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Deforestation and forest fires in Roraima and their relationship with phytoclimatic regions in the Northern Brazilian Amazon

Abstract - Deforestation and forest fires in the Brazilian Amazon are a regional-scale anthropogenic process related to biomass burning, which has a direct impact on global warming due to greenhouse gas (GHG) emissions. Containment of this process requires characterizing its spatial distribution and that of the environmental factors related to its occurrence. The aim of this study is to investigate the spatial and temporal distribution of deforested areas and forest fires in the State of Roraima from 2000 to 2010. We mapped deforested areas and forest fires using Landsat images and associated their occurrence with two phytoclimatic zones: Zone with Savanna Influence (ZIS), and Zone without Savanna Influence (ZOS). Total deforested area during the interval was estimated at 3.06×10^3 km² (ZIS=55%; ZOS=45%) while total area affected by forest fires was estimated at 3.02×10^3 km² (ZIS=97.7%; ZOS=2.3%). Magnitude of deforestation in Roraima was not related to the phytoclimatic zones, but small deforested areas (≤17.9 ha) predominated in ZOS while larger deforestation classes (>17.9 ha) predominated in ZIS, which is an area with a longer history of human activities. The largest occurrence of forest fires was observed in the ZIS in years with El Niño events. Our analysis indicates that the areas most affected by forest fires in Roraima during 2000-2010 were associated with strong climatic events and the occurrence these fires was amplified in ZIS, a sensitive phytoclimatic zone with a higher risk of anthropogenic fires given its drier climate and open forest structure.

Keywords Deforestation, Fire scar, Environmental modeling, Forest understory fire, Mapping

Introduction

Deforestation (forest felling followed by burning) and forest fires (understory fires beneath the canopies of standing forests) occurring in the Brazilian Amazon directly contribute to global warming due to biomass burning and greenhouse-gas (GHG) emissions (Alencar et al. 2006; Harris et al. 2012; Nogueira et al. 2014). These impacts from land-cover change lead to a negative global effect on the environmental services provided by the region (Fearnside 2008a). Most research in the region has indicated that human population growth is the main driving force for deforestation and forest fires in the Brazilian Amazon, especially when associated with environmental factors, highway density and climatic events (Laurance et al. 2001; Nepstad et al. 2001; Nepstad et al. 1999a). Containing the advancement of deforestation, forest fires and unsustainable land uses requires specific understanding of the forces that accelerate or inhibit forest loss by anthropogenic activities in distinct ecoregions of the Amazon (Carrero and Fearnside 2011; Fearnside 2008b; Soares-Filho et al. 2006). One of the tools for the understanding these forces is mapping the spatial and temporal distribution of areas affected by deforestation and forest fires, in combination with information on human occupation, climate, environmental and structural characteristics of the impacted forest areas (Alencar et al. 2011; Aragão et al. 2008; Trancoso et al. 2010).

Various mappings in the Brazilian Amazon have been obtained by remotely sensed data from satellites. These maps have produced useful information for monitoring actions (e.g. indication of areas with higher or lower forest fire risk) and have produced input data for climate modeling and prediction of carbon emissions from deforestation (Cardozo et al. 2014; Gutierrez-Velez and Pontius Jr. 2012). The main base of comparison of these mappings has been PRODES, an official Brazilian project that annually monitors deforestation in the whole region (Brazil-INPE 2013). The PRODES dataset has been an important tool for studies of factors driving deforestation in the region using biophysical, infrastructural and demographic variables. However, PRODES do not quantify small deforestation (< 6.25 ha) and forest fires areas due methodological procedures (Câmara et al. 2013). However, small deforestation and forest fires are associated with distinct histories of land use, vegetation types and climatic conditions that can reach thousands of square kilometers in the Brazilian Amazon and contribute substantially to GHG emissions (Alencar et al. 2004; Morton et al. 2013; Vasconcelos et al. 2013a).

On a large scale, the association between the PRODES dataset and land uses have been the basis of current estimates of GHG emissions in the whole Amazon, taking into account a generalization of the vegetation types in the region (Brazil-MCT 2010). This generalization does not provide a full picture of ecological zones distinct by environmental factors (e.g., climate, geomorphology), which may be sensitive to both deforestation and an increased risk of forest fires (Aragão and Shimabukuro 2010; Cochrane et al. 1999). Due to this problem, regional distinctions in terms of deforestation rate and the size of areas that have been burned or affected by forest fires have been recommended by the IPCC (2006) as a way of improving GHG-emission estimations. The macro- and micro-regionalized data have been indicate as a way to improve understanding of the environmental factors that affect the spatial distribution of deforestation and forest fires, generating a positive effect for GHG-emission models (Yanai et al. 2012), and enabling more effective decisions to be made toward reducing or eliminating the forces that accelerate or cause deforestation in the Brazilian Amazon (Brazil-MCT 2010).

Given this background, an approach based on ecoregions or phytoclimatic zones (sensu Bedia et al. 2013; García-López and Allué Camacho 2011) can be used to distinguish differences in the behavior of fire either through deforestation or out-of-control forest fires to zoning sensitive areas with a higher risk of anthropogenic fires (Cochrane 2003; Schroeder et al. 2008). This zoning of the regional effects of the climatic and phytophysiognomic factors driving deforestation is consistent with the foundation for public policies on rational management of the region's natural resources (Aragão and Shimabukuro 2010; Fearnside 2008b; Nepstad et al. 2009). When properly understood at the landscape level (local and regional), reductions in areas impacted by deforestation and forest fires are made possible by improved governance, particularly in sensitive zones with specific migratory, phytophysiognomic and climatic issues (Araújo et al. 2012). It is essential that we improve our ability to predict interventions in order to minimize operational impacts of deforestation and forest fires in environmental services provided by Amazonia. Thus, understanding both the spatial distribution of deforested areas and of forest fires in Amazonian ecoregions is an integral part of improving GHG emission models in the region, aiding the promotion of objective public policies focused on the effect of environmental particularities associated with land-use change.

Our goal in this study is to do a spatial and temporal analysis of deforestation and forest fires in the State of Roraima, northern Brazilian Amazon, over the 2000-2010 interval, taking into consideration phytoclimatic zones limited by climatic and phytophysiognomic factors. Roraima's phytoclimatic zones can be sensitive to the increase or inhibition of deforestation and forest fires due specific environmental traits. Our specific questions are: (i) Do rate and magnitude of deforested areas and forest fires differ between phytoclimatic regions? (ii) Is frequency of deforested areas and forest fires related to forest types within the two zones?

Methods

Study area

The State of Roraima extends over 224.3×10^3 km² and is located in the northern Brazilian Amazon region, sharing borders with Venezuela and Guyana (Fig. 1). Its climate is typically tropical and is divided into three major types in accordance with the Köppen classification system: "*Af*" under the domain of vegetation type *campinarana* on oligotrophic soil (a forest type on low-nutrient white-sand soils), which makes up part of the ombrophilous forests of Roraima's southeast and northeast; "*Am*" covering other parts of the ombrophilous forests and a smaller section of the semi-deciduous seasonal forest in the southeast and center-west regions of Roraima and; "*Aw*" under the domain of the contact forests (ecotones), the largest section of the seasonal forests, and incorporating of all the savanna areas of low and high elevation that occupy the northeastern section of the state (Barbosa 1997).

[Fig. 1 here]

Roraima's relief is characterized by a set of dissected plateaus surrounded by intramontane pediplains, including individualized residual terrains across the extensive plain areas; ~70–150 meters above sea level (Shaefer and Darlymple 1995). Annual rainfall in these climatic zones is correlates with relief and vegetation type of the area in question. Rainfall generally decreases in a south-southeast (low altitude) to northeast (high altitude) direction. In south-southeast lowland rainforest areas, rainfall usually varies between 2000 and 2300 mm yr^{-1}, afterwards passing across into a forest-savanna transition area with annual rainfall of 1700 to 2000 mm yr^{-1}, finally reaching the savanna formations in the northeast section of the state, with annual rainfall of 1100 to 1400 mm yr^{-1} (Barbosa 1997). Natural vegetation, including all oligotrophic forest ecosystems, is comprised of tropical forest types (81.4%), distributed between the south, center-west and northeast areas of the State, as well as a large area of savanna (17.8%) (regionally known as "*lavrado*") occupying the entire northeastern section of the state. The remaining area is comprised of aquatic environments (0.8%) (Barbosa et al. 2010).

The distribution of human settlements in Roraima can be divided into two regions with distinct vegetation types in terms of structure and species composition, both related to climate, and whose history of land use is different. Land use in Roraima has a history of accelerated deforestation since the end of the 1980s and where biomass burning involving deforested areas and forest fires has been strongly related to population growth (Barbosa and Fearnside 1999). As is the case in much of Brazilian Amazon, the relationship between fire and deforestation is the final result of state and federal public incentives brought about by the policy of granting lands (Barni et al. 2012; Laurance et al. 2001; Nepstad et al. 1999a). In Roraima, this has occurred due to strengthening of existing settlement projects (SPs), creation of new SPs, opening of access roads and asphalting of federal highways with full state government support (Diniz and Santos 2005). At the local level, this policy had a substantial effect on release of large quantities of GHG due to deforestation or forest fires (Fearnside et al. 2013).

Phytoclimatic zones

Delimitation of the two phytoclimatic zones in Roraima follows three distinct criteria:

(i) Geomorphological – defining the delimited region in relation to the Guiana Shield and areas typically established in the lowest interfluvial regions between the Branco River and the Negro River (Brazil-MME 1975). In the first case, the region is located within in the following geomorphological Formations: (a) Boa Vista (sedimentary, with oxisols and ultisols, contact forests and low elevation savannas); (b) Surumu (volcanic, with planosols, oxisols and entisols under low/medium-elevation savannas) and; (c) Roraima (litholic, under montane forests and high-elevation savannas). The lowest interfluvial regions are under the dominion of the ombrophilous forests (open and dense lowland evergreen rainforest types) and oligotrophic systems (*campinaranas*);

(ii) Climatic – limited observation of different Roraima climatic types was made available as part of Roraima's ecological-economic zoning (CPRM 2002) by the Mineral Resources Research Company – CPRM, a Federal Government Agency. Contact between the *Aw* climate (dry savanna climate) and the

Am climate (monsoon climate) has been established as a climatic delimiter, separating the driest zone from the wettest zone;

(iii) Geographic – distance from the great savanna area, taking into consideration the large mass of forest and non-forest regions. This third criterion was used to physically delimit the two phytoclimatic regions taking into consideration the convergence of the isohyets included in the climatic criterion.

The combination of these three criteria generated two distinct phytoclimatic zones (Fig. 2): (i) Zone with Savanna Influence (ZIS) – influenced by the state's vast northeastern savanna, where the oldest colonies are located near the state capital of Boa Vista. These were during the 1950s and 1960s in contact forest areas (seasonal and ecotone forest), under drier climate conditions, with an annual average rainfall of < 1700-2000 mm, and (ii) Zone without Savanna Influence (ZOS) - more recently colonized areas (from the mid-1980s onwards), situated in both dense and open ombrophilous forest areas in the state's south and southeastern regions, established under wetter conditions with an annual average rainfall >2000–2300 mm. In both cases, Indigenous lands (IL) and protected areas (PA) were excluded from the analysis because these categories of land use are already restricted by Brazilian laws. In the context of this work, the collection of deforested areas and forest fire scars took place specifically in forest areas which are not part of these two categories of land use. In addition, only forest ecosystems were considered; savannas were not included in the analysis.

The two zones cover 92.31×10^3 km^2, accounting for 41.2% of the total area of state of Roraima: ZIS (31.75×10^3 km^2) and ZOS (60.56×10^3 km^2). Both are connected by two federal highways which are the largest deforestation axes in Roraima: BR-174 (Manaus-Boa Vista) and BR-210 (Perimetral Norte). The cumulative deforestation up to 1999 in Roraima was 6.26×10^3 km^2 (6.8% of the study area), growing to 9.32×10^3 km^2 in 2010 (10.1%) (Brazil-INPE 2013). About 70% of this deforestation is located in settlement projects established in the two phytoclimatic zones. This estimate was derived from the PRODES dataset (Brazil-INPE 2013).

[Fig. 2 here]

Deforested areas

A deforested area is a portion of forest that has been cleared by people and, after biomass burning has occurred, is used for agropastoral production purposes or simply abandoned. Mapping of deforested areas was carried out using Landsat TM/ETM+ images (30 m resolution) and geoprocessing techniques. The Landsat images used were available from the National Institute for Space Research – INPE (Brazil-INPE 2012). We used a minimum mapping unit of deforested ≥1.0 ha in area in order to capture the annual dynamics of deforestation in a better resolution, individualizing the primary occurrences of deforested areas in Roraima.

Our methodological procedure was manual and is distinct from that adopted by PRODES, which uses digital processing of images with a spatial resolution of 60 m (capable of detecting clearings ≥6.25 ha in area); small clearings (<6.25 ha) are accounted cumulatively over the years by PRODES. The PRODES dataset was used to compare our results on amount of forest loss from deforestation in the four forest types (*campinarana*, ecotone, seasonal forest and ombrophilous forest) for the entire time interval (2000-2010). The total area used for the comparative analysis between the PRODES data and the results of this study was 92.31×10^3 km^2, which corresponds to the sum of the two phytoclimatic zones. Of this total both non forest and aquatic ecosystems (10.68×10^3 km^2), and the forest loss area (6.26×10^3 km^2) accumulated through 1999 for all forest types occurring in each phytoclimatic zone were excluded. Thus, the total area of forest ecosystems without the effect of deforestation in 1999 was 75.37×10^3 km^2. The objective of this procedure was to maintain the same initial geographical basis for the two datasets to allow comparison of results from PRODES (reference map: automated) *versus* our mapping (comparison map: manual procedures).

The comparison took into account the two deforestation datasets (PRODES and this study) for the 2000-2010 interval and is distinct in each forest type present in the study area. We used “quantity disagreement” and “allocation disagreement” as parameters for map comparison using a cross-tabulation matrix procedure suggested by Pontius Jr. and Millones (2011). The first parameter (quantity disagreement) is defined by Pontius Jr. and Millones (2011) as the amount of difference between the reference map (PRODES) and a comparison map (this study) that is a result of the less-than-perfect match in the proportions of the categories used; it is a component of uncertainty indicating disagreement regarding how much area was deforested. The second parameter (allocation disagreement) is defined as the amount of difference between the reference map and a comparison map occurring because of the less-than-optimal match in the spatial allocation of the categories, given the proportions of the categories in the reference and comparison maps. This parameter is a component of uncertainty indicating disagreement concerning where deforestation occurred. The final result of disagreement (quantity and allocation) between the PRODES mapping and this study represents the sum of disagreements (%) that occurred in each forest type from 2000 to 2010 using as comparison the categories "forest loss" (total areal extent deforested) and "forest persistence" (forests without the effect of deforestation) for both phytoclimatic zones.

Our data acquisition process consisted of the following phases: (i) R(5)G(4)B(3) image composition, forming an eight scene mosaic per year, covering the entire state of Roraima between 1999 and 2010, consisting of 126 scenes in total (Supplementary Online Material – SOM: Table S1), in which preference was given to data acquired during the second semester (July to December) of each year due to enhanced visibility conditions; (ii) standardization of UTM projection images, Zone 20, *datum* WGS 1984, using the Geocover 2000 mosaic as a base model (NASA 2012); (iii) manual editing (vectorization) of deforested area polygons (deforested area units) within a Geographic Information System (GIS) environment, using ArcGis software, producing vector files that can be directly placed over the images mosaic for a single year. No system of atmospheric image enhancement or correction was necessary due to the ease in identifying the deforested area polygons which present a clear contrast with the adjacent forest areas.

Manual editing was carried out by circling groups of pixels that indicated changes in the landscape, from one year to the next, forming regular polygons (≥1.0 ha in area). Each polygon represented a deforested area unit, for each year during the investigation interval. These polygons were determined by simultaneously superimposing two images into a fixed "window" at a fixed scale of 1:40,000 - as suggested by Lang and Blaschke (2009); one image from the year prior to deforestation (no changes) and one image for the verification year itself (with changes). A third, optional image for the year after vectorization took place was also used with the purpose of removing any reasonable doubt and to confirm any detected observations. The visual interpretation procedure was carried out based on the spectral features of the observed scenes. In the case of deforestation, the spectral signal is quite characteristic and is associated with the rectangular (linear) pattern of the areas where there was a change caused by the removal of biomass and its subsequent burning. This pattern is easily recognized because it generally occurs at the forest edge, near areas already deforested in previous years or even close to roads, as exemplified in other studies (e.g., Laurance et al. 2002; Soares-Filho et al. 2006).

In order to understand the dynamics of deforested areas in the two phytoclimatic zones of the state of Roraima and, as an approach capable of replication in simulation models of deforestation, five-size frequency classes for deforested area units were created: 1≤ area ≤6.6 ha; 6.6< area ≤12.2 ha; 12.2< area ≤17.9 ha; 17.9< area ≤23.5 ha and area >23.5 ha. The largest class was represented by 5% of the data containing the largest of the physical area polygons (>23.5 ha). The four remaining classes were grouped following Sturge's Rule, which is a method for determining the desirable number of groups or classes (Sturges 1926).

Forest fires

Forest fires were considered here as fires escaping from the burning of residual biomass derived from deforestation, pasture renewal or the clearing areas of secondary forests. Mapping of forest fire scars was carried out using the same Landsat TM/ETM+ image database (Brazil-INPE 2012). Eight different scenes were selected for each year, on different dates from those of the deforestation analysis, according to the following criteria: (i) March to April (primary source) – end of the regional dry period, in which the scars of forest fires are easily visible forming groups of pixels sensitized by the passage of fire (Garcia and Caselles 1991), or (ii) exceptionally from September to October (secondary source) – end of the local rainy season, a period when regional cloud cover is lower and the signs of forest fires can be also visible depending on forest fire severity. In this last case, <10% of the total scenes were used.

All images were enhanced (contrast and brightness) in order to facilitate visual identification of the forest fire scars (e.g., Vasconcelos et al. 2013b). In a process similar to that used for deforested areas (regular shapes), forest fire scars (irregular shapes) were manually vectorized using an image from the previous year (without changes), as well as another image for the verification year (with changes). As part of this procedure, the use of a third image, taken after the verification year, was used in accordance with the forest fire data acquisition protocol. The spectral pattern of forest fires is characterized by the presence of irregular shapes of the forest canopy that were affected by the understory fires, as well as their irregular pattern, are the result of factors related to combustible material (moisture, stock, etc.) which either hinders or facilitates the spread of fire in the forest understory. Although there are interpretation errors derived from the human visual reading, we prefer to undertake manual vectorization instead of digital approaches (e.g., Morton et al. 2011) in order to help reduce non-controlled errors related to algorithms involving spatial and spectral information reading (e.g., under- or over-estimation). Thus, the use of the visual interpretation procedure for extracting the forest fire areas was considered to be the most adequate since digital classification procedures often confuse similar spectral patterns (see Vasconcelos et al. 2013b). Finally, all activities involving georeferencing, image handling, visual detection, and vectorization of forest fire polygons were carried out using ArcGis tools.

Vegetation types affected by deforestation and forest fires

A Roraima vegetation vector map, available from the Programme for Conservation and Sustainable Use of Brazilian Biological Diversity (Brazil-MMA 2012), was used as the base to identify forest types affected by deforestation and forest fires. PROBIO is a Brazilian official land cover map built taking into consideration Landsat images from 2002. PROBIO's vegetation map has 17 forest types for Roraima, including forest areas altered by human activity, classified as "*anthropogenic*". The definition of vegetation types adopted by the PROBIO for the Amazon is the same as the Brazilian Vegetation Classification System (Brazil-IBGE 2012). Thus, we take advantage of this geographic information to reconstruct the original vegetation cover of Roraima, using manual editing of the vegetation types categories directly on the map. We considered the original extent and contours of each affected vegetation type. This was done in order to subsequently obtain information (area and shape) related to original vegetation classes and to re-building vegetation types in the map. The re-built Roraima forest types were overlain by maps of deforested areas and forest fire-affected areas in order to calculate the area of each type affected annually by deforestation and forest fires (Table 1).

[Table 1 here]

Ground reference information

Visual image analysis was supplemented by field trips and the physical collection of data (GPS points and photographs) in areas impacted by deforestation and forest fires. Field trips were aimed at the recognition of impacted areas in the two phytoclimatic zones in Roraima, and to understand patterns of past deforestation observed in Landsat TM/ETM+ images used in the geoprocessing activities. Four field trips were made between 31 March 2011 and 19 January 2013 for the purposes of confirming the deforestation and forest fire patterns observed from viewing the corresponding images in the laboratory.

The field excursions took place on the following dates and at the following destinations: (1) March 31 to April 4, 2011: south and southeast sectors of Roraima, which are regions dominated by ombrophilous forest; (2) October 5-6, 2012: western sector, in the Apiaú, Roxinho and Campos Novos Settlement Projects, a region dominated by seasonal forests and ecotones which has been considered as the epicenter of recent large-scale forest fires in Roraima; (3) July 7-8, 2012: the central-east region of the state; municipalities of Cantá, Caracaraí, Iracema and Mucajaí, where ombrophilous forest, *campinaranas* and ecotones are dominant; (4) January 14-19, 2013: municipalities of Amajari and Pacaraima, in the north of Roraima, where ecotones (between savanna and forest), Seasonal forests and altitudinal forests are predominant.

Data analysis

Normality tests were applied to all procedures involving deforestation patterns (rate and magnitude) in the two phytoclimatic zones. To evaluate the frequency of occurrence of the total number of deforestation-associated units (polygons) in relation to forest types, for both phytoclimatic zones, a contingency table (χ^2) was used. Temporal rates of deforestation and forest fires were tested using the total and average annual area within the forest types (parametric and non-parametric tests). All mean comparison tests and contingency tables calculations assumed a significance level of 0.05. All tests were carried out using the R free software environment, version 2.15.2. (R Core Team 2013).

Results

Magnitude and rate of deforestation and forest fires

The magnitude of accumulated deforested area in the study region from 2000 to 2010 was 3.06×10^3 km^2 (Table 2). Of this total, 54.7% was inside the ZIS and 45.3% to the ZOS (Fig. 3-A; Fig. 4-A). The results for total deforested area were similar to official data from the Brazilian government, established by the PRODES dataset (~3×10^3 km^2). “Quantity disagreement” and “allocation disagreement” in our study diverged from the digital PRODES mapping. The total for disagreement (44%) was 1.3×10^3 km^2, with 550.8 km^2 (18%) of “quantity disagreement” and 795.6 km^2 (26%) of “allocation disagreement”. These results represent disagreement of our deforested area data in relation to total deforestation area in PRODES mapping because the PRODES procedure introduces differences between the two mappings in the size and limits of deforestation polygons observed (SOM: Fig. S1). However, cumulative values in the long-term (2000-2010) produced no distinctions between the total deforested and its allocation in the forest types categories in both phytoclimatic zones (forest persistence during 2000-2010 for both procedures was ~72.3×10^3 km^2). Cumulative forest fire-affected area in ZIS grew precipitously with the great forest fires of 2003 and 2007 (Fig. 3-B; Fig. 4-B).

[Figs. 3 & 4 here]

The highest deforestation year was 2003 with a total of 0.53×10^3 km^2, of which 26.3% occurred in the ZOS and 73.7% in the ZIS. Annual deforestation rate (2000 – 2010) did not differ between the two phytoclimatic zones (test t; p=0.434): 0.152×10^3 km^2 (ZIS) and 0.126×10^3 km^2 (ZOS) (Table 2). Both zones showed decreased trends in deforestation rates between 2008/2009 and 2009/2010. However, the average deforested area unit (i.e., deforestation per polygon) was larger in the ZIS (average ± SD; 9.8 ± 24.8 ha) than in the ZOS (7.4 ± 10.7 ha; $p < 0.0001$).

[Table 2 here]

Forest fire-affected area during 2000–2010 was 3.02×10^3 km^2, of which 97.7% (2.95×10^3 km^2) occurred in the ZIS and 2.3% (0.07×10^3 km^2) in the ZOS. Average total of forest fire-affected area on an annual basis was discrepant between the two zones (Mann-Whitney; p=0.048): 0.27×10^3 km^2 (ZIS) and 0.006×10^3 km^2 (ZOS), in which years 2001, 2003 and 2007 had a 98.5% (3.0×10^3 km^2) concentration of the forest fire areas. It was estimated that 461.38 km^2 (~15%) were areas related to recurrent fires in the ZIS during the analysis interval (Table 3). Of this total, 88.32% (407.43 km^2) occurred in 2007, in areas that were impacted by forest fires in 2003 (394.68 km^2) and 2001 (12.75 km^2).

[Table 3 here]

Frequency of deforested areas in relation to size classes

There was also a discrepancy among the deforestation unit (polygons) frequencies occurring within the classes between the two phytoclimatic zones during the assessment interval (χ^2=309.4; df= 4; $p < 0.0001$). The three classes ≤17.9 ha predominated in the ZOS while the two classes >17.9 ha predominated in the ZIS (Table 4). The total deforested area for the smallest class size (1.0 to 6.6 ha) was 0.85×10^3 km^2 (27.7%). Of this total, 46% (0.39×10^3 km^2) occurred in the ZIS and 54% (0.46×10^3 km^2) in the ZOS. On the other hand, the deforested area in the analysis interval for the highest class (>23.5 ha) was 1.02×10^3 km^2 (33.4%), of which 0.74×10^3 km^2 (72.5%) occurred in the ZIS and 0.28 x10^3 km^2 (27.5%) in the ZOS.

[Table 4 here]

Forest types

Annual total deforested areas in each phytoclimatic zone differed between the forest types (ANOVA; $p < 0.0001$) (Fig. 5). The forest type most affected by deforestation was ecotone (1.56×10^3 km^2), followed by the ombrophilous forest (1.39×10^3 km^2). Ecotones occur predominantly in the ZIS while the ombrophilous forest is predominantly in the ZOS (Table 5). Together, the ecotone and ombrophilous forests totaled 96.7% of the deforested area for the interval in question.

[Table 5 & Fig. 5 here]

The average amount of deforested area in the ombrophilous forest is not significantly different (t-test; $p < 0.3602$) between the ZIS (8.4 ± 15.3 ha; 1846 polygons or deforestation units) and the ZOS (8.1 ± 11.5 ha; 16,092). The average amount of deforested area within the ecotone type was different between zones (t test; $p < 0.0001$): ZIS (10.9 ± 27.9 ha; 14,378) and ZOS (5.9 ± 9.5 ha; 2,157) (SOM: Table S3). The ecotone forest was the most affected by forest fires during the assessment interval, with a total of 2.51×10^3 km² (83.3%) occurring mainly in the ZIS (Fig. 5-C and 5-D; (SOM: Table S4). There were also differences between the annual averages of forest fire-affected areas within the forest types of the ZIS (Kruskal-Wallis; df = 3; $p = 0.03$) and the ZOS ($p = 0.004$).

Discussion

Our results for the total deforested area and annual deforestation rates in the interval investigated (2000–2010) were similar to the official data from the Brazilian government established by PRODES (Brazil-INPE 2013). However, the calculated quantity of disagreement in our mapping *vs*. PRODES mapping resulted in divergences in the total deforested area. This is due to differences in the method of detection of deforested areas between two datasets. The divergences are a result of the following three factors: (i) spatial resolution and scale of mapping (30 m and ≥1 ha for our mapping; 60 m and ≥6.25 ha PRODES mapping), which is diluted over time and has influence only on annual analyzes, but it is not perceived in the long term (Fig. 6), (ii) allocation disagreement, where the PRODES automated processing draws polygons with some limits within areas that are not deforested or open vegetation enclaves (e.g. savannas), and finally (iii) PRODES uses images recorded mainly in August (end of the dry season in the Southern Hemisphere) for the entire Amazon, while we used an image mosaic acquired during the second semester (Jul.–Dec.) of each year in Roraima (the early dry season in northern Amazon).

[Fig. 6 here]

Due to these factors, the total deforested area in the temporal range of our analysis showed no distinctions in relation to the PRODES dataset, although the amount of disagreement was high due to temporal differences in mapping of the deforestation polygons in terms of their limits and spatial allocation (SOM: Fig. S1). Because the entire process has been standardized, these differences do not affect the spatial position and the physiognomic definition of the deforestation polygon, and are also not related to distinctions in *datum* or projection of the images. Thus, our results must be taken in to account in order to better understand how some of the issues in the digital PRODES procedure have led to temporal and spatial variations between the two evaluations. As mentioned earlier, this is primarily a result of differences in sampling techniques adopted for Landsat images. However, use of our dataset does not affect the subsequent analysis of deforestation in the two phytoclimatic zones because our method shows the closest agreement for allocation of deforestation (spatial and temporal) and does not differs in the long term (2000-2010) from results obtained by PRODES in the same area.

Our results for forest fires (~3.02×10^3 km^2) were >25 times higher than those presented by Souza Jr. et al. (2013) specifically for Roraima for the same interval investigated (118 km^2 degraded due to selective logging and forest fires). Souza Jr. et al. (2013) performed automated mapping using Landsat and SPOT imagery datasets. However, as in the PRODES procedure, problems with missing images and issues related to the process of automation in the identification of areas affected by forest fires were implied in this difference. This is an example of errors that we can commit when automatic decision rules that are supposedly valid for the whole Amazon region are used without considering regional particularities. Despite our mapping procedure (visual / manual) representing the opposite of those that use automation of image classification, our forest-fire mapping was much more effective in fulfilling the objectives proposed in this study. The manual editing used in our study allows increased detection resolution, enabling areas of affected by deforestation and forest fires to be individualized by frequency of occurrence, as well as facilitating capture of spatio-temporal dynamics without large cloud cover.

The phytoclimatic zones were not good predictors of the magnitude and rate of deforestation in Roraima (2000–2010). The advance of deforestation was similar across the two phytoclimatic zones, independent of their dimension, historical land use, climatic factors or forest types. Both areas are served by an extensive road network that facilitates human displacement, providing opportunities for opening new deforestation fronts: the ZIS embodies the region close to the capital (Boa Vista) and has a larger road network due to being more developed (5034.1 km; 58.6 %), while the ZOS has a newer and currently expanding road network (3563.2 km; 41.4%). However, the latter has increased as a direct result of the two major colonization highways (BR 174 and BR 210) in the southern part of the state. Therefore, the total deforested area in the two phytoclimatic zones was not affected by general environmental conditions, indicating a positive relationship with the human presence associated with a wide road network, just as in other Amazon localities (Kirby et al. 2006; Laurance et al. 2002; Soares-Filho et al. 2006).

Deforestation in Roraima involves a large number of smallholders, such as small-scale farmers in SP areas, as well as squatters and illegal settlers in land invasion areas. These groups occupy a small amount of deforested areas (≤17.9 ha), with higher occurrences being recorded in the <6.6 ha class (e.g., ZIS = 65%; ZOS = 64%). In terms of the ZIS, the greater occurrence in this latter class relates to the political actions of the Amazonian historical occupation by small farmers in the decades of 1970–80 (Barbosa 1993), and the closure of gold mining in Yanomami Indian Land in the late 1980s (Albert 1992). In both cases, thousands of decapitalized small farmers and miners were placed in SP in forest areas (ZIS) closer to Boa Vista. This region is the financial center of the state, and it has facilities that allow small landowners transit between the urban and rural spaces - a factor that must be taken into account in deforestation models in Roraima (Barbosa and Campos 2011).

In terms of the ZOS (the most recent occupation), the large occurrence of deforestation units in the smallest class (<6.6 ha) is associated with two factors: (i) the origin of the majority of poor migrants legally attracted to the region in the late 1980s and early 1990s - decapitalized migrants failed to deforest large areas in other regions (e.g., Carrero and Fearnside 2011), and (ii) illegal deforestation by squatters on public land. In the latter case, the deforested area is small due to roads being too precarious for transporting logs or agricultural produce, scarce capital and the associated risk of losing possession to another invader, or to public agencies in cases of repossession. This is similar to what is occurring in other Amazon localities and is caused by a lack of understanding of environmental policies (federal and state), leading to the continued use of fire as a management practice and the risk of criminalization of small farmers (Carmenta et al. 2013). In any case, independent of the legality of deforestation, all areas <6.6 ha were strongly related to new deforestation expansion fronts linked with logging activities (SOM: Fig. S2). Indeed, accounting for the contribution of small-scale deforestation on a regional and temporal scale significantly reduces the uncertainties found in global biomass-burning and carbon-flux models (May et al. 2011; Randerson et al. 2012). For our case study, the visual resolution used for detecting small deforested areas (<6.6 ha) amounted to 32 ± 9% (979.2 ± 275.4 km^2) of the total deforested area in the interval analyzed (2000–2010); 80% (784.2 km^2) of this area was found to be below the detection limit of the Brazil-INPE (2013) digital system (≥6.25 ha).

The higher number of large deforested areas (>17.9 ha; large landowners) observed in the ZIS (1588.9 km^2) when compared to the ZOS (1,017.5 km^2) is related to two factors: (i) the establishment of the Agricultural District of Roraima created in the 1970s by the military governments, with rural lots >1000 ha (Barbosa 1993) and (ii) the state government incentive to attract agribusiness investors (beef, soybeans and sugar cane) to Roraima. The latter case contributed to illegal appropriation of large areas located between the SP and demarcated indigenous lands in the ZIS. In terms of the ZOS, a region that historically served as the center of the state's timber industry (Asner et al. 2005; Barbosa 1990), the larger deforested areas are also linked to illegal deforestation and public land invasions by rich farmers to claim property rights. This has become a common occurrence in the Amazon in recent years, mainly motivated by land speculation and the advancement of agribusiness (Fearnside 2008a).

Independent of the size of the deforestation units, we observed a downward trend in deforestation rates during 2009–2010, reducing the amount of deforested areas per year. This fall was a result of improved monitoring by IBAMA (Brazil's Environmental Protection Agency) (Assunção et al. 2013). However, despite the greater accuracy in the inspection by IBAMA that occurred at the end of our interval of analysis, it is expected that both zones will suffer further deforestation when the BR-319 (Manaus-Porto Velho) highway is paved, a task which the federal government plans to undertake (Barni et al. 2012; Fearnside and Graça 2006). Asphalting of this federal highway will facilitate the migration of people into Roraima, creating a population flow from Porto Velho (Rondônia) to Manaus (Amazonas) which would continue along the BR-174 (already paved) up to the deforestation zones in Roraima (Barni et al. 2014; Fearnside et al. 2009). This development would also provide large cattle and soy producers with improved conditions to transport their agribusiness products and to receive raw material from other

Brazilian states at a cheaper cost. In this particular scenario, the forests of Roraima will become more exposed to deforestation, resulting in a greater quantity of potential GHG emissions per unit area.

In the case of areas affected by forest fires, our study indicated that about 98.5% of the total burned area was related to years with El Niño events, mainly in the driest zone associated with ecotone and seasonal forest types (ZIS), where almost all of the fire scars were observed. This is to be expected, since years of pronounced drought added to the anthropogenic synergy and interactions of the burnings have contributed to the great fires that have occurred in the assessment interval throughout the whole Amazon region (Aragão et al. 2008; Brando et al. 2014; Davidson et al. 2012). Similarly, deforestation occurring in regions of a drier climate associated with Seasonal forest has been indicated as a positive factor for the spread of understory fires in areas occupied by SP or selective logging (Alencar et al. 2004; Barbosa and Fearnside 1999; Morton et al. 2011). In terms of the ZOS, the greater moisture of the forest ecosystems (Ombrophilous) tends to inhibit the occurrence of forest fires (Ray et al. 2005), but fires still occur in small areas adjacent to areas of anthropogenic fires, generally during years of severe drought (Carvalho et al. 2010; Vasconcelos et al. 2013b).

Our results show that, independent of the rate and magnitude of deforested areas in the two phytoclimatic zones, the areas affected by forest fires in Roraima were dependent of the forest type and climate. Therefore, climate and forest type must be considered as interactive factors in GHG emissions models, inasmuch as in the Amazon the forest types most vulnerable to forest fires are located in areas of ecological tension (seasonal and ecotone forests), and are also characterized by strong anthropogenic pressure, especially the 'arc of deforestation' along the southern border of the Amazon (Davidson et al. 2012; Nepstad et al. 1999a; Nepstad et al. 1999b).

In Roraima, this distinction between forest types is deeper, since large losses of biomass occur in ZIS areas affected by recurrent forest fires (Martins et al. 2012; Xaud et al. 2013). This is largely because this is the region with the largest area of ecotone and seasonal forest types, and the climate is drier than the ZOS. The occurrence of large forest fire areas following the Roraima mega-fire of 1997/1998 ($\sim 12 \times 10^3$ km^2) (Barbosa and Fearnside 1999), and during the El Niño years of 2003 and 2007, indicates that the recurrence of forest fires tends to accelerate degradation of previously affected forests in the Amazon, particularly due to the prevalence of understory fires associated with drier climate conditions (Alencar et al. 2011; Scholze et al. 2006). The recurrence of fires can be more frequent when considering forest types. For example, we estimated that ca. 15% of forest fire-affected areas were related to recurrent fires in the

ZIS (ecotone and seasonal forests) during the analysis interval. Of this total, 88.3% occurred in 2007 in areas impacted by the 2003 and 2001 forest fires (burned three times). However, depending on the level of forest degradation caused by selective logging, even areas dominated by dense evergreen forest (e.g., ZOS) can suffer a high frequency of fires and abruptly increasing tree mortality (Brando et al. 2014; Vasconcelos et al. 2013b). For example, in the eastern portion of the Brazilian Amazon (Pará state: Tailândia, Tomé-Açú and Ipixuna), a region with a long history of heavy logging, areas burned three times accounted for 86% of total burns during 23 years of analysis (Alencar et al. 2011). Therefore, the location and extent of forest fires is important for determining the degree to which climate conditions and forest types have affected fire occurrence, but the synergism with human activities is also generally conducive to accelerated forest loss due to a strong association with forest fires.

Our approach of using phytoclimatic zones can become an important and effective mechanism in understanding the risk of deforestation and forest fires in Roraima. On the one hand, our procedure showed a strong dependence of forest fires on the ecotone and seasonal forests, which are abundant in the ZIS because of its drier climate, and, on the other hand, with respect to climatic seasonality, it also demonstrated that the deforestation across the study area is independent of environmental conditions related to phytoclimatic zones. These differences can influence the dynamic of deforestation and forest fires, resulting in distinct GHG emission scenarios over the long term, when the current trend observed between the two phytoclimatic zones is taken into consideration. The distinction among phytoclimatic zones can also be emphasized in other parts of the Amazon where climate and vegetation types are sufficiently distinct to affect deforestation and forest fires, with a negative effect on environmental services (Foley et al. 2007).

Conclusion

Based on our own results, we conclude that from 2000 to 2010 the total deforested areas in Roraima are not determined by the phytoclimatic zones, but these zones have a distinct effect on the occurrence of forest fires indicating that the most forest fires-affected areas were related with strong climatic events and were amplified in the zone with savanna influence (ZIS), a sensitive phytoclimatic zone with a higher risk of anthropogenic fires taking into consideration drier climate associated with forest types with open structure. The synergism of drier zones with the activities of longer periods of human colonization in ZIS was conducive to accelerated forest loss associated with forest fires. Finally, our analysis also indicated that the area affected by forest fires in Roraima (2000-2010) was much higher (> 25 times) than that detected in previous studies due to the inherent errors of automated techniques in relation to techniques of manual editing area.

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Table legends

Table 1. Description and original area (km^2; %) of the forest types observed in the ZIS and ZOS phytoclimatic zones: ZIS = Zone with Savanna Influence, and ZOS = Zone without Savanna Influence. (a) = Non-forest, aquatic ecosystems and seasonally flooded open areas. Values in parentheses = forest ecosystems without the effect of deforestation in 1999.

Table 2. Total deforested and forest fire area (km^2; mean ± SE) from 2000–2010 (ZIS = Zone with Savanna Influence, and ZOS = Zone without Savanna Influence). Different uppercase (deforested) and lowercase (forest fires) letters between columns of the same category indicate a significant discrepancy at 5%.

Table 3. Recurrent understory fire area (km^2) during the interval of analysis (2000–2010) in the ZIS (Zone with Savanna Influence).

Table 4. Total frequency of deforested units (n = polygons), total deforested area and mean annual area (km^2) of occurrence within the deforestation size classes in the ZOS and ZIS. The table shows further statistic analysis results (Chi-square) for the number of polygons and t-test statistic analysis results (t-test and Mann-Whitney) between the mean total annual areas occurring within the classes between the two phytoclimatic zones. Different letters within the column represent significant differences (α=0.05).

Table 5. Total deforested and forest fire-affected area (km^2; %) related to each forest type within the phytoclimatic zones during the analysis interval (2000–2010).

Figure legends

Fig. 1 The main forest types and the savanna region of the state of Roraima, Brazilian Amazon. Source: Brazil-MMA (2012). The Köppen system: *Af* = Equatorial climate; *Am* = Monsoonal climate and *Aw* = Tropical savanna climate

Fig. 2 Delimitation of the two phytoclimatic zones in a continuous double boundary line, distribution of the highways and roads, and distribution of the Indigenous Land (IL) and Protected Areas (PA). Zone with Savanna Influence = ZIS and Zone without Savanna Influence = ZOS

Fig. 3 Spatial distribution of deforestation (A) and forest fires (B) in the study area between 2000–2010, taking into consideration the two phytoclimatic zones. Minimum mapping unit ≥1 ha in area

Fig. 4 (A) Accumulated (km^2; columns) and annual rate (km^2; rows) of deforested areas; (B) accumulated (km^2; columns) and annual rate (km^2; rows) of forest fire areas in Roraima, Brazilian Amazon (2000–2010)

Fig. 5 Annual occurrence of deforested area (km^2) and forest fire-affected area (km^2) among forest types observed within the phytoclimatic zones: ZIS (A; C) and ZOS (B; D). The Box plot represents a data variation of 50% between the 1st and 3rd quartile, including the median (horizontal internal line), with the sectioned rows representing the distance of the maximum and minimum values and the points representing the outliers. Forest types: CAMP = Campinarana; ECOT = Ecotone; SEAS = Seasonal, and OMBR = Ombrophilous. Forest fire-affected areas were log transformed for data normalization. The different letters associated with the frequency categories show a level of discrepancy (α=0.05), in accordance with the Tukey test

Fig. 6 Annual deforestation in Roraima from 2000 to 2010. White bars = this study and black bars = Brazil-INPE (2013)

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Table 1.

Forest Types	**ZIS (km^2)**	**%**	**ZOS (km^2)**	**%**	**Total (km^2)**	**%**
Campinarana	383.0	1.2	11,084.1	18.3	11,467.1	12.4
Ecotone	24,525.8	77.3	11,930.5	19.7	36,456.3	39.5
Seasonal	2,004.3	6.3	0.0	0.0	2,004.3	2.2
Ombrophilous	3,724.1	11.7	27,974.5	46.2	31,698.6	34.3
No data [(a)]	1,109.9	3.5	9,571.4	15.8	10,681.3	11.6
Total	31,747.1 (27,322.8)	100	60,560.5 (48,043.5)	100	92,307.6 (75,366.3)	100

Table 2.

Year	ZIS		ZOS		Total	
	Deforested	Forest Fire	Deforested	Forest Fire	Deforested	Forest Fire
2000	131.5	0.6	170.7	2.0	302.2	2.5
2001	205.7	149.8	134.3	1.2	340.0	151.0
2002	51.5	4.0	105.0	0.0	156.5	4.0
2003	391.8	2,085.3	139.6	62.4	531.4	2,147.7
2004	154.8	1.7	154.2	0.1	308.9	1.7
2005	114.1	0.0	160.8	0.0	274.8	0.0
2006	129.3	12.3	100.9	1.0	230.2	13.3
2007	175.3	679.5	138.3	2.1	313.7	681.6
2008	226.9	5.5	148.3	0.4	375.1	5.9
2009	49.4	0.1	64.9	0.0	114.3	0.1
2010	41.4	15.7	67.5	1.2	108.9	16.9
Total	**1,671.7**	**2,954.4**	**1,384.4**	**70.4**	**3,056.0**	**3,024.8**
Annual mean	**152.0^{A}**	**268.6^{b}**	**125.9^{A}**	**6.4^{a}**	**277.8**	**275.0**
Deforestation units (n)	**17,028**	_	**18,619**	_	**35,647**	_
Deforestation area (ha n^{-1})	**9.8^{B}**	_	**7.4^{A}**	_	**8.6**	_

Table 3.

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Total
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2001	-	0.67	24.50	0.39	0.00	0.00	12.75	0.00	0.00	1.15	39.46
2002	-	-	1.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.14
2003	-	-	-	1.42	0.00	8.62	394.68	0.00	0.00	2.92	407.64
2004	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2005	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
2006	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
2007	-	-	-	-	-	-	-	0.00	0.01	13.02	13.04
2008	-	-	-	-	-	-	-	-	0.00	0.00	0.00
2009	-	-	-	-	-	-	-	-	-	0.00	0.00
Total (km^2)	**0.00**	**0.67**	**25.64**	**1.81**	**0.00**	**8.62**	**407.43**	**0.00**	**0.01**	**17.10**	**461.28**

Table 4.

Zone	Parameter	1≤6.6	>6.6≤12.2	>12.2≤17.9	>17.9≤23.5	> 23.5	Total
ZIS	Units (n)	11,095 [A]	3,287 [A]	1,064 [A]	463 [A]	1,119 [B]	17,028 [A]
	Area (km^2)	395.4	283.1	156.2	95.6	741.3	1,671.7
	Mean (km^2)	35.4	26.4	14.2	8.6	67.4	152.0
ZOS	Units (n)	11,985 [B]	4,450 [B]	1,177 [B]	415 [A]	592 [A]	18,619 [B]
	Area (km^2)	465.3	381.8	171.0	85.9	280.5	1,384.4
	Mean (km^2)	41.6	35.5	15.6	7.6	25.5	125.8

Table 5.

Forest types	ZIS		ZOS		Total	
	Deforested	**Forest Fire**	**Deforested**	**Forest Fire**	**Deforested**	**Forest Fire**
Campinarana	10.1	153.5	17.20	11.4	27.3	164.9
Ecotone	1,434.1	2,493.0	127.5	20.9	1,561.6	2,513.9
Seasonal	73.2	31.3	0.00	0.5	73.2	31.8
Ombrophilous	154.3	276.6	1,239.6	37.5	1,393.9	314.2
Total (km^2)	1,671.7	2,954.4	1,384.4	70.4	3,056.1	3,024.8
(%)	54.7	97.7	45.3	2.3	100	100

Figura 1

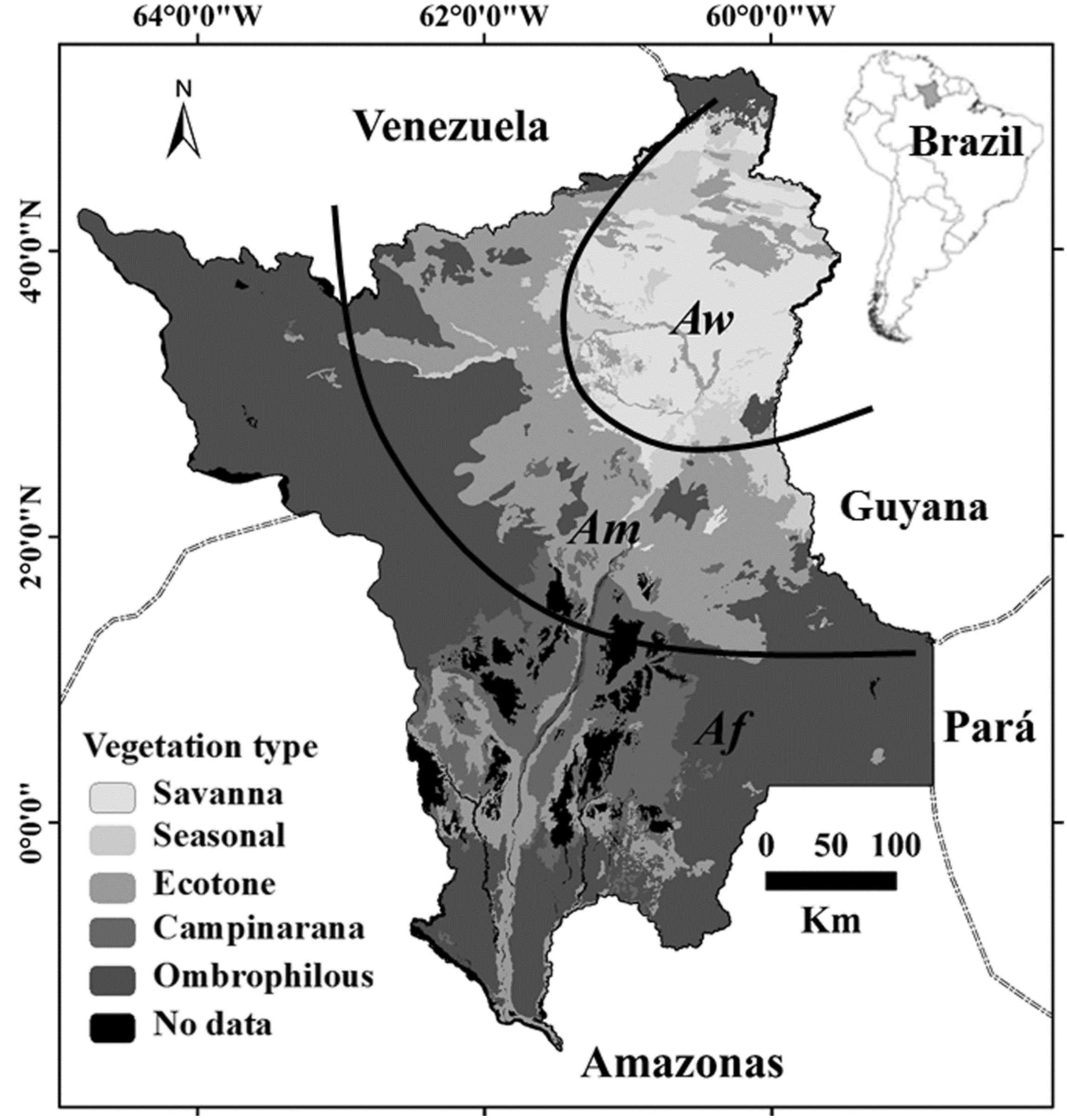

64°0'0"W
62°0'0"W
60°0'0"W
4°0'0"N
2°0'0"N
0°0'0"
N
Venezuela
Brazil
Aw
Am
Af
Guyana
Pará
Amazonas
Vegetation type
Savanna
Seasonal
Ecotone
Campinarana
Ombrophilous
No data
0 50 100
Km

Figura 2

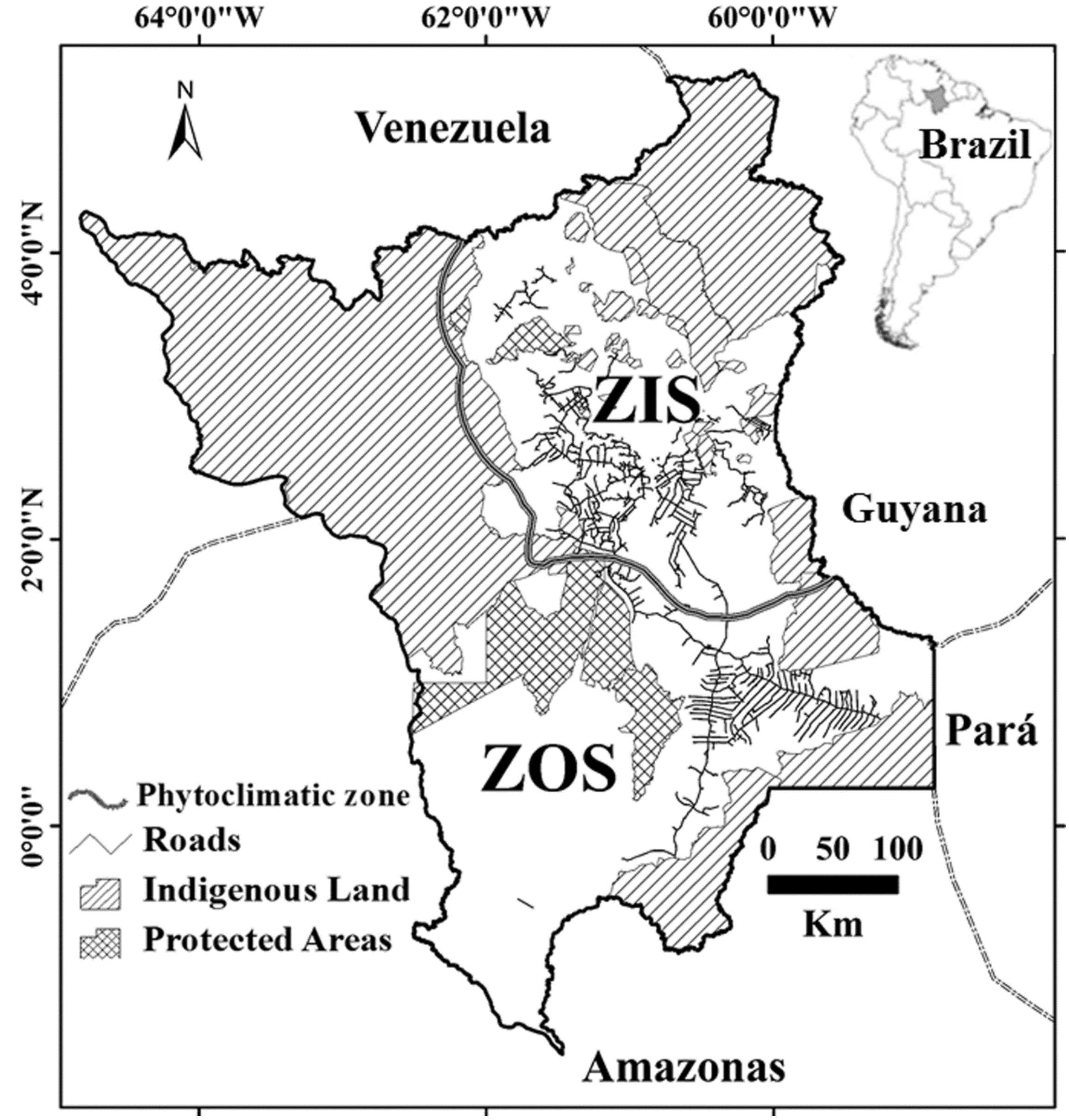

64°0'0"W
62°0'0"W
60°0'0"W
4°0'0"N
2°0'0"N
0°0'0"
N
Venezuela
Brazil
ZIS
Guyana
ZOS
Pará
Amazonas
0 50 100
Km
Phytoclimatic zone
Roads
Indigenous Land
Protected Areas

Figura 3

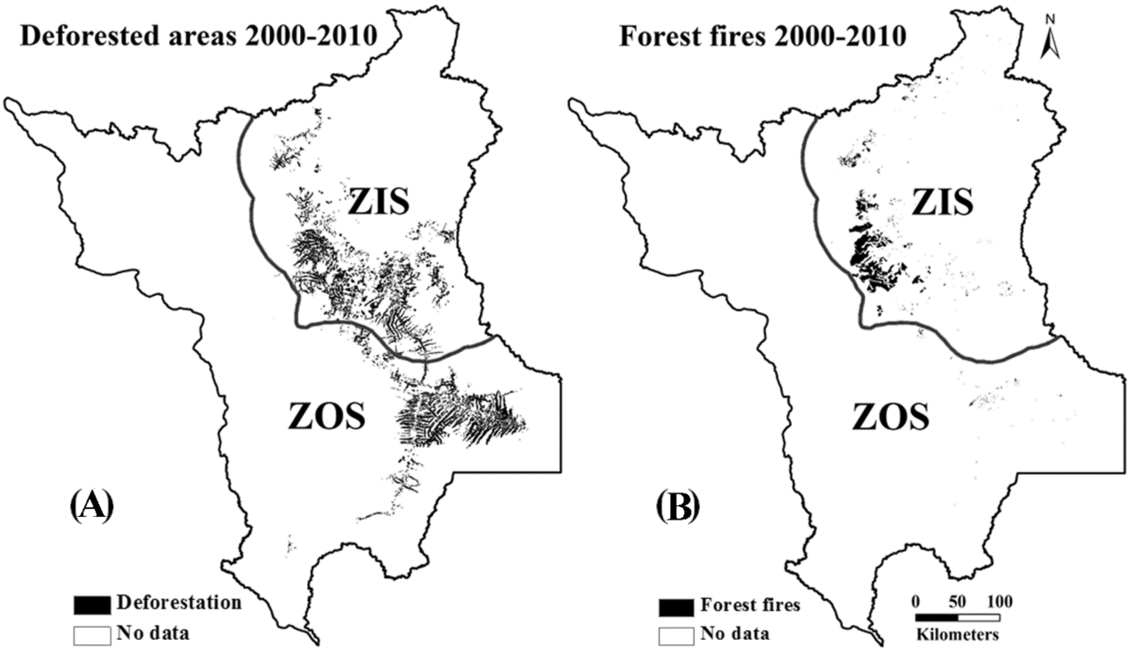

Deforested areas 2000-2010
ZIS
ZOS
(A)
Deforestation
No data
Forest fires 2000-2010
N
ZIS
ZOS
(B)
Forest fires
No data
0 50 100
Kilometers

Figura 4

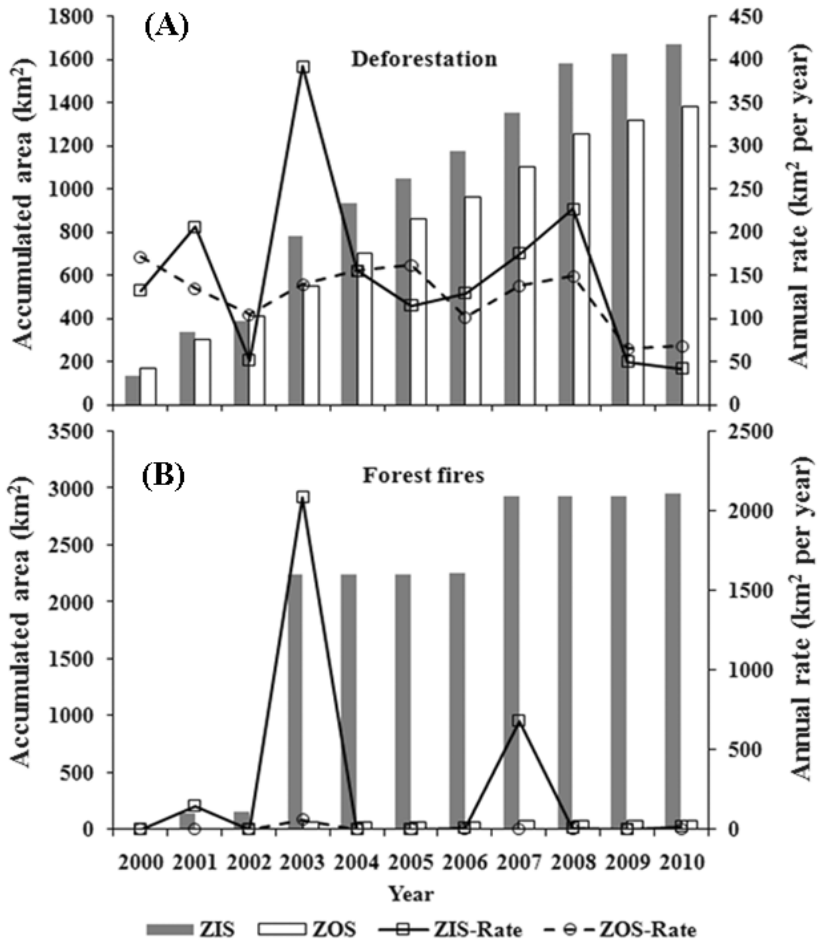

(A)
Deforestation
Accumulated area (km2)
Annual rate (km2 per year)
1800
1600
1400
1200
1000
800
600
400
200
0
450
400
350
300
250
200
150
100
50
0
(B)
Forest fires
Accumulated area (km2)
Annual rate (km2 per year)
3500
3000
2500
2000
1500
1000
500
0
2500
2000
1500
1000
500
0
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010
Year
ZIS
ZOS
ZIS-Rate
ZOS-Rate

Figura 5

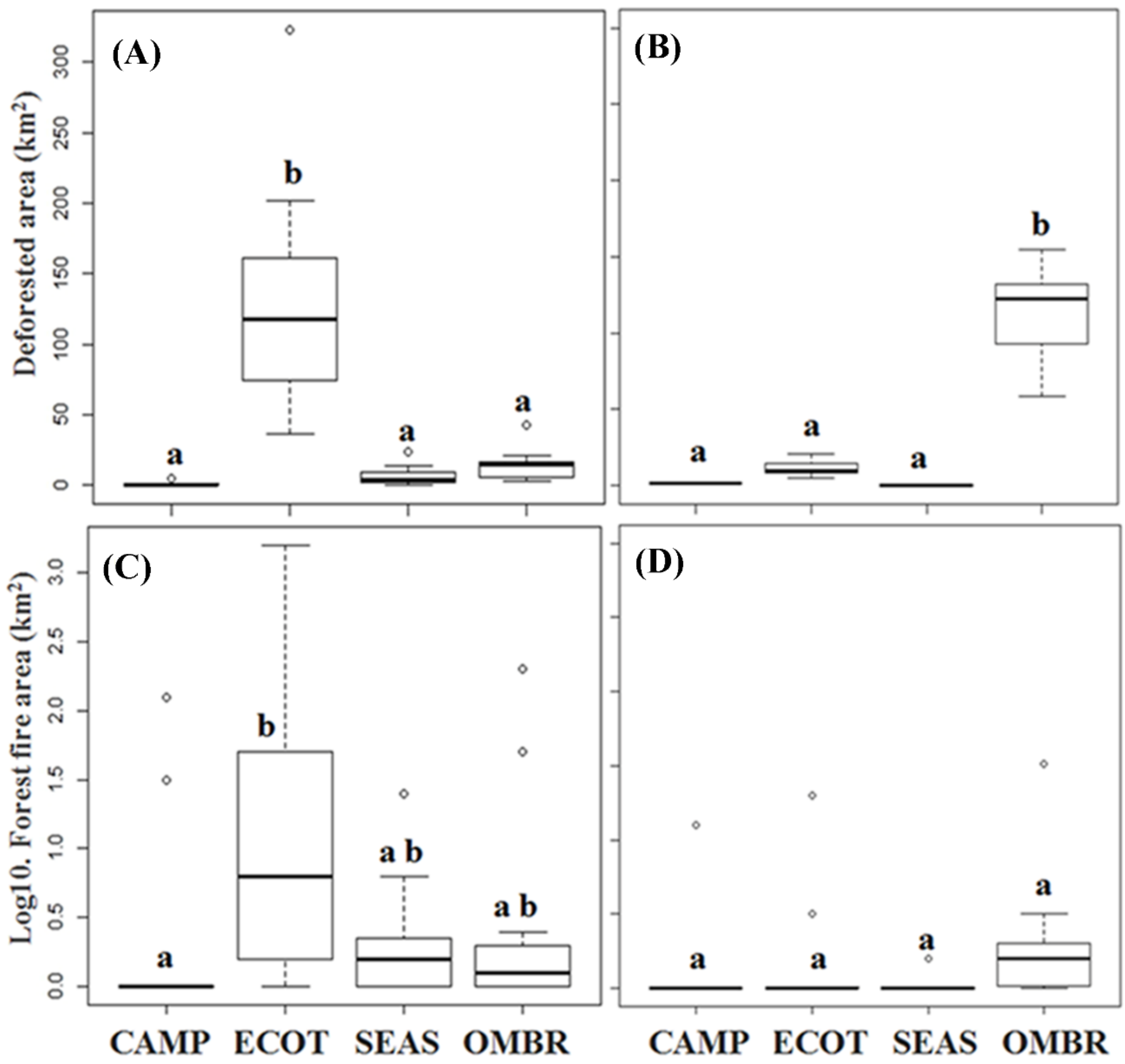
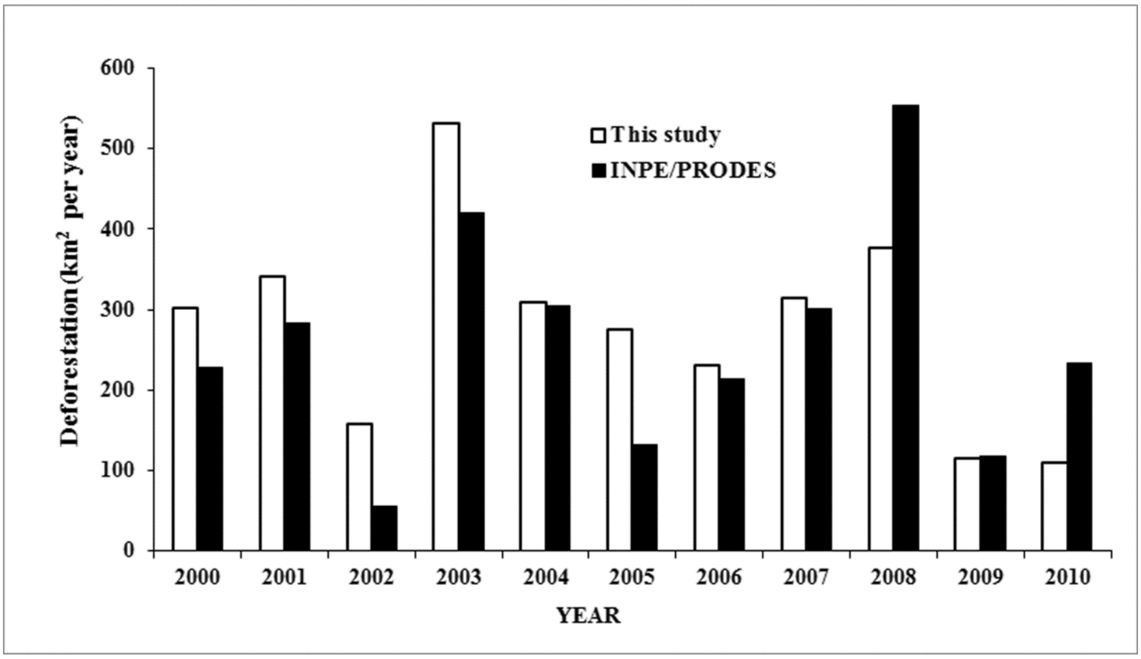

(A)
(B)
(C)
(D)
Deforested area (km²)
Log10. Forest fire area (km²)
CAMP
ECOT
SEAS
OMBR
CAMP
ECOT
SEAS
OMBR

Figura 6


Deforestation (km2 per year)
600
500
400
300
200
100
0
This study
INPE/PRODES
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
YEAR

Eletronic Supplementary Online Material

Barni P E, Pereira V B, Manzi A, Barbosa R I [(*)]. Deforestation and forest fires in Roraima and their relationship with phytoclimatic regions in the Northern Brazilian Amazon. **Environmental Management**.

(*) Corresponding author (reinaldo@inpa.gov.br)

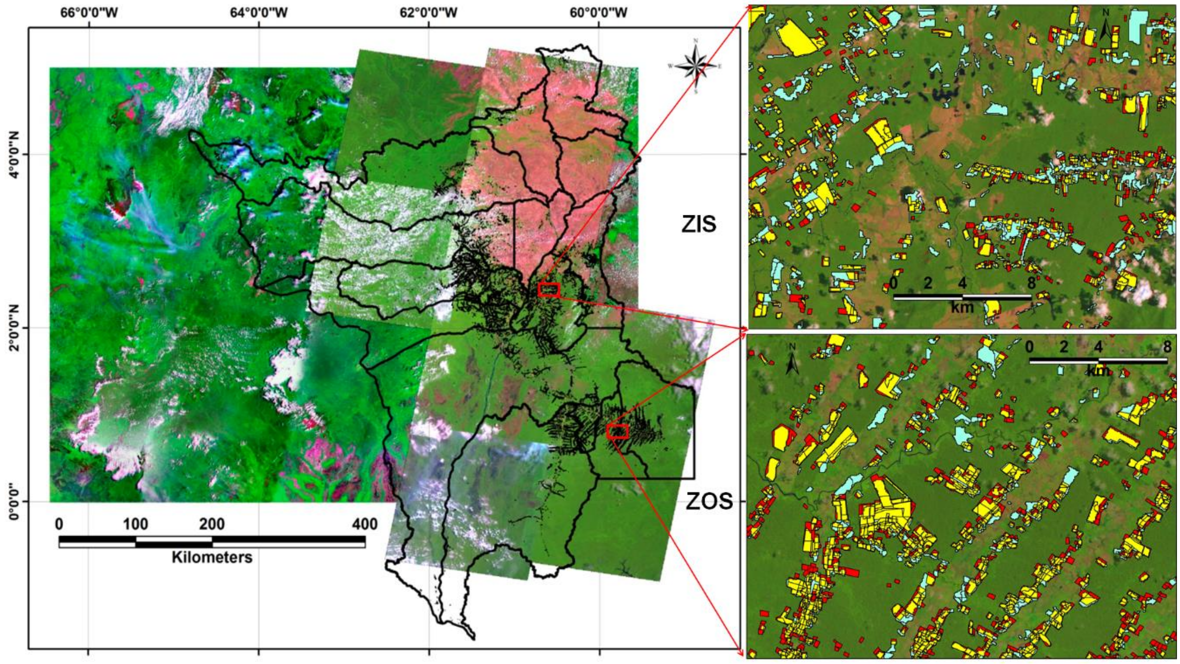


Fig. S1. Comparison of procedures for detection of deforestation in the interval under analysis (2000-2010) within the two phytoclimatic zones (ZIS and ZOS). Where: Yellow polygons = Deforestation by both PRODES (reference mapping) and this study (comparison mapping); Blue polygons = Deforestation by PRODES only; Red polygons = Deforestation by this study only. All spatial information on deforested areas in the Brazilian state of Roraima was obtained from a mosaic of Landsat-TM scenes (Geocover 2000, Zone 20 / North).

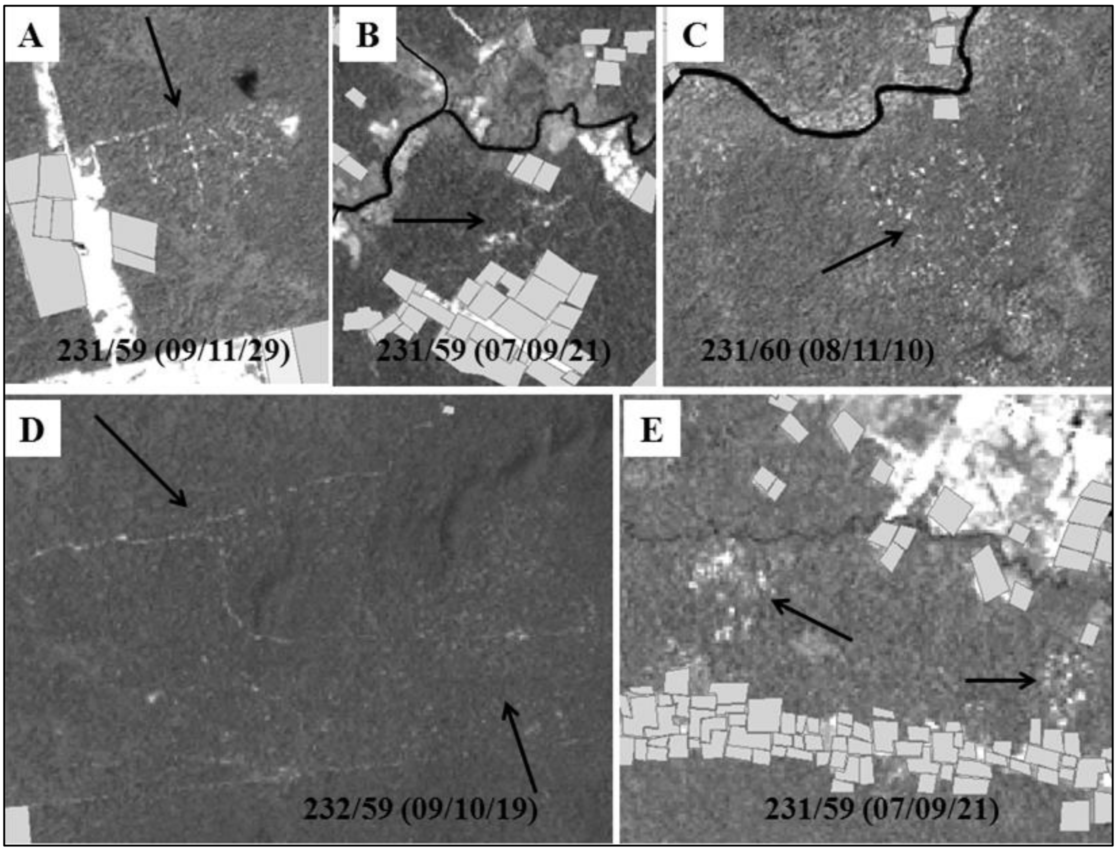


Fig. S2. Logging areas (arrows) detected through TM Landsat 5 images (R5G4B3 in grayscale) located in forest regions adjacent to deforestation areas. Where A, B, C and E are logging areas situated in ZOS; D is located in the ZIS. Path/row and date (yy/mm/dd) of the scenes in bold.

Table S1. Path-row and date (mm/dd) for Landsat 5 TM and Landsat 7 ETM images used to compose the mosaic for mapping deforestation and forest fires in Roraima (126 images). (a) = not available or with high cloud cover images.

Year	Path-row								
	231/58	**231/59**	**231/60**	**232/57**	**232/58**	**232/59**	**232/60**	**233/57**	**233/58**
1999	07/13	07/13	07/13	(a)	07/20	07/20	07/20	02/01	(a)
2000	(a)	11/04 08/16	11/04 10/19	04/01	10/26 04/01	10/26	10/26	10/17	02/04 09/15
2001	(a)	11/23 09/28	11/23 03/12	04/20	07/01 04/20	07/01	04/20	10/04	10/04
2002	10/01	10/01	10/01 02/27	01/01	01/17	08/05	08/05	09/13	09/13
2003	(a)	09/10	09/10 08/09	08/16	12/22	12/22 10/03	06/29	09/24	09/24
2004	12/01	10/14	10/14	07/01	12/08 03/11	12/08 09/19	10/21	10/12	10/12
2005	10/11	11/02 08/30	08/30	09/22	09/22	09/22	09/22	03/21	03/21
2006	(a)	10/04 09/02	10/04 09/02	04/02	04/02	09/25	09/25	04/09	04/09
2007	02/09	09/21	09/21	03/04	03/20	03/20	07/26	03/11	03/11
2008	(a)	11/10 08/06	11/10 08/06	02/03	04/07	04/07	04/07	10/23	10/23
2009	(a)	11/29 08/25	11/29 07/24	09/17	11/04 10/19	11/04 09/17	09/17	11/11 09/08	11/11 09/08
2010	(a)	10/15 04/22	10/15 04/22	10/06	10/06	10/06	09/04	01/30	04/04
2011	(a)	04/09	04/09	(a)	(a)	(a)	(a)	(a)	(a)

Table S2. Annual total area of deforestation (km^2) occurring in the forest types for the ZIS and the ZOS (between brackets). Mean test (Mann-Whitney) per polygon size occurring within the same forest type and in the same year between the two phytoclimatic zones, as well as the participation percentage of each type in relation to the total deforestation area in each zone.

Year	**Forest type**				**Total (km^2)**
	Campinarana	**Ecotone**	**Seasonal**	**Ombrophilous**	
2000	0.4^{A}	105.3^{A}	11.2^{A}	14.6^{A}	131.5
	(1.4)^{A}	(13.6)^{A}	(0.0)^{B}	(155.7)^{A}	(170.7)
2001	0.1^{A}	170.4^{A}	14.3^{A}	20.9^{A}	205.7
	(1.4)^{A}	(9.9)^{B***}	(0.0)^{B}	(123.0)^{A}	(134.3)
2002	0.1^{A}	46.6^{A}	1.1^{A}	3.7^{A}	51.5
	(1.2)^{A}	(8.1)^{A}	(0.0)^{B}	(95.7)^{A}	(105.0)
2003	1.2^{A}	323.4^{A}	24.0^{A}	43.1^{A}	391.8
	(2.3)^{A}	(20.9)^{B***}	(0.0)^{B}	(116.4)^{B***}	(139.6)
2004	1.2^{A}	133.3^{A}	3.6^{A}	16.7^{A}	154.8
	(2.4)^{A}	(16.2)^{B***}	(0.0)^{B}	(135.6)^{A}	(154.2)
2005	0.2^{A}	102.9^{A}	2.9^{A}	8.0^{A}	114.1
	(1.2)^{A}	(8.6)^{B**}	(0.0)^{B}	(150.9)^{B***}	(160.8)
2006	0.6^{A}	117.5^{A}	2.9^{A}	8.2^{A}	129.3
	(0.9)^{A}	(8.9)^{B*}	(0.0)^{B}	(91.1)^{B***}	(100.9)
2007	4.8^{A}	151.5^{A}	4.2^{A}	15.0^{A}	175.3
	(2.0)^{A}	(12.1)^{B***}	(0.0)^{B}	(124.2)^{B***}	(138.3)
2008	0.4^{A}	202.0^{A}	7.6^{A}	16.8^{A}	226.9
	(1.6)^{A}	(17.3)^{A}	(0.0)^{B}	(129.4)^{B***}	(148.3)
2009	0.4^{A}	44.8^{A}	0.8^{A}	3.5^{A}	49.4
	(1.3)^{A}	(4.8)^{A}	(0.0)^{B}	(58.8)^{B*}	(64.9)
2010	0.7^{A}	36.3^{A}	0.6^{A}	3.7^{A}	41.4
	(1.5)^{A}	(7.1)^{A}	(0.0)^{B}	(58.8)^{B***}	(67.5)
Total (km^2)	**10.1**	**1,434.1**	**73.2**	**154.3**	**1,671.7**
	(17.2)	**(127.5)**	**(0.0)**	**(1,239.6)**	**(1,384.4)**
%	**0.6**	**85.8**	**4.4**	**9.2**	**100**
	(1.2)	**(9.2)**	**(0.0)**	**(89.5)**	**(100)**

Different letters within the column and for the same year represent significant differences. *, ** and ***, correspond to α=0.05, α=0.01 and α=0.001, respectively.

Table S3. Mean, standard deviation (SD), number of deforested units (Count) and corresponding deforested area (Total) by forest type in the study area from 2000 to 2010. Different letters in the line for the same forest type represent significant differences between means (t-test, $\alpha = 0.05$).

Forest type	ZIS				ZOS			
	Mean (ha)	SD (ha)	Count (unit)	Total (km^2)	Mean (ha)	SD (ha)	Count (unit)	Total (km^2)
Campinarana	10.9^{A}	12.1	93	10.1	4.7^{B}	4.7	369	17.1
Ecotono	9.9^{A}	27.9	14,378	1,434.1	5.9^{B}	9.5	2,157	127.5
Seasonal	10.3	18.0	712	73.2	-	-	-	-
Ombrophilous	8.3^{A}	15.3	1,846	154.3	7.7^{A}	11.5	16,092	1,239.6

Table S4. Annual forest fire-affected area (km²) within the forest types for the ZIS and the ZOS (values between brackets). The table further shows the participation percentage of each forest type in terms of the total forest fire affected area within each phytoclimatic zone.

Year	Forest type				Total (km^2)
	Campinarana	Ecotone	Seasonal	Ombrophilous	
2000	0.0	0.1	0.5	0.0	0.6
	(0.0)	(0.0)	(0.0)	(2.0)	(2.0)
2001	0.1	143.4	4.9	1.5	149.8
	(0.0)	(0.0)	(0.0)	(1.1)	(1.2)
2002	0.0	1.9	1.7	0.4	4.0
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
2003	124.2	1,717.2	22.6	221.3	2,085.3
	(11.4)	(19.1)	(0.5)	(31.4)	(62.4)
2004	0.0	1.5	0.0	0.2	1.7
	(0.0)	(0.0)	(0.0)	(0.1)	(0.1)
2005	0.0	0.0	0.0	0.0	0.0
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
2006	0.0	11.8	0.5	0.0	12.3
	(0.0)	(0.0)	(0.0)	(1.0)	(1.0)
2007	29.3	609.9	1.1	52.8	693.1
	(0.0)	(1.8)	(0.0)	(0.3)	(2.1)
2008	0.0	5.2	0.0	0.3	5.5
	(0.0)	(0.0)	(0.0)	(0.4)	(0.4)
2009	0.0	0.1	0.0	0.0	0.1
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
2010	0.0	15.7	0.0	0.0	15.7
	(0.0)	(0.0)	(0.0)	(1.2)	(1.2)
Total (km^2)	**153.5**	**2,513.9**	**31.3**	**276.6**	**2,954.4**
	(11.4)	**(20.9)**	**(0.5)**	**(37.5)**	**(70.4)**
%	**5.2**	**84.5**	**1.1**	**9.3**	**100**
	(16.2)	**(29.7)**	**(0.8)**	**(53.3)**	**(100)**