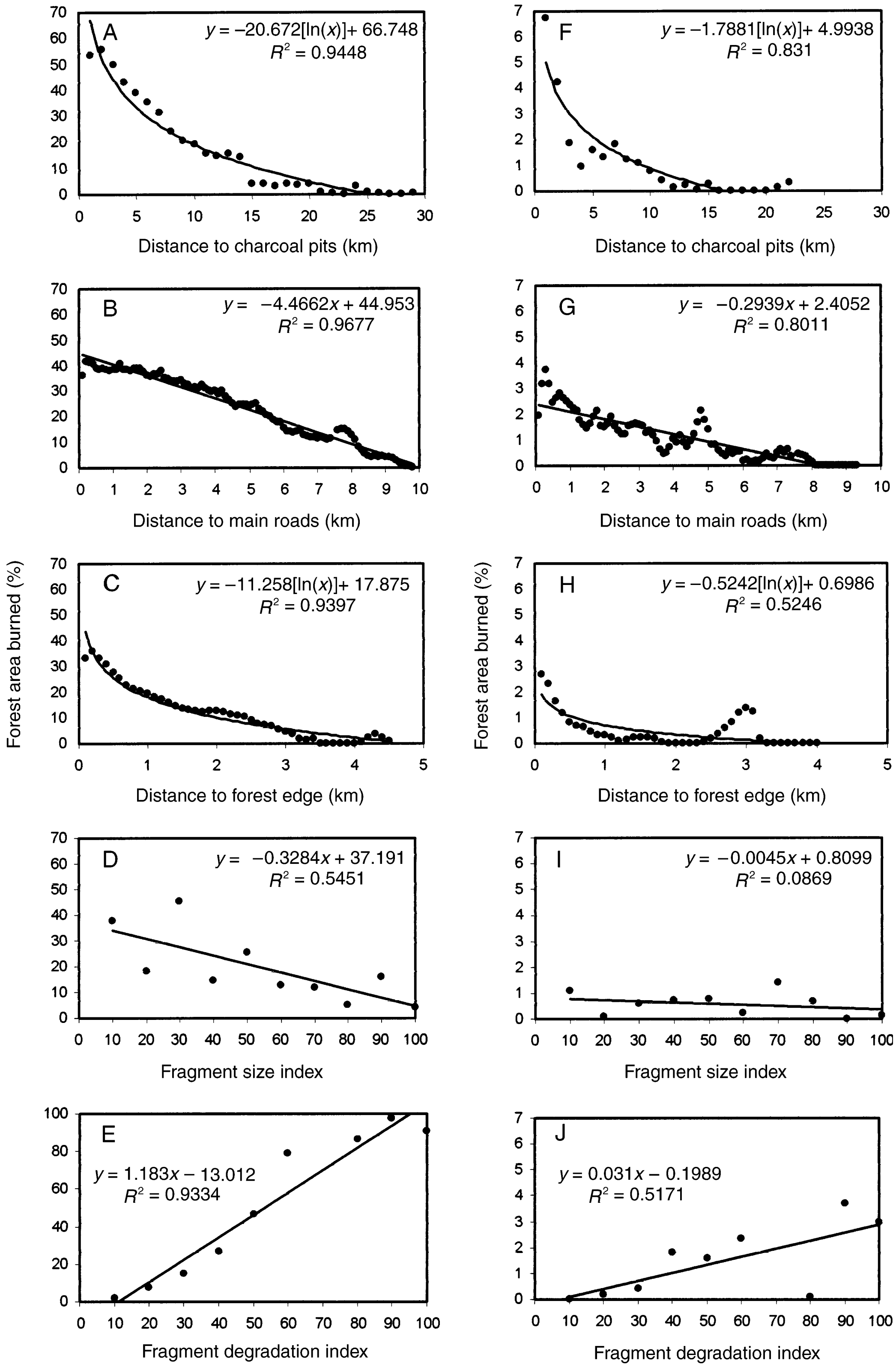

FIG. 5. Forest understory fire as a function of landscape features in Paragominas, eastern Amazonia. The independent variable, percentage of forest area burned, was calculated as a function of distance to charcoal pits (A, F), distance to main roads (B, G), and distance to the forest fragment edge (C, H). ENSO-year results are in the left column; non-ENSO years are in the right column. Vertical scales vary between ENSO and non-ENSO graphs.

TABLE 1. Stepwise forward logistic regression of forest understory fire (dependent variable) on five independent variables that characterize the Paragominas landscape for ENSO and non-ENSO years.

Independent variable	Estimate	SE	t	P
ENSO				
Fragment degradation index (DEGRADATION)	0.035	0.005	6.745	0.000
Distance to charcoal pits (CHARCOAL)	−14.331	3.884	−3.689	0.000
Distance to main roads (MAINROAD)	−16.434	6.119	−2.686	0.007
Distance to forest edge (EDGE)	−69.308	26.259	−2.639	0.008
Fragment size index (SIZE)	−1.089	0.486	−2.239	0.025
NON-ENSO				
Distance to main roads (MAINROAD)	−40.927	18.531	−2.209	0.027
Distance to forest edge (EDGE)	−382.068	183.728	−2.080	0.038
Fragment size index (SIZE)	2.439	1.120	2.177	0.029

Notes: Distance to settlements and distance to charcoal ovens (CHARCOAL) were autocorrelated, and the regression was run with only one of these variables at a time. The regression for ENSO years was significant (chi-square test, P value < 0.001) but explained only 31% of the spatial variation of forest understory fires (McFadden's rho-squared). For non-ENSO years, McFadden's rho-squared = 0.195 (chi-square P value < 0.001).

ments (SETTLEMENT), the resulting model ranked highest in explaining the fires of the ENSO validation year (1998; Table 2). The five two-variable models that best explained 1998 fires all included DEGRADATION (Table 2). The most accurate models that did not employ the DEGRADATION variable (which is very difficult to estimate without a time series analysis and extensive field work) were driven by: SIZE and CHARCOAL (ROC = 0.71), and EDGE and CHARCOAL (ROC = 0.71) (Table 2). For non-ENSO years, MAINROAD and EDGE provided the best predictor model for the non-ENSO fires of 2000 (ROC = 0.74), followed by the model of DEGRADATION and ''settlements'' (ROC = 0.72) (Table 2, Fig. 6B). The model that best predicted understory fires in both ENSO and non-ENSO years was the model employing all five variables that contributed significantly to forest fire in the stepwise regression. The ROC of this model was 0.778 and 0.751 for ENSO and non-ENSO respectively (Fig. 6C), indicating that 78% and 75% of the randomly sampled forest fire cells had been assigned a higher than average probability of catching fire (a random selection of cells would give an ROC of 0.5).

DISCUSSION

Undisturbed forests extend like giant firebreaks across the Amazon landscape, restricting the spread of fires that escape beyond their intended boundaries

TABLE 2. Forest understory fire probability models for ENSO and non-ENSO years and their respective ROC (relative operating characteristic) for predicting understory fires observed in 1998 for ENSO years and 2000 for non-ENSO years.

Probability model	B_0	B_1	B_2	P	McFadden's rho-squared	ROC
ENSO						
Pr = B_0 + B_1(DEGRADATION) + B_2(SETTLEMENTS)	−2.298	0.046	−3.110	<0.001	0.21	0.82
Pr = B_0 + B_1(DEGRADATION) + B_2(EDGE)	−1.904	0.047	−95.124	<0.001	0.24	0.81
Pr = B_0 + B_1(DEGRADATION) + B_2(CHARCOAL)	−0.775	0.034	−20.147	<0.001	0.27	0.80
Pr = B_0 + B_1(DEGRADATION) + B_2(SIZE)	−1.601	0.042	−2.344	<0.001	0.25	0.78
Pr = B_0 + B_1(DEGRADATION) + B_2(MAIN ROAD)	−1.337	0.044	−28.187	<0.001	0.27	0.77
Pr = B_0 + B_1(SIZE) + B_2(CHARCOAL)	1.339	−2.250	−23.403	<0.001	0.22	0.71
Pr = B_0 + B_1(EDGE) + B_2(CHARCOAL)	0.960	−43.089	−24.494	<0.001	0.18	0.71
Pr = B_0 + B_1(MAIN ROAD) + B_2(CHARCOAL)	1.349	−20.008	−22.839	<0.001	0.21	0.71
Pr = B_0 + B_1(MAIN ROAD) + B_2(EDGE)	0.259	−25.249	−46.249	<0.001	0.11	0.63
Pr = B_0 + B_1(SIZE) + B_2(EDGE)	0.102	−2.347	−55.529	<0.001	0.11	0.61
Non-ENSO						
Pr = B_0 + B_1(MAIN ROAD) + B_2(EDGE)	−2.971	−26.507	−153.455	<0.001	0.09	0.74
Pr = B_0 + B_1(DEGRADATION) + B_2(SETTLEMENTS)	−4.230	0.009	−9.118	<0.001	0.02	0.72
Pr = B_0 + B_1(SIZE) + B_2(EDGE)	−3.434	−1.690	−151.002	<0.001	0.07	0.71
Pr = B_0 + B_1(EDGE) + B_2(CHARCOAL)	−2.705	−151.66	−18.084	<0.001	0.10	0.71
Pr = B_0 + B_1(SIZE) + B_2(MAIN ROAD)	−3.253	−1.677	−27.498	<0.001	0.07	0.69
Pr = B_0 + B_1(MAIN ROAD) + B_2(CHARCOAL)	−2.548	−25.802	−18.254	<0.001	0.10	0.69
Pr = B_0 + B_1(DEGRADATION) + B_2(EDGE)	−4.000	0.011	−193.187	<0.001	0.07	0.68
Pr = B_0 + B_1(DEGRADATION) + B_2(MAIN ROAD)	−3.669	0.007	33.522	<0.001	0.06	0.68
Pr = B_0 + B_1(SIZE) + B_2(CHARCOAL)	−2.774	−2.183	−19.740	<0.001	0.09	0.65
Pr = B_0 + B_1(DEGRADATION) + B_2(CHARCOAL)	−3.151	0.001	−23.069	<0.001	0.07	0.63

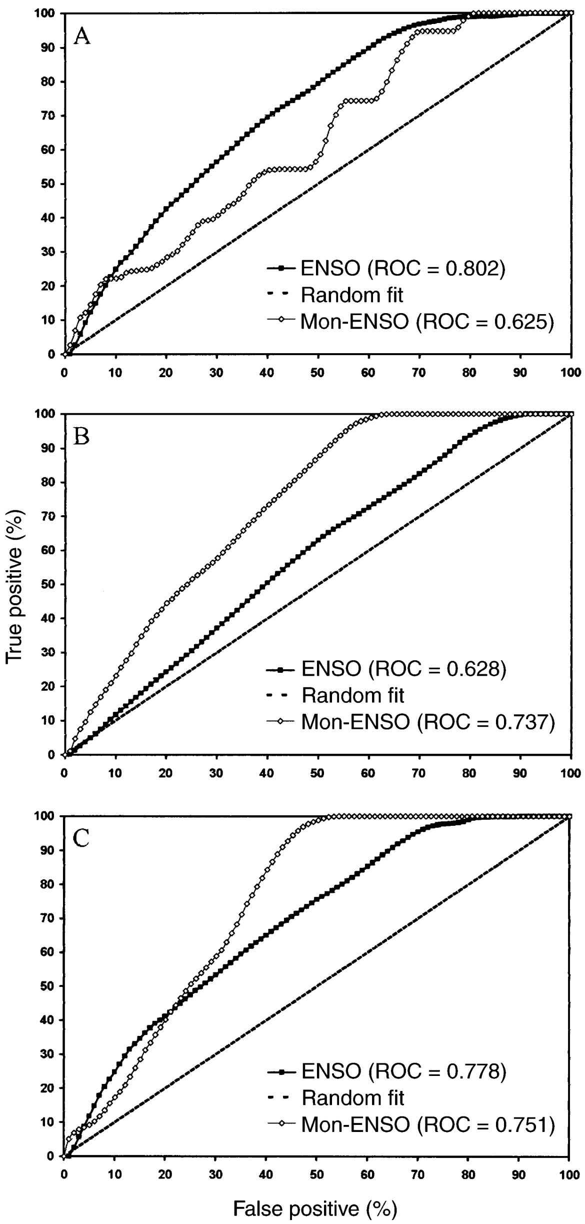

FIG. 6. Curves of relative operating characteristic (ROC) comparing modeled probability of forest understory fire for ENSO and non-ENSO years with maps of observed forest fires for ENSO (1998) and non-ENSO (2000). Each curve represents the cumulative tallies of false and true positives for all of the cells in the modeled area. True positives are cells where the model and observed forest condition (burned vs. unburned) coincide, i.e., where the observed condition coincides with a modeled probability of >0.5. The straight line is the expected ROC for a random distribution of forest fire probability. (A) Probability model using the variables forest degradation and distance to charcoal pits. (B) Probability model using the variables distance to main roads and distance to forest edge. (C) Probability model using the five most important variables identified by the stepwise logistic regression. An ROC value of 1 indicates that there is perfect spatial agreement between the observed understory fires and the probability map.

(Nepstad et al. 1999*a*). Human activities are making large areas of forests more prone to understory fire both through logging and fragmentation that increase forest susceptibility to fire, and through fire use as an agricultural management tool (Cochrane et al. 1999, Nepstad et al. 1999*b*, 2001). Previous studies have focused on attributes of the forest that are associated with forest fire, and have found that Amazon forest fires are associated with forest impoverishment through selective timber harvest (Uhl and Buschbacher 1985, Uhl and Kauffman 1990, Holdsworth and Uhl 1997), with severe drought (Nelson 1994, Nepstad et al. 1999*b*) and with edge effects (Cochrane 2001, Cochrane and Laurance 2002). Once burned, forests are more likely to catch fire again because of the increases in fuel loads and canopy thinning that accompany fire-induced tree mortality (Nepstad et al. 1995, Cochrane et al. 1999, Cochrane and Schulze 1999). We report that the occurrence of forest understory fires is also associated with landscape characteristics such as forest fragment size, distance to sources of ignition such as settlements and charcoal pits, and distance to main roads.

The most robust predictor of forest understory fire during ENSO years was the degree to which forest fragments had previously been disturbed through logging and understory fire. This finding is partially explained by the positive effect of both logging and understory fire on forest flammability. Both disturbances kill and/or remove trees, increasing the amount of solar radiation that penetrates into the forest interior and increasing the amount of fuel on the forest floor (Uhl and Kauffman 1990, Nepstad et al. 1999*a*). These results are consistent with our earlier evidence of a positive feedback cycle between forest understory fire and the likelihood of repeated fire (Nepstad et al. 1995, 2001, Cochrane et al. 1999). Beyond flammability, the occurrence of these disturbances may reflect landscape attributes that we did not test directly in the regression analysis.

Distance to settlements and charcoal pits as ignition sources also correlated strongly with forest understory fires. These autocorrelated variables reflect the high concentration of fire-dependent farm families in agricultural settlements and charcoal production systems. Slash-and-burn cultivation relies on the annual burning of plots of felled forest in preparation for cultivation, and many of these farm families have insufficient labor resources to prevent their fires from escaping into the surrounding forest (Nepstad et al. 1999*a*). Once a forest is ignited, it can burn for weeks and is difficult to extinguish. In addition, forest biomass is burned in charcoal pits, and these fires may occasionally escape into surrounding vegetation, or may release glowing embers that can ignite nearby flammable forests. More importantly, however, we observed some charcoal producers intentionally igniting the forests around their charcoal production systems. We do not know which of these sources of ignition is the most important.

Although distance to government roads was a significant predictor of understory fires, proximity to all roads explained little of the spatial variation, in contrast to findings in other vegetation types (Minnich 1983, 1997, Chou et al. 1993). In the highly fragmented Paragominas landscape, where all forest fragments were within 4 km of the complete road network, other landscape attributes exerted a stronger influence on the forest fire regime. We would expect proximity to roads to play a more important role in younger frontiers.

There are impediments to the application of our forest understory fire probability models in other moist tropical landscapes in Amazonia. The most robust predictor of forest fire (logging and previous fire) is difficult to map using Landsat TM imagery (Stone and Lefebvre 1998); neither logging nor forest fire have been systematically mapped for the entire Amazon Basin (Nepstad et al. 1999*b*). Progress is being made in addressing this remote sensing challenge, however (e.g., Asner et al. 2002). Our model was possible because of six months of fieldwork systematically interviewing the region's landholders.

A second challenge to the expanded application of these models is the representation of ignition sources. Charcoal pit ovens have not been mapped for large areas of Amazonia and it is likely that they become less abundant farther from the charcoal-consuming pig iron industry in southern Pará state and Maranhão (Carvalho 1998). The study site is located ~300 km from this charcoal-consuming region. The co-occurrence of charcoal pit ovens and agricultural settlements in the Paragominas landscape confounded the relative contributions of charcoal production and slash-and-burn agriculture to forest understory fire occurrence. Our models should be tested in Amazon landscape with little charcoal production, to better understand the contribution of agriculture settlements alone to forest understory fire.

Conclusion

This study highlights the importance of examining multiple causes of forest understory fire. Forest fires in the Paragominas region are caused by at least five spatially explicit variables, and their relative effect varies strongly in time associated with ENSO.

As logging, agricultural expansion, and forest fragmentation proceed in Amazon frontiers, fires may affect larger areas of forest, especially during the severe dry seasons associated with ENSO events. The future of forests in these landscapes is a function of two competing processes: the recovery of forest resistance to fire following burning (e.g., Holdsworth and Uhl 1997) and the number of years between ENSO episodes. Under a scenario of increasing ENSO frequency (Trenberth and Hoar 1997), forests may be replaced by fire-prone secondary vegetation in much seasonally dry Amazonia.

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