Forest Understory Fire in the Brazilian Amazon in ENSO and Non-ENSO Years: Area Burned and Committed Carbon Emissions

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ABSTRACT: Understory fires, which burn the floor of standing forests, are one of the most important types of forest impoverishment in the Amazon, especially during the severe droughts of El Niño–Southern Oscillation (ENSO) episodes. However, the authors are aware of no estimates of the areal extent of these fires for the Brazilian Amazon and, hence, of their contribution to Amazon carbon fluxes to the atmosphere. In this paper, the area of forest understory fires for the Brazilian Amazon region is calculated during an El Niño (1998)
and a non–El Niño (1995) year based on forest fire scars mapped with satellite images for three locations in eastern and southern Amazonia, where deforestation is concentrated. The three study sites represented a gradient of both forest types and dry season severity. The burning scar maps were used to determine how the percentage of forest that burned varied with distance from agricultural clearings. These spatial functions were then applied to similar forest/climate combinations outside of the study sites to derive an initial estimate for the Brazilian Amazon. Ninety-one percent of the forest area that burned in the study sites was within the first kilometer of a clearing for the non-ENSO year and within the first four kilometers for the ENSO year. The area of forest burned by understory forest fire during the severe drought (ENSO) year \((3.9 \times 10^6 \text{ ha})\) was 13 times greater than the area burned during the average rainfall year \((0.2 \times 10^6 \text{ ha})\), and twice the area of annual deforestation. Dense forest was, proportionally, the forest type most affected by understory fires during the El Niño year, while understory fires were concentrated in transitional forests during the year of average rainfall. The estimate here of aboveground tree biomass killed by fire ranged from 0.049 to 0.329 Pg during the ENSO and from 0.003 to 0.021 Pg during the non-ENSO year.

**KEYWORDS:** Understory fires; Carbon emissions; ENSO

1. **Introduction**

Amazon deforestation through clear-cutting and burning has become the principal measure of human effects on tropical rain forests. In the Brazilian Amazon, the world’s most intensive satellite-based deforestation monitoring program reveals an annual conversion of 11 000–29 000 km\(^2\) of forest to agriculture each year (INPE 2003). These deforestation rates provide the basis for estimating the substantial carbon emissions associated with Amazon land use (Houghton et al. 2000; Fearnside 1997; Fearnside and Laurance 2004), and for assessing the performance of the Brazilian government in regulating human activities in this region, which contains 40% of the world’s remaining tropical rain forest.

Other forms of forest impoverishment, such as selective logging and understory fires that do not completely remove the forest canopy, are omitted from this deforestation monitoring program (Nepstad et al. 1999a) even though they affect areas that are as large, or larger, than the areas deforested each year. Selective logging impoverishes approximately 10 000 to 15 000 km\(^2\) of forest each year, beyond the scope of deforestation monitoring (Nepstad et al. 1999a). Similarly, understory fires affect a large but poorly quantified area of Amazon forest each year (Nepstad et al. 1999a; Cochrane et al. 1999). During the El Niño–Southern Oscillation (ENSO) event of 1998, 10 000 to 13 000 km\(^2\) of standing forest were burned by understory fire in the northern Amazonian state of Roraima alone (Barbosa and Fearnside 2000; Kirchoff and Escada 1998).

The forest damage associated with both selective logging and understory fire extends beyond their direct effects on tree mortality and canopy openness since they increase the probability of recurrent fire through a positive feedback loop (Nepstad et al. 2001; Alencar et al. 2004). Both of these disturbances increase forest susceptibility to fire by increasing the amount of fuel on the forest floor and creating openings in the forest canopy that allow the forest floor fuel layer to dry
Hence, the spatial pattern of understory fires is closely associated with the pattern of selective logging and previous fire. In addition, fire is associated with landscape features such as distance from clearings, charcoal ovens, and roads (Alencar et al. 2004b). Understory fire is also most likely in forests that are highly flammable because of their low stature, thin canopies (low leaf area index), and extended periods without rain (Ray et al. 2005). Undisturbed Amazon dense and open forests are generally not susceptible to understory fires during years of average rainfall (Uhl and Kauffman 1990), because of their capacity to maintain dense leaf canopies by absorbing soil moisture stored deep in the soil (Nepstad et al. 1994). Even undisturbed "dense" and "open" forests (floresta densa and aberta in Portuguese) can become susceptible to understory fire during the severe droughts associated with the ENSO phenomenon (Nepstad et al. 2001; Nepstad et al. 2004; Jipp et al. 1998), and these episodes are getting more frequent (Trenberth and Hoar 1997). Transitional forest, which is located between the cerrado (savanna of central Brazil) and the closed canopy forests of the Amazon in a region with a severe dry season (Ackerly et al. 1989; Ratter 1992), is more vulnerable to understory fires because of its low height, low leaf area index, and lower dry-season relative humidity (D. Nepstad and J. Balch 2005, unpublished manuscript).

Understory fires provoke a series of costs to society through the emission of carbon and other greenhouse gases to the atmosphere (Nepstad et al. 1999b; Nepstad et al. 2001), in causing damage to faunal populations (Barlow et al. 2002), and in increasing the incidence of smoke-induced respiratory ailments in Amazon (Mendonça et al. 2004). Although some studies have documented the areal extent and carbon emissions associated with particular fire events, such as the Roraima fire of 1998 (Barbosa and Fearnside 1999), we are aware of no published estimates for the Brazilian Amazon frontier region (in eastern and southeastern Amazonia) or for non-ENSO years.

Satellite images have been employed to map areas affected by recent understory fires using the spectral response of the charcoal and ashes left by the fire (Alencar et al. 2004b). Pixel end-member techniques developed to map Amazon forest fire scars detect the high concentration of standing dead trees following fire (Cochrane and Souza 1998). However, the potential of identifying understory fires is diminished by the leaf shedding that is provoked by the fire and by vegetation regrowth, which hide the scar within a year of burning (Nepstad et al. 1999b). We developed a method to estimate the area affected by understory fires in the Brazilian Amazon based on satellite image mapping of forest fire scars for three representative forests and rainfall patterns in eastern and southern Amazonia, where deforestation is concentrated.

2. Methodology

Forest fire scar maps for an average rainfall year (1995) and a year of severe drought (1998) were used to quantify the spatial relationship between understory fire and mature forest boundaries with agricultural clearings for non–El Niño and El Niño years, respectively. Scars were mapped through classification of satellite images and through interviews with local land managers for three areas along the arc of deforestation. These three local spatial functions were then combined with
stratified maps of regional rainfall and vegetation type to estimate the areal extent of understory fires in the Amazon for non–El Niño and El Niño years.

2.1. Study sites

To provide a preliminary appraisal of the range of fire occurrence patterns across different forest types and dry season severities, we selected three subregions in the Legal Amazon that represent different combinations of these variables (Table 1). The study sites were selected to represent a gradient of vegetation types, rainfall regimes, and because they are located in areas of high anthropogenic pressure. The locations selected include a major center of cattle and timber production (Paragominas), an area of giant ranches that are gradually being divided into smaller properties (Santana do Araguaia), and a region with small colonization projects (Alta Floresta; Figure 1). Each of the regions has a seasonal rainfall regime, with a period of at least three months with less than 100 mm of rain per month, and is therefore climatically typical of most of the region’s expanding agricultural frontier; approximately 80% of the deforestation in the Brazilian Amazon has taken place in regions with a pronounced dry season (Nepstad et al. 1994). The predominant forest formations included in this study are dense evergreen forest (Paragominas), open forest with palms and/or bamboo (Alta Floresta), and dry forest in the transition zone from closed-canopy forest to savanna woodland (cerrado) (Santana do Araguaia).

2.2. Mapping understory fire scars

To represent the behavior and the areal extent of understory fires in El Niño and non–El Niño years for various types of vegetation, landscape fragmentation, and rainfall ranges, we mapped all the understory fire scars that happened in a dry season of 1995 and 1998 for Paragominas (northeast of Pará), Alta Floresta (north of Mato Grosso), and Santana do Araguaia (south of Pará). The forest fire scars were mapped through classification of six Landsat satellite images (path and row 222/62, 224/66, and 227/67) from the beginning of the 1996 and 1999 dry season (Figure 2). Landsat images are able to capture recent burning events’ signals due to charcoal and ash accumulation just after the fire having an impact on reducing the near-infrared vegetation signal.

The classification routines were preceded by an extensive field survey from December 1995 to August 1996 in which 202 landowners were interviewed. These landowners had mapped onto printed Landsat scenes the understory fires that occurred on their properties. The total property area included in these surveys was \( \sim 1 \times 10^6 \) ha (Nepstad et al. 1999b). The landowners interviewed were randomly sampled based on official property maps obtained for each region from local

<table>
<thead>
<tr>
<th>Study areas</th>
<th>Region</th>
<th>Forest typology</th>
<th>Rainfall per day (mm day(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paragominas</td>
<td>Northeast of Pará</td>
<td>Dense forest with vines</td>
<td>0.5–1.0</td>
</tr>
<tr>
<td>Santana do Araguaia</td>
<td>South of Pará</td>
<td>Transitional forest</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Alta Floresta</td>
<td>North of Mato Grosso</td>
<td>Open forest</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>
government offices or from the headquarters of the colonization programs. During the field survey, 10% of the understory fire scars cited in the interviews for all the study sites were visited and mapped in loco using GPS, except for Paragominas, where 50% of the fire scars were visited. Of the understory fires reported by the landowners 98% were confirmed during the field visit to their property. Only understory fire scars from Paragominas and Alta Floresta were visited in 1999 and 2000. Santana do Araguaia ENSO understory fire scars were mapped for this period based on visual interpretation of Landsat images.

Half of the field survey burn scar maps were used to train a supervised classification routine using the maximum likelihood algorithm for all the study sites (ENVI 3.2). The accuracy of the classification was assessed using the other part of the dataset from the interviews not used to train the classifier.

2.3. Spatial relationship between understory fire scars and agricultural clearings

In each study site and for each period of analysis (1995, 1998), we found an inverse relationship between the distance from the nearest clearing and the fraction
Figure 2. Understory fire scars maps from (a),(c),(e) 1995 and (b),(d),(f) 1998 representing a non-ENSO and an ENSO year, respectively, for the three study sites along the arc of deforestation ((a),(b) Paragominas; (c),(d) Santana do Araguaia; and (e),(f) Alta Floresta).
of the forest that had burned. We employed the fraction of forest burned in each 1-km buffer around the clearings to delimit the portion of the forest area affected by understory fire in the two climatic scenarios (average rainfall and ENSO years). These spatial relationships were then applied to landscapes with similar forest types and rainfall regimes.

### 2.4. Areal estimate of forest understory fire

The relationships between the percentage of forest burned and the distance to the nearest agricultural clearings derived from the study sites were used to estimate the area affected by understory fires at a regional scale. This estimate assumes that forest areas with the same forest type and similar rainfall regime (dry season severity) as the relevant study site would have the same spatial relationship between the forest understory fire and the distance to agricultural clearings. Based on this assumption, a stratification routine established by deforestation, forest typology, and average daily rainfall maps for the entire Legal Amazon was used to define the representative area for each study site (Figure 5).

The forest type map used in this analysis was from the Instituto Brasileiro de Geografia e Estatística (IBGE 1997), where the dense, open, and transitional forests were delimited and extracted (Figure 3). These three forest types were used to extrapolate results for Paragominas (dense forest), Alta Floresta (open forest), and Santana do Araguaia (transitional forest), respectively (Table 1). Dry season severity was the second map used to help delimit those areas with similar rainfall regimes as the study areas. Dry season severity was represented by ranges of millimeter of rainfall per day that vary from less than 0.5 mm of rainfall per day to more than 3 mm of rainfall per day (Figure 4). This map is based on a 20-yr precipitation dataset for weather stations across the Brazilian Amazon (Nepstad et al. 1994).

The forest areas under risk of fire were delimited based on the 4-km buffers from the forest edge generated from a 1996 deforestation map of the entire Legal Amazon region (available online at http://www.trfic.msu.edu/products/amazon_products/amazonmaps.html; Figure 1). This map was overlaid with the stratified forest typology map and daily rainfall and was used to assign appropriate spatial relationships between the percentage of forest burned and the distance to the nearest agricultural clearings. For example, the percentage of forest burned from 0 to 1 km from agricultural clearings (deforested pixels) in Paragominas (0.2% for a non-ENSO year and 16.6% for an ENSO year; Figure 2) was applied to all areas within 1 km of deforested pixels having the same forest type (dense forest) and dry season severity (0.5–1.0 mm of rain per day) as the Paragominas study site. Those areas within 4 km of deforested pixels that did not match both forest type and dry season severity of one of the study sites were excluded from the analysis. In this regard, our estimate of the areal extent of understory fire is conservative. We excluded 65% of the forest area lying within 4 km of an agricultural clearing because daily rainfall was either too high or the combination of daily rainfall and forest type was not represented by our three study sites. Some of these forest areas certainly burned for the study period, but we do not have a basis upon which to estimate the area of this burning in these high-rainfall regions. The areas for each reference area were tallied to generate the areal estimate of under-
story fires in the Brazilian Amazon for El Niño and non–El Niño years. This estimate does not include the northern dry areas such as Roraima.

2.5. Biomass loss and carbon emission from understory fires

The biomass loss from understory fires was estimated based on the biomass map representing the high of the seven biomass estimates summarized in Houghton (Houghton 2003). This map was derived from the RADAMBRASIL forest volume data measured at over 1500 locations and interpolated using the extent of different forest types (Fearnside and Laurance 2004; Houghton et al. 2000). This interpolated biomass map was overlaid with the stratified map of forest areas under risk of fire. We calculated the mean and standard deviation biomass values across all pixels occurring within each stratified zone (Figure 6). We estimated the 95% confidence intervals of forest biomass for each of the three forest zones of the stratified map using the interpolated biomass values for each of the 1 km × 1 km pixels in each forest zone. Hence, the range of biomass estimate was 222 to 263 [95% confidence interval (CI)] MgC ha⁻¹ for dense forest, 173 to 217 MgC ha⁻¹ (95% CI) in open forest, and the transitional forest was 133 to 237 MgC ha⁻¹ (95% CI).
The biomass values were multiplied by the estimated area burned for ENSO and non-ENSO years. To the total biomass calculated for the burned areas in the two periods (ENSO and non-ENSO) were applied percentages of aboveground biomass mortality reported in the literature (Holdsworth and Uhl 1997; Cochran and Schulze 1999; Barlow et al. 2002), which range from 10%–50% of total aboveground tree biomass killed by understory fire. We assumed that half of tree biomass killed by fire is the carbon that will eventually be released to the atmosphere through decomposition, which we refer to as committed carbon emissions (Fearnside 1997). This estimate is conservative because it excludes large portions of the Amazon (>4 km from clearings and with dry season rainfall >1 mm day⁻¹).

We overestimate committed carbon emissions because we do not account for the forest regrowth that takes place following the burn event.

Summarizing, the total amount of live forest biomass killed by understory fires was estimated using the following equation:

\[ K_{ij} = \alpha_{ij} A B_{ij}, \]

where \( K_{ij} \) represents the amount of biomass killed by understory fires for low \((i)\) and high \((j)\) assumptions; \( A \) is the burned area by forest type for years ENSO and non-ENSO; \( B_{ij} \) is the biomass density by forest type (using two estimates defined

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**Figure 4.** Dry season severity represented by ranges of millimeters of rainfall per day during the driest trimester of the year. This parameter varies from less than 0.5 mm of rainfall per day to more than 3 mm of rainfall per day.
as the extreme values of the 95% CI); and $\alpha$ is aboveground biomass lost after the fire (low 10% and high 50%, $i$ and $j$, respectively).

3. Results

3.1. Effective understory fire scars

An area of 42 000 to 250 000 ha of understory fire scars were mapped for the three study sites in 1996 and 1999 images, respectively, representing non–El Niño (1995) and El Niño (1998) years. These areas accounted for 1.2% and 7.6% of the total forest area of the images surveyed for each period of analysis. However, there were variations among the study sites in terms of the percentage of the forest area affected by an understory fire. For the Paragominas region the area of forest fires mapped varied from 0.2% to 14.7% of the total forest cover area in the region for the years 1995 and 1998. In the Alta Floresta study site the percentage of the forest area burned varied from 0.8% to 4.8%. While for Santana do Araguaia region the range was 1.6% and 7.7% of the forest cover for the two years studied.

The variation in percent forest burned was associated with a gradient of forest...
type and dry season severity. From the three study sites, Paragominas represented the most extreme difference between burned areas by understory fire areas in a non–El Niño year in relation to an El Niño year. This difference highlights the importance of landscape fragmentation in determining large areas of understory fire in dense forest during El Niño years. In other words, areas of dense forest such as Paragominas, which had a 30-yr history of human intervention and was a landscape with a high degree of forest fragmentation (Souza et al. 2003; Alencar et al. 2004b), are highly sensitive to understory fires in El Niño but have low vulnerability in non–El Niño years. However, the opposite is the case in the transitional forest region represented by Santana do Araguaia, which presented high levels of burning in both ENSO and non-ENSO years. Transitional forests may be more flammable in non-ENSO years than dense forests because of lower rainfall and shorter forest stature (Ray et al. 2005).

Fire scars penetrated farther into the forest during the ENSO year, when 91% of the area burned occurred in the first 4 km from agricultural clearings. The maximum distances of penetration into the forests varied between 4 and 5 km for the Paragominas and Alta Floresta areas, up to 14 km for the transitional forest areas of Santana do Araguaia. In contrast, during the 1995 (non-ENSO) year, 91% of the understory fire scars were mapped within the first kilometer from the forest edge,
penetrating a maximum of 5 km into the forest from agricultural clearings, in Santana do Araguaia. A spatial function demonstrated that the major distance of fire penetration inside the forest was 4 km from the forest edges, except for a fire in Santana do Araguaia, which entered 14 km inside the forest (Figure 7).

Since most of the forest areas affected by understory fires were located within the 4 km from the forest edge, a percentage of the forest areas burned was calculated by each kilometer buffer for the three study sites (Table 2).

3.2. Understory fire estimate and carbon emissions in the Amazon

In the 1998 El Niño year, forest understory fire burned $2.6 \times 10^6$ ha (Table 3). This amount does not include the $1.3 \times 10^6$ ha of forest areas burned in Roraima in that year (Barbosa and Fearnside 2000), which would increase the estimate to $3.9 \times 10^6$ ha, 2 times more than the average annual area deforested in the Amazon. During the ENSO year, the dense forest was the most affected by understory fire, representing 58% of the total area burned, followed by the transitional forest with 38% and the open forest with 4% during the El Niño year. For the year 1995 (non–El Niño), the area of forest burned by understory fire was $0.2 \times 10^6$ ha burning mainly the transitional forest (84%).

The amount of live, aboveground biomass killed by understory fires in the non-ENSO year (1995) ranges from a low of 0.003 Pg (assuming the low biomass estimate, and low biomass loss to fire—10% tree mortality) to a high of 0.021 Pg (assuming high biomass and high levels of biomass loss—50% tree mortality). This corresponds to 0.001 to 0.011 Pg of carbon that are committed to eventual emission from the forest through decomposition or combustion during subsequent fires. This range increases more than tenfold from 0.049 to 0.329 Pg for the ENSO year, equivalent to 0.024 to 0.165 Pg of carbon. Actual emissions to the atmosphere of this carbon in any particular year will depend upon the balance between the rate at which fire-killed trees decompose and the regrowth of forest. These committed emissions are comparable to those attributable to forest clear-cutting (approximately 0.2 Pg yr$^{-1}$; Houghton et al. 2000).

4. Discussion

We present a first estimate of the areal extent of forest understory fires in the Brazilian Amazon that combines extensive mapping of forest fire in the field with classification of fire scars in Landsat imagery. The results demonstrate that during the 1998 ENSO episode, understory fires affected an area of forest that is approximately twice the size of the forest area that is clear-cut each year in the region, killing trees that have a similar amount of carbon (0.049–0.329 Pg) to that released each year through deforestation (ca. 0.2 Pg). Although considerable attention has been drawn to the forest fires of Roraima that burned in 1998, located in the northern portion of the Brazilian Amazon (Barbosa and Fearnside 2000), approximately two-thirds of the forests that burned in 1998 are located in the eastern and southeastern portion of the region, primarily in Mato Grosso and Pará states.

During 1995, when rainfall was in a non-ENSO pattern, the total area of understory fire was 14 times smaller than in 1998. The tall, dense forests that dominate much of the core of the Amazon Basin appear to resist fire under the
Figure 7. Function graph on understory burned area × distance to forest edge for three study sites.

Paragominas
\[ y = -0.2433 \ln(x) + 0.4675 \]
\[ R^2 = 0.8263 \]

Santana do Araguaia
\[ y = -0.1552 \ln(x) + 0.3342 \]
\[ R^2 = 0.8961 \]

Alta Floresta
\[ y = -0.1926 \ln(x) + 0.3909 \]
\[ R^2 = 0.9378 \]
relatively moist conditions of non-ENSO years, even if they have been previously logged and/or burned. In contrast, the transition forest appears to become susceptible to fire every year. This finding has two likely explanations. First, the dry season of non-ENSO years is far more severe in transition forests than in dense forest regions. Second, and perhaps owing to drought constraints, transition forests are low in stature and present lower canopy densities (leaf area indices) than dense forests, which are both important determinants of forest flammability (Ray et al. 2005).

Our estimate of the area of understory fires is conservative to the extent that it excluded all those areas of the region that receive more than 1 mm of rainfall per day during the driest trimester of the year, it excluded areas that did not match one of the three combinations of forest type and dry season severity captured in the study sites, and it excluded all forest fires that were farther than 4 km from the nearest agricultural clearing. The estimate assumes that the three study sites, Paragominas, Santana do Araguaia, and Alta Floresta, have fire regimes that are representative of much larger forest areas with the same forest types and rainfall regimes. Our overflight surveys of fire scar conducted at the end of the 1998 dry season (D. Nepstad and P. Moutinho 1998, unpublished manuscript) indicate that the Santana do Araguaia site had a similar incidence of forest fire as neighboring landscapes.

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Northeastern Pará</th>
<th>South of Pará</th>
<th>North of Mato Grosso</th>
</tr>
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<tbody>
<tr>
<td>Precipitation (mm day(^{-1}))</td>
<td>Dense forest</td>
<td>Transition forest</td>
<td>Open forest</td>
</tr>
<tr>
<td>Total forest area from the forest edge (ha)</td>
<td>0.5–1.0</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Buffer at 1 km from the forest edge</td>
<td>36 464</td>
<td>30 780</td>
<td>12 323</td>
</tr>
<tr>
<td>Buffer at 2 km from the forest edge</td>
<td>25 287</td>
<td>27 585</td>
<td>7 822</td>
</tr>
<tr>
<td>Buffer at 3 km from the forest edge</td>
<td>20 222</td>
<td>29 887</td>
<td>6 128</td>
</tr>
<tr>
<td>Buffer at 4 km from the forest edge</td>
<td>12 495</td>
<td>22 752</td>
<td>3 811</td>
</tr>
<tr>
<td>Total area burned in 1995 (%)</td>
<td>0.2%</td>
<td>3.7%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Buffer at 1 km from the forest edge</td>
<td>0.0%</td>
<td>0.9%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Buffer at 2 km from the forest edge</td>
<td>0.0%</td>
<td>0.4%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Buffer at 3 km from the forest edge</td>
<td>0.0%</td>
<td>0.1%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Total area burned in 1998 (%)</td>
<td>16.6%</td>
<td>12.7%</td>
<td>8.6%</td>
</tr>
<tr>
<td>Buffer at 1 km from the forest edge</td>
<td>26.6%</td>
<td>7.4%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Buffer at 2 km from the forest edge</td>
<td>11.7%</td>
<td>7.4%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Buffer at 4 km from the forest edge</td>
<td>0.6%</td>
<td>7.3%</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Table 3. Estimates of area affected by understory fires, biomass mortality for dense, open, and transitional forest during an El Niño and a non-El Niño year.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Dense forest</td>
<td>0.15</td>
<td>0.99</td>
</tr>
<tr>
<td>Open forest</td>
<td>0.02</td>
<td>0.11</td>
</tr>
<tr>
<td>Transition forest</td>
<td>0.01</td>
<td>1.52</td>
</tr>
<tr>
<td>Total</td>
<td>0.2</td>
<td>2.6</td>
</tr>
</tbody>
</table>
The scaling-up assumption of understory fire extent only considers two factors: forest structure and drought conditions. There are other factors, such as past forest disturbances, which contribute to determining understory fire extent (Alencar et al. 2004a,b). However, we do not take these into consideration in this study because of the difficulty of mapping historical events of understory fires and logging for a large area. In addition, the broad scale of the vegetation typology and drought maps does not take into account the small patches of different forest types within the 4-km forest areas under analysis that underestimates the understory fire extent.

The important goal of monitoring the basinwide occurrence of understory fires in the Amazon will depend upon new satellite techniques, some of which are under development. A new classification technique that employs estimates of canopy gap fraction using Landsat imagery has been developed that detects understory fire scars that are up to three years old (A. Alencar and X. Asner 2005, unpublished manuscript).

Understory fire represents one of the most important threats to the biological integrity of Amazon forests. Frontier expansion into the Amazon forest is causing fragmentation and canopy thinning (through logging) of dense forests that have a high risk of burning during dry years. Both ENSO- and deforestation-driven inhibition of rainfall (Silva Dias et al. 2002) are therefore associated with extensive damages to standing forests that are currently beyond the scope of forest monitoring programs. Transitional forests, located between the core Amazon region and the savannas of central Brazil, emerge as one of the most threatened ecosystems in the Amazon Basin, both because of their vulnerability to fire and because of the explosive expansion of mechanized agriculture and cattle ranching onto the flat, well-drained landscapes that are occupied by this forest (Alencar et al. 2004b). The remaining forest areas along the rapidly expanding agricultural frontier tend to be more fragmented and disturbed by logging activities and recurrent understory fires. Simultaneously, over the past decades, there has been a tendency toward more extreme and frequent El Niño events. The confluence of more degraded forests with more extreme climate events indicates that forest understory fires are likely to play an even more important role in the future of Amazonian forests.

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