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Forest fires in southwestern Brazilian Amazonia: Estimates of area and potential carbon emissions

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Abstract.

Areas affected by forest fires that occurred in 2005 were mapped in the municipalities of Boca do Acre and Lábrea (in the southern part of Brazil's state of Amazonas) and estimates were made of the loss of biomass and carbon stock and the committed emissions from increased tree mortality due to fire. Fire scars observed on Landsat-5 TM satellite images from 2004 to 2006 were visually interpreted and digitized; over 865.6 km² of forest affected by fire were mapped, the majority (2.9% of the total forest cover) concentrated along the southern edges of the municipalities, which border on the states of Rondônia and Acre. The greatest loss of biomass due to the increase in tree mortality was indicated by the survey made four years after the fires: 4.5×10^6 Mg total (above + below-ground) and 3.7×10^6 Mg (only above-ground). Consequently, 2.2×10^6 Mg C (total) and 1.8×10^6 Mg C (above-ground) of potential carbon emissions were committed from the initial burn of forest biomass and from trees killed by the fire. Emissions occur both through oxidation of dead biomass by decomposition or through combustion in subsequent fire events. Our results indicate that fires can affect extensive tracts of forest and can emit significant amounts of carbon to the atmosphere in periods of drought. Fire plays a significant role as a threat to the biological balance of the forest and causes loss of biomass and emission of greenhouse gases that have critical implications for the future of forests in the Amazon.

Keywords: Amazon forest; Brazil; carbon emission; greenhouse gases; global warming; satellite imagery; understory fires

1. Introduction

On a global scale, fire is one of the most important agents of disturbance in terrestrial ecosystems and is widely used by humans in transforming the forest, especially in tropical and subtropical ecosystems (van der Werf et al., 2010). Although fire without an anthropogenic source of ignition continues to be rare in tropical forests, the spread of roads, ranches and settlements provides human ignition sources to ever-wider areas of forest. Currently in years with pronounced droughts these ecosystems are already considered to be seasonally flammable (Malhi et al., 2008). Various studies demonstrate that fires in tropical forests have occurred with greater frequency in recent decades (Cochrane and Schulze, 1999; Nepstad et al., 1999; Barbosa and Fearnside, 1999; Barlow et al., 2002; Alencar et al., 2004, 2006; Brown et al., 2006; Vasconcelos and Brown, 2007).

Forest fires represent an emission source of greenhouse gases and aerosol particles (Fearnside, 2003). Increased concentrations of these components have been reported in connection with fire events in Amazonia (Longo et al., 2009). In the “great Roraima fire” during the drought prompted by the El Niño of 1997-1998 between 11.4 and 13.9 × 10^3 km^2 of primary forests were burned accidentally (Barbosa and Fearnside, 1999). In terms of carbon, committed emissions from this primary forest area totaled 31.3 × 10^6 Mg C (Barbosa and Fearnside, 1999). This was one of the largest forest fires to date in Amazonia (Laurance and Fearnside, 1999).

In Amazonia, periods of lower precipitation co-occur with peaks of fire activity (Aragão et al., 2008). Moreover, anomalous climatic conditions, such as warming of sea-surface temperatures (SSTs) in the tropical eastern Pacific (El Niño) and warming of SSTs in the tropical North Atlantic (the Atlantic dipole), can exacerbate the severity of the dry season (Cox et al., 2008; Marengo et al., 2008, 2011), providing favorable conditions for large-scale fire events (Schroeder et al., 2005). In 2005, anomalously high SSTs in the tropical North Atlantic resulted in a severe drought that had its epicenter in southwestern Amazonia (Aragão et al., 2007), with an impact on biomass carbon totaling 1.2 – 1.6 Pg (1 Pg = 1× 10^{15}g); this indicates that Amazonian forests are vulnerable to increases in water stress, with potential for great losses of carbon and for initiating a positive feedback between dieback and climatic alterations (Phillips et al., 2009). Drought events of this magnitude, in addition to increasing the susceptibility of the forest, increase the impact of forest fires. This occurred in 2005 in the MAP area (the trinational area encompassing Madre of Dios [Peru], Acre [Brazil] and Pando [Bolivia]), a region where more than 360,000 ha of standing forests were affected by accidental fire during that Atlantic-dipole event (Brown et al., 2006).

Logging activities also increase the susceptibility of the forests to fire (Uhl and Kauffman, 1990; Holdsworth and Uhl, 1997; Cochrane, 2003). The severity of fire in logged forests can be substantially aggravated by large amounts of available combustible material left on the ground in the forest due to the cutting operations, while damage to the tree crowns provides openings in the canopy that allow light and wind to enter the understory, speeding up the drying of the slash (Cochrane, 2003; Cochrane and Laurance, 2008). This makes forest highly vulnerable to droughts and fires (Asner et al., 2006), these being the major factors responsible for the degradation and impoverishment of the forest over the long term (Nepstad et al., 2001).

For estimates of carbon emissions it is essential to know the extent of the area affected by the fire. Satellite imagery can be used to map the areas burned based on the spectral response of the charcoal and leached ashes left by the fire and also to map the scars left from alterations in the structure and abundance of the vegetation (Cochrane and Souza, 1998; Lu et al., 2003; Souza et al., 2003, 2005; Alencar et al., 2006; DeFries, et al., 2008; Goetz et al., 2009; Shimabukuro et al., 2009; Morton et al., 2011). Forest-fire mapping by means of orbital data with medium or high resolution is a key step in understanding the evolution forest fires and their impact on biomass carbon in extensive areas in Amazonia. This is critical, given the frequency with which major forest fires have been occurring in this region in recent decades.

The objectives in this study are: (i) to map the areas affected by forest fires that occurred in 2005 in Boca do Acre and Lábrea (in the southern portion of the state of Amazonas), and (ii) estimate the loss of biomass and the carbon stock committed to be emitted from the increase in tree mortality due to these fires.

2. Materials and Methods

2.1. Study area

The study area encompasses the municipalities of Boca do Acre and Lábrea, totaling 90,187 km² (Brazil, IBGE, 2011) in the southern part of the state of Amazonas (Fig. 1). These municipalities are now part of the "arc of deforestation," a crescent-shaped strip along the southern and eastern edges of Brazil's Amazon forest where there has been intense human pressure in recent decades. During the drought of 2005, forest areas located to the southern portions of these municipalities were strongly affected by fires from uncontrolled burning.

[Fig. 1 here]

The predominant forest formations in the study area are: open ombrophilous sub-montane forest dominated by bamboo, open ombrophilous sub-montane forest, dense ombrophilous sub-montane forest, dense lowland ombrophilous forest, open lowland ombrophilous forest and dense alluvial ombrophilous forest (Brazil, Projeto RadamBrasil, 1983). The climate is classified as Am (Köppen), with annual rainfall between 2000 and 2400 mm and with four to five consecutive months with less than 100 mm of precipitation (Sombroek, 2001). The average annual temperature is 25.4° C. Predominant soils are red-yellow Ultisol, red-yellow Argisol and Inceptisol (Brazil, IBGE, 2001).

2.2. Mapping of forest fire scars

In order to map the areas of forests affected by the fire in 2005 we used a total of 24 Landsat-5 TM scenes, with eight scenes from each of the years 2004, 2005, and 2006 (Table 1). The images were obtained from the website of the National Institute for Space Research (INPE) (http://www.dgi.inpe.br/CDSR/).

[Table 1 here]

The scenes were acquired for the period between May and November, when there is a minimum of cloud cover. The scenes from 2004 and 2006 were used to avoid any inclusion in the mapping for 2005 of areas that had been affected by fires in the previous year or in the succeeding year. The spectral bands used were: red (channel 3), near-infrared (channel 4) and mid-infrared (channel 5). All of the scenes were geo-referenced based on Geocover 2000 images (http://zulu.ssc.nasa.gov/mrsid/), with a maximum RMS error (Root Mean Square error) of 0.5. Pre-processing operations (geo-referencing of the images, formation of R(5)-G(4)-B(3) color composites, contrast stretching enhancement and mosaicking) were performed in ENVI software. Visual analysis and vectorial editing were done in ArcGIS software at a fixed scale of 1:20,000.

Forest fires can be detected on satellite imagery based on the scars left in the forest cover. In general, the forest areas affected by fire make a greater contribution to the spectral response of the non-photosynthetic material (dry twigs and stems) as a result of the death of some trees, the loss of leaves from the canopy, the energy reflected by the exposed soil and the charcoal deposited on the forest floor. These scars are often easier to observe in images acquired in the year following the fire (Graça, 2006). In order to insure that the fire scars mapped were the result of fires that occurred in 2005, we determined that there had been no forest fires in 2006 in the study area based on the statements of farmers and ranchers during our field visits in 2009 in Boca do Acre, Lábrea and in several municipalities in eastern Acre.

In order to quantify the areas affected by forest fires, all fire scars were mapped in the different forest types by means of visual interpretation of satellite images in R(5)-G(4)-B(3) color composites, digitizing the areas affected by fire on the image displayed on a computer screen and storing the information in the form of polygons in a spatial data base (Geographical Information System - GIS).

Areas were delimited on the 2006 images, which had more visible fire scars than the 2005 images. Vectorization of the polygons of the fire scars was performed, analyzing each area in all three years (Fig. 2). After vectorization, the area of each polygon was calculated in each forest type.

[Fig. 2 here]

The mapping was preceded by fieldwork in 2009 when the rural properties in Boca do Acre and Lábrea with forest-fire occurrence in 2005 were visited. During these visits the ranchers were asked the dimension of the burned area and whether there had been a recurrence of fire in the properties during the same year (2005). In all of these areas geo-referenced points were collected with a navigation global positioning system (GPS) to serve as a record of fire occurrence in 2005 and reference images for 2006. Along the BR-317 (Rio Branco – Boca do Acre) Highway some areas of forests affected by the fire were also identified and points of fire occurrence were geo-referenced.

2.3. Evaluation and Accuracy of the mapping

Due to the magnitude of the study area, a 15 km × 26 km (390 km²) sub-area was delimited for evaluation in scene 001/67, where the areas of forests affected by fire and unbroken forest were classified. In this sub-area 300 check points were geo-referenced: 91 points in areas of forests affected by fire, 48 points in randomly distributed areas of intact forest and 161 points in deforested areas. Evaluation of the mapping was carried out by observing the agreement between the points generated in the field (ground truth) and the areas classified as "forest affected by fire," as "intact forest," and as "deforested area," in order to produce an error matrix as proposed by Congalton and Green (1999) (Table 2). The mapping had an overall accuracy of 96%, and the conditional Kappa coefficient of the producer for the class (K_{j+}) of the area of forest affected by fire had a value of 0.82.

[Table 2 here]

2.4. Structure of the forest affected by fire

We used data obtained in 15 permanent 0.2-ha plots, of which 10 plots were affected by fire and five were not affected. The plots are situated in the Community Forest Management Project of Embrapa-Acre in the municipalities of Senator Giomard and Acrelândia, in the state of Acre (Fig. 1). They are located 5 to 11 km from the southern edges of the municipalities of Lábrea and Boca do Acre, in the state of Amazonas. All live trees with DBH ≥ 10 cm (diameter at breast height: 1.30 m above the ground or above of any deformities) were inspected and recorded before the fire occurred in 2005 (1996, 1997, 1998, 1999 and 2001), one year after the fire (2006) and 4 years after the fire (2009).

The dry above-ground biomass for each tree with DBH ≥ 10 cm in the permanent plots before and after the fire was estimated using the equations of Nogueira et al. (2008a). Since the equation by Nogueira et al. (2008a) was developed in primary forest, an overestimate could occur in the surveys carried out after 2005 in the plots that were affected by fire. This would result from an expected increase in the abundance of fast-growing species with lower wood density. However, since in the present study the post-burn effect was only evaluated in trees with DBH ≥ 10 cm, we would expect that no bias in the biomass estimates due to changes in the species composition would be perceptible by 2009, and that there would be no substantial impact on the total biomass estimate because any effects would be restricted to the smallest diameter classes.

The estimates of dry above-ground and total (above- and below-ground) biomass by Nogueira et al. (2008a) were used for the different phyto-physionomies in the region under study. The exception was the biomass of the open forest dominated by bamboo (*Guadua* sp.), which was obtained from the estimates of Nogueira et al. (2008b) for trees with DBH ≥ 5 cm. Additions were made for the remaining components of the above-ground live biomass (trees and palms with DBH < 5 cm (5.5 Mg ha^{-1}), bamboo (6.9 Mg ha^{-1}) and lianas (5.8 Mg ha^{-1}): based on diameter measurements from inventories in Acre by de Oliveira **(**2000) and allometric equations by Gehring et al., 2004 for lianas and Nelson et al., 1990 for bamboo) and necromass (38.2 Mg ha^{-1}: this addition was based on Nogueira et al., 2008a; Table 1). This estimate allows inclusion of the effect of bamboo on the structure of the forest; this decreases the biomass stock of the vegetation due to lower height and lighter wood density of trees and palms (Nogueira et al., 2008b).

2.5. Data analysis

2.5.1. Calculation of the stock of live biomass affected by fire and of carbon emissions

The stocks of live biomass in the mapped areas of forests affected by fire were obtained by multiplying areas affected in each type of forest by the mean live biomass (total and above-ground) corresponding to what existed before the fire. The estimated loss of live biomass per hectare in the areas of forests affected by fire one and four years after burning were obtained from the 10 plots affected by fire by applying the proportion of committed absolute loss of dry biomass since 2001 due to the increase in the mortality of trees with DBH ≥ 10 cm. Since all 10 plots were in dense submontane ombrophilous forest, we assume that the proportions of trees killed in the other forest types are the same. We do not believe that this poses a significant limitation, since the only forest types with differences expected to be relevant represent only a small part of the area affected by fire: open submontane ombrophilous forest dominated by bamboos (which has more flammable material) represents 5.4% and dense alluvial forest (which has a different topography) represents 1.8% (Table 3). The committed absolute loss of dry biomass refers to the difference between the stock of live biomass (without considering necromass) before the fire and the stock of live biomass after the fire, calculated in the second measurement.

[Table 3 here]

The amount of biomass (total and above-ground) killed by forest fires was represented by the equation (Alencar et al., 2006):

$K = \alpha AB$,

where: "K" is the amount of biomass killed by the fire (Mg ha^{-1}); "A" is the area affected by the fire for each type of forest (ha); "B" is the biomass density for each type of forest (Mg ha^{-1}); "α" is proportion of the biomass lost after the fire. To estimate the carbon stocks in the forest, both affected by fire and not affected by fire, we used the relation determined in forests near Manaus by da Silva (2007) where one ton of dry biomass contains 0.485 tons of C.

The burning efficiency of forest biomass was not considered in the current study because estimates of efficiency require calculating the loss of biomass for each tree using measurements of the diameter of the trees before and after the fire event. Studies of this type are more common in areas burned after felling for agriculture and ranching (Kauffman et al., 1995; Fearnside et al., 1999, Graça et al., 1999, Righi et al., 2009).

2.5.2. Disentangling the effects of drought and fires

The lack of forest inventory data in the experimental plots for 2004 (one year before the drought and fire) and for the year 2005 makes it difficult to isolate the effect on mortality caused by the fire from the effect of the 2005 drought. However, to separate these effects on the forest we used the absolute mean values of stems and dry above-ground biomass in each plot for the years 2001, 2006 and 2009. A paired Student's *t* test was applied to assess the differences between mean numbers of stems and mean biomasses in the plots affected by fire ($n = 10$) and in the plots not affected by fire ($n = 5$).

3. Results

3.1. Mapping forests affected by fires

The total area of forests affected by fire in 2005 in Boca do Acre and Lábrea was 865.6 km², corresponding to 2.9% of the forest cover of these municipalities in 2009 (Table 3). These municipalities had the greatest areas of cumulative deforestation of the 62 municipalities in the state of Amazonas, contributing 14.7% of the total detected up to 2009 by the Project for Monitoring Deforestation in Amazonia (PRODES) of Brazil's National Institute for Space Research (Brazil, INPE, 2010). In Boca do Acre 440.2 km² (2.2% of the forest cover) and in Lábrea 425.4 km² (0.7% of the forest cover) of forests affected by fires were mapped.

The types of forest most affected by fire were: dense ombrophilous submontane forest (41.3% or 357.5 km²), open ombrophilous submontane forest (242.8 km² or 28%) and open lowland ombrophilous forest (179.6 km² or 20.7%). More than 54% of the forest area affected by fire was in open forests.

The majority of the area of forest affected by fire was concentrated on the southern edges of the municipalities, which is the region that is subject to the greatest human pressure due to the expansion of cattle ranching from the neighboring states of Acre and Rondônia. Most of the forest affected by fires is adjacent to pastures and to roads, indicating that the sources of ignition for the fires may have been derived from these areas (Fig. 3).

[Fig. 3 here]

3.2. Changes in stem density

In the plots affected by fire the density of live trees with DBH ≥ 10 cm was 237 ± 8.1 (mean ± S.E.) stems ha^{-1} in 2001, declining to 210 ± 11.7 stems ha^{-1} one year after the fire (2006) and increasing to 291 ± 14.8 stems ha^{-1} four years after the fire (2009). The density of trees presumed to be dead (individuals no longer present as live trees) was 51 ± 7 stems ha^{-1} was one year after fire (Table 4). This corresponds to a five-year period (2001-2006), and therefore represents an average loss of 51/5=10.2 stems ha^{-1} yr^{-1}, although mortality was undoubtedly much higher than this average in the last year of the period (when the fire occurred). Even the 10.2 stems ha^{-1} yr^{-1} average value is much higher than the pre-burn level: for the 1999-2001 period 10 ± 0.5 stems ha^{-1} died (Table 4), or only 10/5=2 stems ha^{-1} yr^{-1}. In the 2006-2009 period, 28 ± 0.5 stems ha^{-1} died (Table 4) or 28/3=9.3 stems ha^{-1} yr^{-1}. The 2006-2009 time period had much more mortality of large-diameter trees (Table 4).

[Table 4 here]

In the plots affected by fire, one year after the fire event the density of trees killed was greater in the smaller diameter classes (10-19.9 cm, 20-29.9 cm and 30-39.9 cm, corresponding to 83% of the total). Four years after the fire the density of dead trees per hectare in these diameter classes increased to 89% of the individuals. In the plots not affected by fire, the density of live trees was 180 ± 18.6 (mean ± S.E.) stems ha^{-1} in 2001, declining to 163 ± 19.1 stems ha^{-1} one year after the drought and increasing to 175 ± 14.6 stems ha^{-1} four years later (Table 5).

[Table 5 here]

In the plots affected by fire, the mean densities of stems were significantly different one and four years after the fire (paired t test, n = 10; t = 3.655, p = 0.005; 2001-2006 and t = -4.576, p = 0.001; 2001-2009), this possibly being related to the substantial increase observed in pioneer species such as C*ecropia* sp. in the smaller diameter classes (10 – 19.9 cm and 20 – 29.9 cm). In the plots not affected by fire, even with the effect of the slight increase in the mortality of the trees in 2006 due to the drought in 2005, the number of stems per hectare did not show significant differences (paired t test, n = 5) one year after the drought (t = 1.327, p = 0.255; 2001-2006) and four years after the drought (t = 0.270, p = 0.800; 2001-2009).

3.3. Loss of biomass and potential carbon emissions at the plot level

Dry biomass of the live trees in 2001, represented 210.3 ± 13.8 Mg ha^{-1} (mean ± S.E.), 199.1 ± 17 Mg ha^{-1} in 2006 and 180 ± 6.8 Mg ha^{-1} in 2009 (Table 4). Dry biomass of trees presumed dead was 26.9±6.2 Mg ha^{-1} one year after the fire and 45.1±5.4 Mg ha^{-1} four years after the fire.

The committed absolute loss of biomass caused by the increased mortality of trees due to the forest fires that occurred in 2005 was 11.2 Mg ha^{-1} (5.3%) one year after the fire and 30.3 Mg ha^{-1}(14.4%) four years after the fire. The difference between the loss of dead biomass (36.6 Mg ha^{-1}) and the committed absolute loss of biomass since 2001 (30.3 Mg ha^{-1}) four years after the fire could be related to the effect of recruitment in the smaller diameter classes (an increase of approximately 112% in the number of individuals per hectare in the 10-19.9 cm DBH class: Table 4).

One year after the fire the smaller diameter classes (10-19.9 cm, 20-29.9 cm and 30-39.9 cm) contained most of the presumed-dead biomass: 17.2 Mg ha^{-1} (64%). However, four years after the fire, despite the percentage of dead individuals being high (89%), the dead biomass was only 10.6 Mg ha^{-1} or 24% of the total. The greatest amount of dead biomass was observed in the larger diameter classes, indicating that four years after the fire mortality had increase in trees with DBH ≥ 40 cm, which represented 34.5 Mg ha^{-1} or 76% of the total dead biomass in 2009.

In the plots not affected by fire, dry biomass in live trees was 149.5 ± 26.7 Mg ha^{-1} (mean ± S.E.) before the drought, 147.2 ± 24.1 Mg ha^{-1} one year after the drought and 150 ± 18.1.1 Mg ha^{-1} four years after the drought (Table 5). The density of dead trees one year after the drought was 28 ± 9.3 stems ha^{-1}, falling to 15 ± 8.8 stems ha^{-1} four years later; the dry biomass estimates of dead trees at one and four years were 18.1 ± 10 Mg ha^{-1} and 9.7 ± 6.8 Mg ha^{-1}, respectively.

The committed absolute loss of biomass due to the increase in mortality of trees due to the drought of 2005 was only observed in the measurements in 2006 (2.3 Mg ha^{-1}). However, four years after the drought, the forest showed a gain in biomass of 0.6 Mg ha^{-1}.

3.4. Effect of the fire and of drought on biomass

In the plots affected by fire, even though the averages of live biomass one and four years after the fire (mean ± S.E.: 199.1 ± 17 Mg ha^{-1} and 180 ± 6.8 Mg ha^{-1}, respectively) declined when compared with the live biomass before the fire (210 ± 13.8 Mg ha^{-1}), the difference was not significant (paired t, n = 10; $t = 1.758$, $p = 0.113$) one year after the fire (2001-2006) but was significant four years after the fire ($t = 2.607$, $p = 0.028$; 2001-2009) (Table 6). These results could be associated with the increase in mortality of trees in the larger diameter classes four years after the fire.

[Table 6 here]

In the plots not affected by fire, even with the effect of the slight increase in the mortality of the trees in 2006 due to the drought in 2005, the mean biomass per hectare did not show significant differences (paired t test, n = 5) one year after the drought ($t = 0.229$; $p = 0.830$; 2001-2006) and four years after the drought ($t = 0.050$, $p = 0.962$; 2001-2009).

3.5. Loss of biomass and potential carbon emissions at the regional level

The estimates of live biomass lost per hectare in the mapped areas of forest affected by fire were 30.9 × 10^6 Mg for total (above + below-ground) live biomass and 25.7 × 10^6 Mg for above-ground live biomass (Table 7). The committed absolute losses of live biomass one year after the fire were 1.6 × 10^6 Mg (total) and 1.4 × 10^6 Mg (above-ground), respectively. Four years after the fire the losses had increased by amounts almost double the amount observed in 2006: 4.5 × 10^6 Mg (total) and 3.7 × 10^6 Mg (above-ground). In carbon terms, one year after the fire the amounts of potentially committed emissions were 0.8 × 10^6 Mg C (total) and 0.7 × 10^6 Mg C (above-ground), and four years after the fire they were 2.2 × 10^6 Mg C (total) and 1.8 × 10^6 Mg C (above-ground). The emissions can occur by means of the initial burning, from decomposition, or from combustion in subsequent fire events.

[Table 7 here]

Similar to the areas of fire scars mapped by forest type, dense ombrophilous submontane, open ombrophilous submontane and open lowland ombrophilous forests had the largest values for total and above-ground biomass stock before the fire (13.8×10^6 Mg and 11.4×10^6 Mg, 8.2×10^6 Mg and 6.8×10^6 Mg, and 6.5×10^6 Mg and 5.4×10^6 Mg, respectively). This represents more than 92% of the total biomass of the 865.6 km² of forests affected by the fire.

4. Discussion

4.1. Extent of forest fires in southern Amazonas

Our results supply estimates of the extent of forests affected by fires in the southern portion of the state of Amazonas during the drought of 2005, in addition to improving understanding of the consequences of fire on Amazonian tropical forest dynamics and the effect of forest fires on carbon emissions from this region. During the severe drought in 2005, which was attributed to the anomalous warming of sea-surface temperatures in the tropical North Atlantic, the area of forest affected by the fire (865.6 km²) was about 10% greater that the area deforested in the entire state in the same year (788 km², PRODES) and equivalent to 6% the area deforested in all of Brazilian Amazonia in 2005 (14,109 km²).

In the state of Amazonas the forest fires were concentrated in areas along the BR-317 and BR-364 Highways and the agricultural settlements on the southern and southwestern edges of the municipalities of Boca do Acre and Lábrea. Areas of forests affected by the fire were mapped in the Apurinã, Jamamadi and Jaminawa indigenous lands and in the Arapixi extractive reserve. Roads and settlements adjacent to the forest areas that are supposedly protected provide ignition sources that have a high probability of escaping control and entering the forest (Fearnside, 2003). Forest fires, together with logging, are the main factors responsible for forest degradation and consequent impoverishment (Nepstad et al., 2001). In addition, these forests become highly vulnerable to droughts and future fires (Asner et al., 2006).

Studies by Brown et al. (2006) demonstrated that, in 2005, hundreds of squared kilometers of standing forests were accidentally burned in the MAP trinational border of region; more than 2500 km² in eastern Acre (Brazil), about 1000 km² in Pando (Bolivia) and approximately 100 km² in Madre de Dios (Peru). Estimates by Shimabukuro et al. (2009) indicate that ~2800 km² of standing forest were burned in the state of Acre during the drought of 2005. Alencar et al. (2006) showed that in a year with a major El Niño drought (1998) the estimated area of the forest fire was an order of magnitude larger (2.6×10^6 ha) than in a year without El Niño (1995) (0.2×10^6 ha). Barbosa and Fearnside (1999) estimated 1.1×10^6 ha of forest burned in Roraima during the El Niño of 1998. Modeling studies of fire in the forest understory by Alencar et al. (2004) indicate that 91% of the forest area that burned during a sequence of 10 years caught fire during the El Niño years, when severe drought increased the flammability of the forest, allowing fire from agricultural areas to escape into the forest. However, the strongest predictor of forest fires was the percentage of each forest fragment that had been previously logged or burned.

4.2. Increase in mortality of trees, loss of biomass and carbon emission

Fires of the magnitude of those that occurred in southern Amazonas in 2005 cause a significant increase in the mortality of trees in the smaller diameter classes one year after the fire and increase the loss of total and above-ground biomass four years later. This pattern of mortality in the first year after the fire was similar to that found in previous studies elsewhere in Amazonia (Holdsworth and Uhl, 1997; Cochrane and Schulze, 1999; Barlow et al., 2002; 2003; Barlow and Peres, 2008). This behavior was observed both in the plots affected by fire and in those not affected by fire (effect of drought alone), with a greater decline in live biomass in the burned plots (5.3%) than in the unburned plots (1.6%). However, four years after the fire, in spite of the mortality of stems having declined less (10%), the live biomass declined by 14.4% in the burned plots. This occurred due to the increase in the mortality of trees in the larger diameter classes (DBH ≥ 40 cm). Similar dynamics were observed in the studies by Barlow et al. (2003) in the area near the Arapiuns and Tapajós Rivers in the state of Pará, eastern Amazonia. In our study the unburned plots four years after the drought had an average gain in live biomass of 0.4%.

The percentage of committed absolute loss of total and above-ground biomass four years after the fire was 14.4% (4.5×10^6 Mg and 3.7×10^6 Mg), this being more than twice the value found one year after the fire. The carbon stocks estimated for potentially committed emissions from the initial burning, from decomposition of the dead wood (including the activity of termites) and during the process of combustion in recurrent fire events in these forests were 0.8 and 2.2×10^6 Mg C (total) one year and four years after the fire, respectively. The above-ground portions of the carbon stocks that represent committed emissions were 0.7 and 1.8×10^6 Mg C one and four years after the fire, respectively. Alencar et al. (2006), using assumed values for low (10%) and high (50%) percentages of loss of aerial biomass in areas of burned forests, calculated that the amount of biomass killed by forest fires in the Brazilian Legal Amazon would be between 49 and 329×10^6 Mg in an El Niño year (1998) and between 3 and 21×10^6 Mg during in a year without El Niño (1995). In carbon terms, this corresponds to between 24 and 165×10^6 Mg for El Niño years and between 1 and 11×10^6 Mg for years without El Niño.

The estimate of the loss of total carbon stock in Boca do Acre and Lábrea ($0.8 + 2.2 = 3 \times 10^6$ Mg C) would be equivalent 0.87% of the Brazilian emissions in 2005 attributed to land-use change and forestry (342.9×10^6 Mg C) reported in the Second National Communication to the United Nations Framework Convention on Climate Change (UN-FCCC) (Brazil, MCT, 2010).

The estimates of biomass and carbon stock reported in this study are for areas of forests without logging and evidence of previous disturbance. However, fragmented landscapes with a history of human interventions over a period of years are highly susceptible to recurrent fire events, mainly in drought years (Alencar et al., 2006). This suggests that the percentage of the forest area that is affected by fire in previously disturbed landscapes could be substantially greater than those found in this study. Nepstad et al. (2001) warn that disturbance to the forest associated with fires in the understory and disturbance from selective logging extend beyond their direct effect on the mortality of the trees and openings in the canopy. These disturbances increase the probability of recurrent fire by means of a positive feedback. They increase the susceptibility of the forest to fire, increasing the amount of fuel on the ground in the forest and creating openings in the canopy that allow the fuel layer on the forest floor to dry faster. Recurrent forest-fire episodes can cause drastic changes in the structure and composition of the forest (Barlow and Peres, 2008). We emphasize that in some areas where low-intensity fire occurred in the understory it was not possible to detect scars of these events on the satellite images. There is no standard spectral behavior of the fire scars in the reflected region of the electromagnetic spectrum, and the characteristics of the scars on the images depend mainly on the ecosystem, the soil type, the structure and phenological stage of the vegetation, and the intensity of the fire (França, 2004). Consequently, the loss of live biomass and the carbon stock committed to potential emissions derived from areas where low-intensity fire occurred in the understory was not computed in this study.

Barlow et al. (2012) compared above-ground live biomass in six burned and six unburned 0.5-ha plots in bamboo-dominated forest in the Chico Mendes Extractive Reserve in Acre three years after the 2005 fires. The study was unable to detect any significant difference in the mean above-ground live biomass present in the burned and unburned plots. In our case, permanent plots established before the fires allowed us to follow the fate of individual trees, thus allowing significant biomass losses to be quantified despite the inherently high variability that exists in biomass among small plots in Amazonian forests. We note that the best value for mean biomass of dense submontane ombrophilous forest is the estimate derived from the extensive RadamBrasil surveys (Table 7), not the lower values that happened to apply to our plots (Table 6).

The post-burn surveys of live trees in permanent plots we studied provide information one year and four years after the fire. This does not allow additional conclusions about the time trajectory of tree mortality and biomass change within the second time interval (years 2-4), since the mortality observed “four years after the fire” may have occurred at any time in the interval. We also cannot draw conclusions about what happens after the fourth year, and the losses up to the fourth year may not represent the total impact if tree mortality after the fourth year continues to be higher than in unburned forests (especially for large trees). A study in Roraima (in northern Amazonia) addressed the time path of post-fire mortality (Martins et al., 2012). In this case, a comparison of plots in forests where fires had occurred different numbers of years prior to being surveyed indicated that the mean live above-ground biomass decreased up to a point 3-7 years after the fire (as compared to the mean in unburned plots), but biomass stocks recovered to the levels in unburned plots by 12 years after the fire.

4.3. Implications for policy

Various general circulation models (GCMs) project an increase in the frequency and in the severity of drought events in the Amazon region as a consequence of anthropogenic emissions of greenhouse gases (Cox et al., 2008; Malhi et al., 2008; Poulter et al., 2010). Peaks of fire events occur during periods of drought (Aragão et al., 2008). Amazonian forests are vulnerable to increased water stress with possible heavy losses of carbon (Phillips et al., 2009). With the convergence of increased extreme weather events and more degraded forests that are prone to fire, fires can reach increasingly extensive areas and emit significant amounts of carbon into the atmosphere. Critical thresholds could lead to much larger fire events should global warming continue to increase, together with its expected effect in intensifying Amazonian droughts (Pueyo et al., 2010). The vulnerability of forests to fires threatens not only carbon stocks but also other environmental services such as maintenance of water cycling and biodiversity (Fearnside, 2008). These impacts add to the justification for adopting more aggressive measures to contain global greenhouse-gas emissions in order to avoid these levels of climate change.

Our results also have implications for forest managers. Virtually all plans for sustainable forest management in Amazonia simply assume that there will be no forest fires. The existence of fire and associated tree mortality affects the sustainability of these systems. It also points to the need for increased investment in fire-prevention measures and indicates need for the establishment and enforcement of regulations to minimize fire-ignition sources, for example by requiring fire breaks around pastures and fields to be burned near forest areas.

5. Conclusions

Forest fires pose a serious threat to the conservation of the forests in Amazonia. Currently, Boca do Acre and Lábrea have 865.6 km² of forests affected by fire. These forests have lost biomass and are more likely to burn again in recurrent fire events.

The losses of biomass (total and above-ground) due to the increase in tree mortality one year after the fires were 1.6×10^6 Mg and 1.4×10^6 Mg, and were almost twice as large four years after the fires (4.4×10^6 Mg and 3.7×10^6 Mg). The carbon stocks committed as emissions one year after the fire were 0.8×10^6 Mg C (total) and 0.7×10^6 Mg C (above-ground), and four years after the fire they were 2.1×10^6 Mg C (total) and 1.8×10^6 Mg C (above-ground).

Although our results show lower percentages than most other studies on fires in Amazonia, both in terms of trees killed and terms of loss of biomass, the results show that in a period of four years after fires the gross committed loss of biomass is double the value found one year after the fire. The net emissions to the atmosphere from this carbon in the subsequent years will depend on the balance between the rate of decomposition of the trees killed by the fire and the regrowth of the forest in a given period of time.

Forest fires are playing a significant and critical role both as a threat to the biological balance of the forest, and to the global climate by means of increasing atmospheric CO_2 concentrations. Impacts coming from these fires will have decisive implications for the future of Amazonian forests because fire probability can increase significantly as a function of the increase of frequency of drought events as predicted by general circulation models (GCMs).

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Figure legends

Fig. 1. Location of the municipalities of Boca do Acre and Lábrea (Amazonas state) and permanent plots (black circles) in the municipalities of Acrelândia and Senador Guiomard (Acre state) in the southwestern Amazon.

Fig. 2. Clipping of an area of forest affected by fire in an R(5)-G(4)-B(3) color composite, showing the different dates used in the mapping process: (a) area on 1 Sept. 2004 without fire; (b) area on 20 Sept. 2005 with recent fire scars, (c) areas on 21July 2006 showing scars of fire that occurred in 2005, and (d) mapping of forests affected by the fire in 2005.

Fig. 3. Areas of forests affected by fires (polygons in yellow) in 2005 in Boca do Acre and Lábrea, Amazonas, Brazil.

Table 1 – Orbit and row with the dates of each Landsat-5 TM scenes in the years 2004, 2005 and 2006.

Orbit and row	Date		
001/65	16/08/2004	04/09/2005	07/09/2006
001/66	01/09/2004	04/09/2005	22/08/2006
001/67	01/09/2004	03/08/2005	21/07/2006
002/66	08/09/2004	11/09/2005	14/09/2006
002/67	24/09/2004	11/09/2005	26/06/2006
003/66	10/05/2004	05/11/2005	16/05/2006
233/65	25/08/2004	28/08/2005	28/06/2006
233/66	09/08/2004	28/08/2005	28/06/2006

Table 2 – Error matrix for the mapping of the area of forest not affected by fire (FnAF), of the area affected by fire (FAF) in 2005, and of the deforested area.

		Ground Reference			Total	Errors of Omission (%)
		FnAf	FAF	Deforested area		
Thematic Classes	FnAf	35	13	0	48	27
	FAF	0	91	0	91	0
	Deforested area	0	0	161	161	0
Total		35	104	161	300	
Errors of Commission (%)		0	13	0		
Overall accuracy		96%				
Kappa Coefficient		93%				
User accuracy [a] (K_{i+})		100%				
Producer accuracy [a] (K_{j+})		82%				

[a]Conditional Kappa calculated for the "forest affected by fire" class.

Table 3 - Areas of forests affected by fire (km²) in 2005, by forest type in Boca do Acre and Lábrea, in Amazonas, Brazil.

Forest Type (IBGE code[a])	Boca do Acre (km²)	Lábrea (km²)	Total (km²)	Share of total area (%)
Open ombrophilous submontane forest dominated by bamboos (Asb)	46.4	0	46.4	5.4
Open ombrophilous submontane forest (As)	139.2	103.6	242.8	28.0
Dense ombrophilous submontane forest (Ds)	88.2	269.3	357.5	41.3
Dense lowland ombrophilous forest (Db)	0.2	23.3	23.6	2.7
Open lowland ombrophilous forest (Ab)	166.2	13.4	179.6	20.7
Dense alluvial ombrophilous forest (Da)	0	15.8	15.8	1.8
Total area	440.2	425.4	865.6	100.0

[a]Brazil, IBGE (1992).

Table 4- Density of live and dead trees (stems ha^{-1} ±SE[a]) with DBH ≥ 10 cm, dry biomass in live and dead trees (Mg ha^{-1} ±SE[a]) and committed absolute loss of dry biomass[b] since 2001 (Mg ha^{-1}) in the trees killed in the plots affected by the fire.

DBH Class (cm)	Live trees (stems ha^{-1} ±SE)			Dead trees (stems ha^{-1} ±SE)			Dry biomass of live trees (Mg ha^{-1} ±SE)			Dry biomass of dead trees (Mg ha^{-1}±SE)			Committed absolute loss of dry biomass[b] since 2001 (Mg ha^{-1})	
	2001	2006	2009	2001	2006	2009	2001	2006	2009	2001	2006	2009	2006	2009
10-19.9	85±6.0	77±5.0	163±15.0	3±0.5	22±1.0	6±2.0	12.4±1.1	11.7±0.7	19.7±0.7	0.2±0.1	2.9±0.2	0.9±0.4	-0.7	6.8
20-29.9	73±7.0	62±12.0	65±14.0	4±1.5	14±6.0	8±1.0	29.3±2.6	24.3±3.8	26.2±5.8	1.2±0.3	5.7±2.3	3.1±0.1	-5.0	-3.0
30-39.9	42±6.5	35±9.0	30±6.0	2±0.5	9±1.0	7±1.5	39.9±5.1	34.3±6.7	29.2±5.1	1.5±0.6	8.6±0.7	6.6±1.8	-5.6	-10.7
40-49.9	19±0.5	17±2.0	15±5.0	2±0.5	5±1.0	4±0.5	32.3±1.1	29.2±1.9	25.0±7.6	2.7±1.2	8.2±1.4	6±0.3	-3.1	-7.3
≥ 50	19±3.5	19±3.0	18±3.0	1±0.5	1±0.5	4±1.5	96.5±12.6	99.6±11.8	80.4±12.0	3.0±2.9	1.6±1.4	28.5±4.3	3.1	-16.1
Total	237±8.1	210±11.7	291±14.8	10±0.5	51±7.0	28±0.5	210.3±13.8	199. 1±17.0	180.0±6.8	8.5±1.5	26.9±6.2	45.1±5.4	-11.2	-30.3

[a]The standard error (SE) of the per-hectare means were obtained after the values of the 10 subplots had been normalized for an expected per-hectare frequency.
[b]Committed absolute loss of dry biomass refers to the difference between the stock of live biomass (without considering necromass) before the fire and the stock of live biomass after the fire, calculated in the second measurement.

Table 5- Density of live and dead trees (stems ha^{-1}±SE[a]) with DBH ≥ 10 cm, dry biomass in live and dead trees (Mg ha^{-1}±SE[a]) and committed absolute loss of dry biomass[b] since 2001 (Mg ha^{-1}) in dead trees in the plots that were not affected by fire.

DBH Class (cm)	Live trees (stems ha^{-1})			Dead trees (stems ha^{-1})			Dry biomass of live trees (Mg ha^{-1})			Dry biomass of dead trees (Mg ha^{-1})			Committed absolute loss of dry biomass[b] since 2001 (Mg ha^{-1})	
	2001	2006	2009	2001	2006	2009	2001	2006	2009	2001	2006	2009	2006	2009
10-19.9	65±0.7	54±1.0	70±1.4	4±0.4	16±1.3	5±0.5	7.8±0.2	7.9±0.2	9.9±0.2	0.4±0.1	1.8±0.1	0.7±0.1	0.1	2.1
20-29.9	67±2.3	54±2.2	51±2.0	8±0.5	6±0.7	4±0.4	27.5±1.0	22.2±0.9	21.6±0.8	3.8±0.3	2.4±0.3	1.7±0.2	-5.3	-5.1
30-39.9	17±0.7	26±0.7	27±0.2	5±0.4	2±0.2	3±0.6	16.9±0.9	22.5±0.6	24.6±0.2	4.5±0.4	2.0±0.2	2.7±0.5	5.6	7.6
40-49.9	13±0.7	13±0.8	10±0.7	1±0.2	1±0.2	3±0.4	21.5±1.2	22.1±1.3	17.7±1.2	1.3±0.3	1.6±0.3	4.7±0.7	0.6	-3.9
≥ 50	18±0.9	16±0.6	17±0.7	0	3±0.4	0	75.7±3.3	72.5±2.6	76.4±2.9	0	10.2±1.5	0	-3.3	0.7
Total	180±18.6	163±19.1	175±14.6	18±2.5	28±9.3	15±8.8	149.5±26.7	147.2±24.1	150.1±18.1	10.1±3.4	18.1±10.0	9.7±6.8	-2.3	0.60

[a]The standard error (SE) of the per-hectare means were obtained after the values of the 10 subplots had been normalized for an expected per-hectare frequency.
[b] Committed absolute loss of dry biomass refers to the difference between the stock of live biomass (without considering necromass) before the fire and the stock of live biomass after the drought, calculated in the second measurement.

Table 6 – Number of trunks (mean ± SE[a]; stems ha^{-1}) and live dry biomass above-ground (mean ± SE[a]; Mg ha^{-1}) in the 10 plots affected by fire and in the five plots not affected by fire.

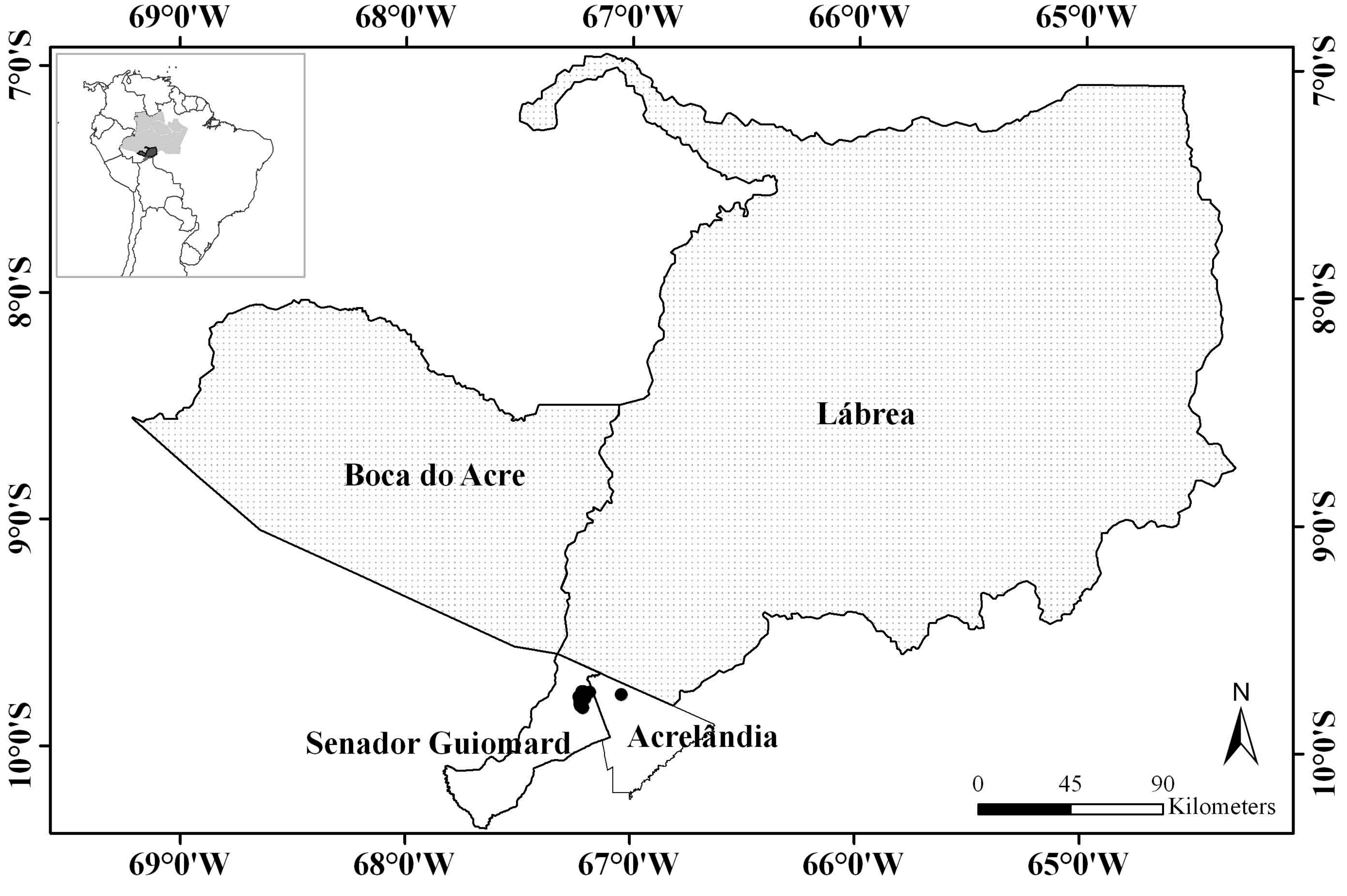
Year	Number of trunks (mean ± SE; stems ha^{-1})		Live above-ground dry biomass (mean ± SE; Mg ha^{-1})	
	Plots affected by fire	Plots not affected by fire	Plots affected by fire	Plots not affected by fire
2001	237 ± 8.1	180 ± 18.5	210.3 ± 13.8	149.5 ± 26.7
2006	210 ± 11.7	163 ± 19.1	199.1 ± 17.0	147.2 ± 24.1
2009	291 ± 14.8	175 ± 14.6	180.0 ± 6.8	150.1 ± 18.1

[a]The standard errors (SE) of the per-hectare means were obtained after the values of the 10 subplots had been normalized for an expected per-hectare frequency.

Table 7 - Estimates of the mean total live biomass and (above-ground live biomass) by type of forest (dry weight in Mg ha^{-1}), total live biomass in the areas of forest affected by fire (10^6 Mg), ratio of the committed absolute loss of biomass and committed emissions of carbon one and four years after the fire (5.3% and 14.4%)[a].

Type of Forest (IBGE code[b])	Biomass before the fire		Biomass loss (10^6 Mg)		Carbon loss (10^6 Mg)	
	Mean (Mg ha^{-1})	Total (10^6 Mg)	1 year 5.3%	4 years 14.4%	1 year	4 years
Open ombrophilous submontane dominated by bamboos (Asb)	206.4 (174.4)	1.0 (0.8)	0.1 (0.0)	0.1 (0.1)	0.0 (0.0)	0.1 (0.1)
Open ombrophilous submontane (As)	336.0 (280.2)	8.2 (6.8)	0.4 (0.4)	1.2 (1.0)	0.2 (0.2)	0.6 (0.5)
Dense ombrophilous submontane (Ds)	385.3 (319.6)	13.8 (11.4)	0.7 (0.6)	2.0 (1.6)	0.4 (0.3)	1.0 (0.8)
Dense lowland ombrophilous (Db)	384.5 (318.9)	0.9 (0.8)	0.0 (0.0)	0.1 (0.1)	0.0 (0.0)	0.1 (0.1)
Open lowland ombrophilous (Ab)	363.4 (303.1)	6.5 (5.4)	0.4 (0.3)	0.9 (0.8)	0.2 (0.1)	0.5 (0.4)
Alluvial dense ombrophilous (Da)	360.8 (299.3)	0.6 (0.5)	0.0 (0.0)	0.1 (0.1)	0.0 (0.0)	0.0 (0.0)
Total live biomass		30.9	1.6	4.5	0.8	2.2
Above-ground live biomass		(25.7)	(1.4)	(3.7)	(0.7)	(1.8)

[a]Proportion of committed absolute loss of total live biomass one year after the fire (5.3%) and four years after the fire (14.4%) in the 10 permanent plots affected by the 2005 fire. Values in parentheses refer to average above-ground live biomass and carbon.
[b]Brazil, IBGE (1992).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7°0'S
8°0'S
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10°0'S
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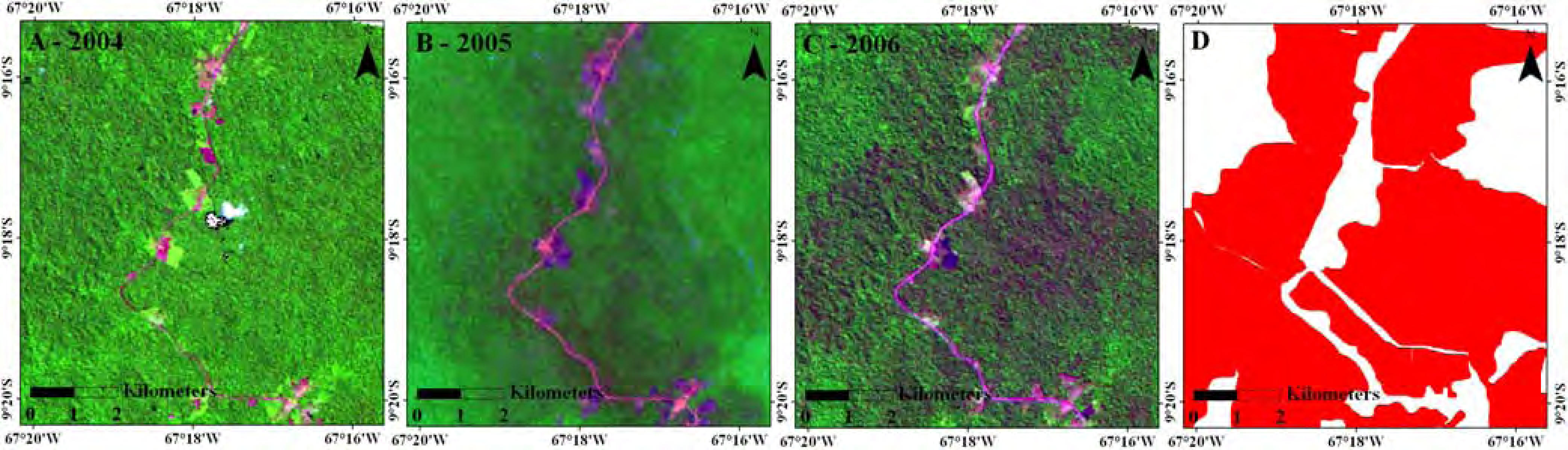
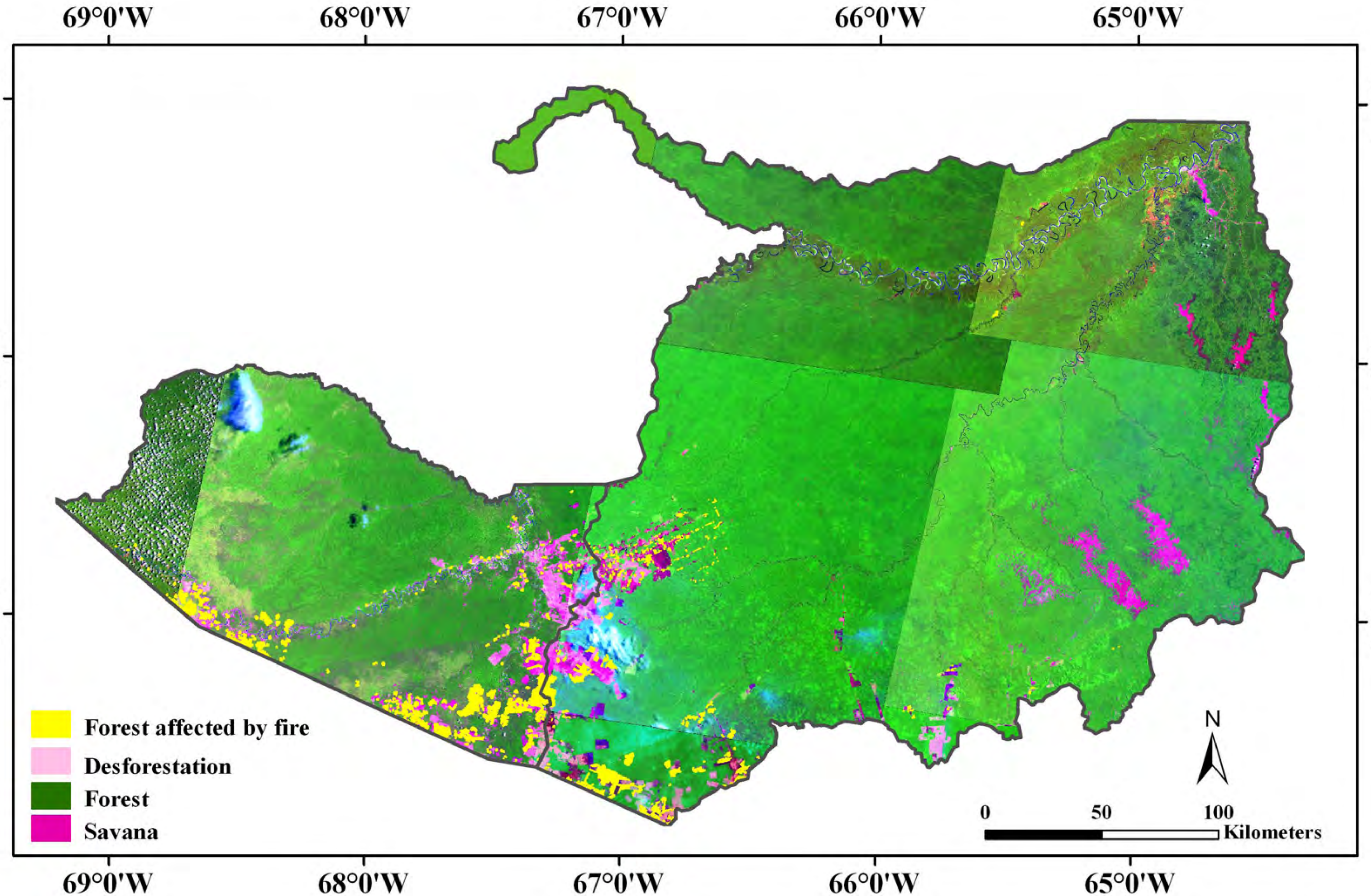
Boca do Acre
Senador Guiomard
Acrelândia
N
0
45
90
Kilometers


A - 2004
B - 2005
C - 2006
D
67°20'W
67°18'W
67°16'W
9°16'S
9°18'S
9°20'S
Kilometers
0 1 2


69°0'W
68°0'W
67°0'W
66°0'W
65°0'W
7°0'S
8°0'S
9°0'S
Forest affected by fire
Desforestation
Forest
Savana
N
0
50
100
Kilometers

Highlights

Forest fires occurred in western Amazonia during a major drought in 2005.

Carbon emissions are estimated from biomass maps and satellite images.

Forest fires represent a major but relatively little-studied degradation source.

Predicted climatic changes make this form of perturbation a major concern.