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Dynamics of forest fires in the southwestern Amazon

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Abstract

The synergism between climatic change and human action has provided conditions for the occurrence of forest fires in the Amazon. We used annual mapping to reconstruct the history of fire in Brazil's state of Acre to understand the forest-fire regime over a period of 33 years (1984 to 2016). The burn-scar index (BSI) derived from the fractions of soil and of photosynthetic and non-photosynthetic material was generated by CLASlite© software using Landsat-TM and OLI satellite images. The area of forest-fire scars totaled 525,130 ha in the period analyzed. This total includes forests that fire affected only once (388,350 ha), twice (59,800 ha) and three times (5727 ha). The years 2005 and 2010 represent 90% of the total area of forest fires in Acre, coinciding with severe droughts caused by the anomalous warming of the tropical North Atlantic Ocean. The most heavily impacted portion of Acre was in the eastern part of the state, which has the greatest forest fragmentation, consolidation of agricultural activity and presence of settlement projects. In 2005, the municipalities of Acrelândia, Plácido de Castro and Senador Guiomard accounted for more than 50% of the forest remnants impacted by fire. Of the total extent of forest fires in Acre, 43% occurred in settlement projects administered by the National Institute for Colonization and Agrarian Reform (INCRA) and 16% in conservation units administered by the Ministry of Environment (MMA). The area of forest fires was 36 times greater in the 16 years after 2000, compared to the 16 years before 2000. The frequency of fires increased dramatically from one fire episode roughly every ten years (period from 1984 to 2004), to one fire every five years (period from 2005 to 2016). With the projections of warmer climate and advancing deforestation, the dynamics of forest fires in Acre will tend be more intense and frequent.

Keywords

droughts, forest degradation, fragmentation, climate change, tropical forest, rain forest, Brazil, Amazonia, Acre

1. Introduction

Forest fires and logging have stood out as the principal causes of forest degradation in the Amazon in recent years (Aragão and Shimabukuro, 2010; Barlow et al., 2016; Bowman et al., 2009; Cochrane and Barber, 2009; Trumbore et al., 2015). Souza et al. (2013) estimated that forest degradation represents 30% of the deforested area in Brazilian Amazonia as a whole.

The normal conditions of the Amazonian climate, with high humidity and rainfall, do not favor the occurrence of natural fires (Fernandes et al., 2011). The Amazon has experienced Mega El Niño events accompanied by large fires at intervals ranging from 300 to 500 years from 1800 to 400 BP (Bush et al., 2008; Meggers, 1994). However, in recent years the synergism between climatic extremes and human action has provided conditions for the occurrence of large forest fires at much shorter intervals than in the past (Aragão and Shimabukuro, 2010; Cochrane and Barber, 2009; Lewis et al., 2011). Over the past 40 years, forest-fire peaks have occurred every 4 to 5 years in different parts of the basin (Alencar et al., 2004; Aragão et al., 2018; Silva et al., 2013; Vasconcelos et al., 2013; Xaud et al., 2013).

Vulnerability of Amazonian forests to fires, as well as the spatial and temporal distributions of the fires, have been associated with extreme droughts caused by anomalous increases in sea-surface temperature in the Pacific in the case of El Niño and in the tropical North Atlantic in the case of the Atlantic dipole. The northern and northeastern portions of Brazilian Amazonia are most affected by El Niño (Alencar et al., 2004; Chen et al., 2013; Fearnside, 1990; Schroeder et al., 2009). In the southern and southeastern portions of Amazonia, extreme drought is often associated with warming the surface of the tropical portion of the North Atlantic Ocean (Aragão et al., 2018, 2007; Chen et al., 2013; Marengo et al., 2008; Zeng et al., 2008). There is also a combination of these two types of anomalous warming that has an impact throughout the Amazon, as in 1982-83, 1997-98, 2009-10 and 2015/2016 (Aragão et al., 2018; Marengo and Espinoza, 2016).

Mapping forest-fire scars in the Amazon allows integration of temporal resolution with the geographical context of the fire. Alencar et al. (2011) mapped such scars over a 23 year period at a fine spatial resolution (30-m pixels). Morton et al. (2013) monitored forest fires over a period of 13 years in southern Amazonia, but with low spatial-resolution images (250-m pixels). Mapping using political boundaries of states, which represents the level at which decisions to control and prevent deforestation and fires are taken, has been done in a few studies for specific years: Acre in 2005 (Shimabukuro et al., 2009), Mato Grosso in 2010 (Anderson et al., 2015) and Roraima in 1997/98 (Barbosa and Fearnside, 1999; Barni et al., 2015). With an increasing number of mappings of forest fires, there has been an evolution in the validation and calculation of uncertainty (Anderson et al., 2017; Foody, 2008; Mack et al., 2014; Padilla et al., 2014).

Acre was the epicenter of the severe droughts of 2005 and 2010 (Lewis et al., 2011) that provided conditions for large forest fires. However, no historical analysis has been done with mapping of areas impacted by forest fires, their frequency and recurrence, and the relationship with human activity and extreme droughts. The objective of this study was to analyze the extent and characterize the spatial and temporal dynamics of forest fires in the state of Acre in the southwestern portion of the Brazilian Amazon. Our study was intended to answer the following questions: (1) What was the extent of forest fires over a period of 33 years? (2) What extreme drought type had the greatest influence on the occurrence of forest fires, years of El Niño or of warm surface water in the tropical North Atlantic? (3) What is the relationship between deforestation and forest fires? (4) What is the spatial distribution of fires between municipalities and land-tenure types?

2. Data and methods

2.1. Study area

The analysis covers the entire state of Acre (Figure 1). Acre is at the western end of the "arc of deforestation," an area that extends from Paragominas, Pará to Rio Branco, Acre; this area is connected by highways and is the location of most deforestation in the Brazilian Amazon (Fearnside, 2005). In Acre, the agricultural frontier is expanding between the municipalities of Rio Branco and Cruzeiro do Sul along Highway BR-364 and in the northern portions of the municipalities of Porto Acre and Sena Madureira, which border on the state of Amazonas.

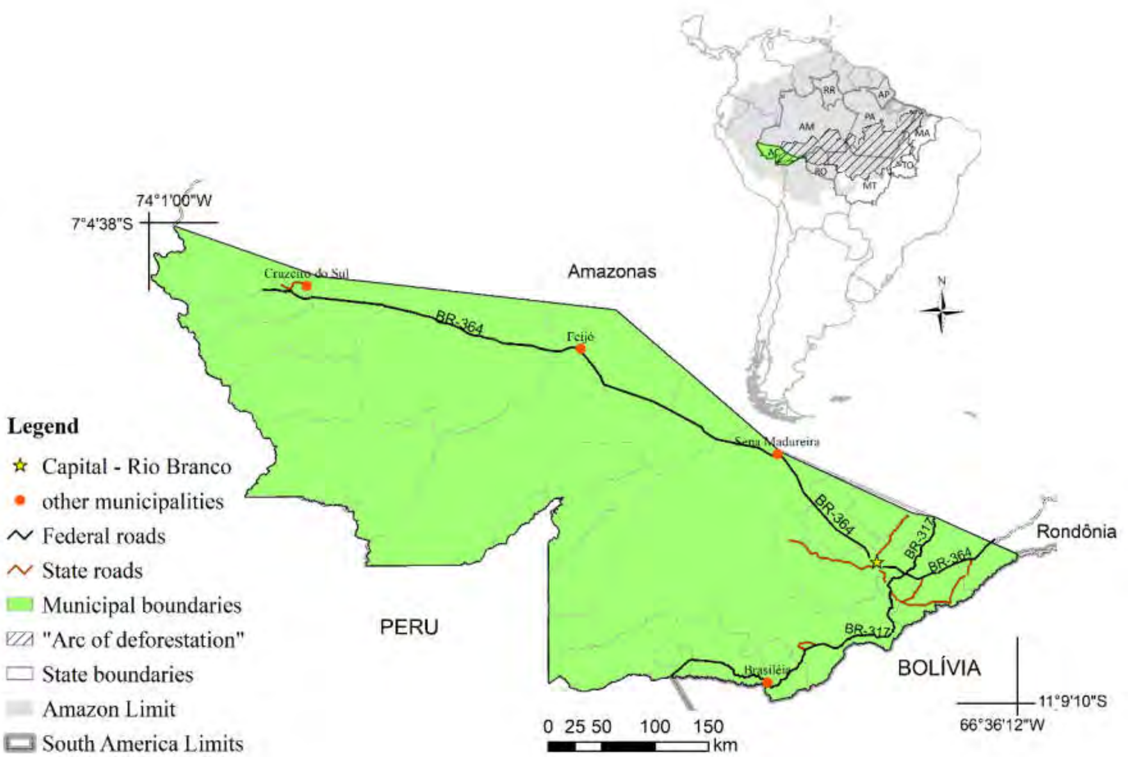


Figure 1. Location of the study area, Acre state, Brazil.

2.2. Mapping of forest fires based on Landsat satellite data

Forest fires were defined in this study as those in which the crowns of the trees were directly or indirectly affected by fire to the point that they cause a detectable impact on the optical satellite images, representing the scar left by the fire. Many fires were probably not detected because they were not strong enough to reach the canopy, affecting only the understory of the forest.

To identify forest-fire scars in the state of Acre we used Landsat 5 TM (Thematic Mapper), Landsat 7 ETM + (Enhanced Thematic Mapper Plus) and Landsat 8 OLI (Operational Land Imager) satellite images from 1984 to 2016. The images were accessed without cost on the United States Geological Survey (USGS) website (http://earthexplorer.usgs.gov/). The dates of the images used for processing are from September to December. Images were used from March to June for years with cloud problems or with very large fires in order to map the fire events in their totality (Supplementary Material, Table S1 and Figure S1).

Image processing was performed using CLASlite 3.0 free software, a compact version of the Carnegie Landsat Analysis System (CLAS). This software uses a spectral-mixing model associated with a robust spectral library to generate fractions that represent the main biophysical components of the landscape in a pixel (Asner et al., 2009). The gross images in DN (digital number) were automatically corrected radiometrically for atmospheric effects and transformed into reflectance (Figure 2a).

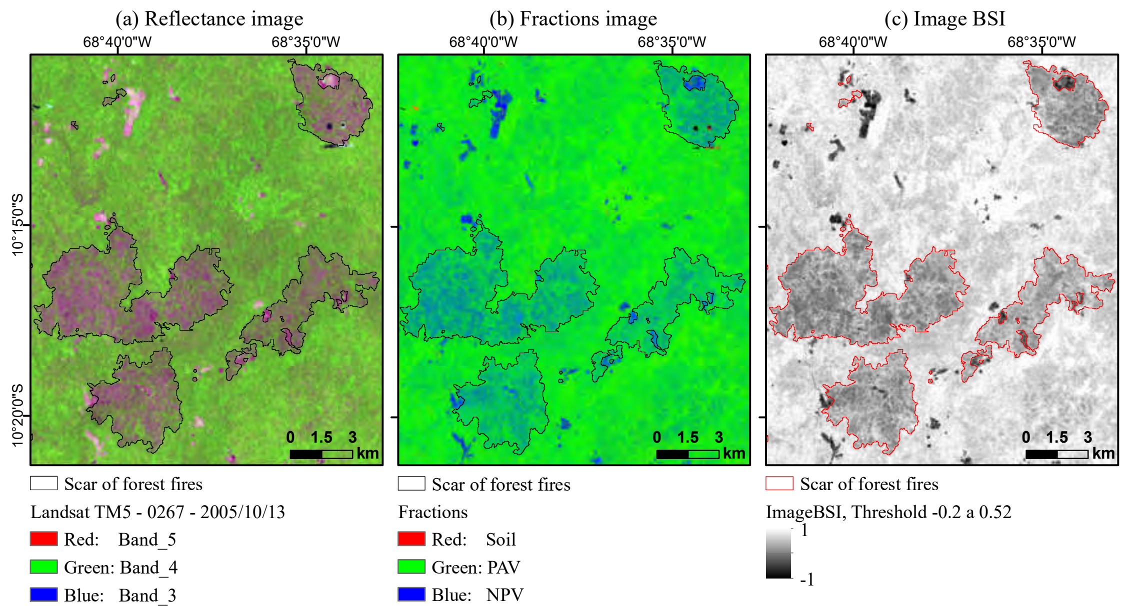


Figure 2. Example of (**a**) reflectance, (**b**) fractions and (**c**) Burn-scar index (BSI) in a Landsat TM5 image from 13 October 2005, Path 002, Row 067.

Fraction-images were derived from the linear spectral mixing model. The following fractions were identified: photosynthetically active vegetation (PAV), non-photosynthetic vegetation (NPV) and soil (S). Based on the fraction images (Figure 2b), the burn-scar index (BSI) (Figure 2c) was applied following Alencar (2010), as in Equation (1).

$$BSI = (PAV - NPV) / (PAV + NPV) \quad (1)$$

In order to analyze only forested areas and reduce errors of commission, a deforestation mask was applied year-by-year to the images used to calculate the BSI. This reduces the interpositions of the NPV fraction between deforested areas and forest-fire areas, mainly where the fire was intense.

For the years 1997 to 2016 a deforestation mask was applied with data from the PRODES program of INPE (National Institute for Space Research), which monitors Brazil's Amazon rainforest annually (Brazil, INPE, 2016). For the period from 1984 to 1986 the image interpretation for deforestation was done by manual editing. Local knowledge of an interpreter is necessary in order to avoid commission errors with specific punctual events, such as blowdowns, vegetation under extreme water stress and senescent bamboo populations in open forests (Carvalho et al., 2013; Espírito-Santo et al., 2014; Nelson et al., 1994) (Supplementary Material, Figure S2).

We obtained the final product for forest-fire mapping by the BSI image-slicing method, subjectively defining the thresholds by trial and error using the color composition of the reflectance images as a guide to identify forest-fire scars. For each scene we set an average of 10 thresholds, after which it was possible to standardize the threshold value for the scene. Silva et al. (2013) observed that there is no standard or fixed threshold for this identification, which changes from scene to scene according to fire intensity, vegetation contrast, and image noise. In this study, the average threshold in all years and scenes identified by slicing ranged from -0.15 to 0.4. In years of extreme drought the threshold ranged from -0.3 to 0.53, while in normal years the threshold ranged from -0.1 to 0.38.

After slicing the BSI image, a medium smoothing filter with a window of 5 × 5 pixels was applied to reduce the number of isolated badly classified pixels. The next step was to convert the raster map into a vector map for visual auditing, allowing deletion of poorly sorted polygons.

2.3. Validation of the mapping of forest fires

Remote sensing has been widely used for assessing the dynamics of land use, but field validation is indispensable in order to compare remotely sensed data with ground truth and estimate the margin of error. Validation of mapping in a large area like the state of Acre requires visiting a sufficient number of points in the field – a task that requires substantial financial resources. To supplement our field points we therefore used additional points at randomly selected locations on the images, and the classifications of these points were confirmed by experienced interpreters.

Validation in the field was performed for 139 points, and an additional 2500 random points were identified on the Landsat images (Figure 3). Verification in the field was performed between 2015 and 2016; 22 points were checked in intact forest areas and 106 forest points were checked at locations mapped as forest-fire scars. In addition, 21 points were observed by Irving Foster Brown in overflights in 2005. Field observations determined whether charcoal was present at the base of standing or fallen trees, and residents confirmed the impossibility of entering the forest. To validate the mapping using random points we used the Landsat image base to map the 2005 scars, generating 500 points in areas mapped as scars and 2000 points in intact forest areas. These points were audited by two interpreters.

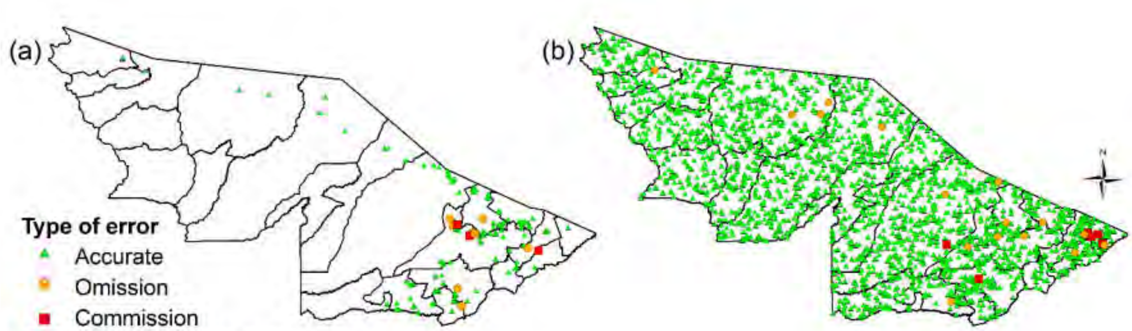


Figure 3. Location of (**a**) validation points in the field and (**b**) random points of forest-fire scars.

Assessment of the overall accuracy of the classification and estimation of errors of omission and commission were performed using an error matrix as proposed by Anderson et al. (2017). The accuracy of the mapping (global accuracy) was 98%; errors of omission were 0.7%, and errors of commission were 0.6% (Table 1). The main errors of omission identified were: forest fires occurring after the date of the image used for mapping, low-intensity fires with little impact on the canopy and fires in small forest fragments. The errors of commission were: shading by thin clouds and smoke, displacement of the deforestation mask and vegetation under extreme water stress.

Table 1. Error matrix for mapping forest-fire scars.

Classification	**Burned forest**	**Unburned forest**	**Total**
Mapped as burned forest	626	9	635
Mapped as unburned forest	24	2006	2030
Total	650	2015	2665
		Confidence interval	
	Estimate	Lower bound	Upper bound
Accuracy Fire forest class user's accuracy[a]	99%	97%	99%
Not fire forest class user's accuracy[b]	99%	98%	99%
Fire forest class producer's accuracy[c]	63%	54%	72%
Unburned forest class producer's accuracy[b]	100%	100%	100%
Overall accuracy	99%	98%	99%
Area error	-1%	-2%	-1%

a. This combines two different data sets: field observations and images.
b. "User's accuracy" = Probability of a pixel as classified on the map representing the same category on the ground.
c. "Producer's accuracy" = Probability of a reference pixel being correctly classified.

2.4. Temporal and spatial relations of forest fires with drought, deforestation, land-use category and logging

Drought

As an indicator to separate normal drought years from those with extreme droughts we used satellite rainfall data from the Tropical Rainfall Measuring Mission (TRMM) and calculated anomalies in the maximum cumulative water deficit (MCWD) for the period from 1998 to 2016 using the method of Aragão et al. (2018). We generated the MCWD for the dry season (June to September), a period in which fire is used in agricultural practices. To characterize the water deficit in the dry season we applied a 100-mm month^{-1} limit to define the dry-season months based on Aragão et al. (2007). From the MCWD anomaly we calculated pixel-by-pixel means and standard deviations of MCWD for each year in the 1998-2016 period, with exception of 1998, 2005 and 2010. Values of positive or negative anomalies (σ) for $1.65 \leq \sigma < 1.96$ are significant at the 90% confidence level, and for $1.96 \leq \sigma < 2.58$ these values are significant at the 95% confidence level.

To characterize the entire period of forest-fire mapping we used data from the conventional meteorological station at Rio Branco reported in the Meteorological Database for Teaching and Research (BDMEP) of the National Institute of Meteorology (INMET) for the period from 1984 to 2016. We used the maximum number of consecutive days with rainfall less than 3 mm and the number of days with maximum daily temperature above 35 ° C for the dry season period, from June to October. The choice of daily maximum temperature was defined by sensitivity tests that could or differentiate years of extreme drought from other years.

Deforestation

We used data from the PRODES program of INPE (National Institute for Space Research) for the period from 1997 to 2016 to evaluate the reduction of forest-fire scars by subsequent deforestation. We analyzed the percentage of deforestation of scars burned only once, burned two times and burned three times. We also analyzed the time elapsed between forest burning and subsequent deforestation.

Land-use category

The spatial distribution of forest fires for 2005 and 2010 was analyzed in relation to the municipal (county) boundaries and land -use categories that were maintained from 2004 to 2016. Municipal boundaries were obtained from the IBGE (Brazilian Institute of Geography and Statistics) database updated to 2005, containing 22 registered municipalities (Brazil, IBGE, 2016). The data on Acre's land tenure were provided by the Acre state government from the 2nd version of the Economic Ecological Zoning of Acre, which is considered to be an official database. The following classes were analyzed: INCRA settlement projects (SPs), private properties (PPs), federal government lands (GLs), conservation units (CUs) and indigenous lands (ILs). Identification of the years of fires and the delimitation of municipal boundaries and of land-use categories were carried out to determine where there were the most fires and whether these could be related to the type of land use. This also serve to avoid misleading results that could be caused by alterations of land-use categories and political boundaries, which can occur over time.

Logging

We used Landsat scene 002/067 as the reference for exploratory mapping of the area with logging. The identification was made visually in the period from 1984 to 2016 using the same scenes that were used to map forest fires. We analyzed four combinations: logging that did not coincide with forest fires, logging before forest fires, logging in the same year as forest fires and logging after forest fires.

3. Results

3.1. History of forest fires

The total area of forest-fire scars mapped over the 33-year period was 525,132 ha (Figures 4a and 4b), with a 95% confidence interval of 521,369 ha - 528,426 ha calculated by the method of Anderson et al. (2017). This total includes forests that were affected by fire only once (388,351 ha), twice (59,800 ha) and three times (5727 ha). The years 2005 and 2010 accounted for 471,745 ha, or 90% of the total area affected by forest fires over the 33-year period.

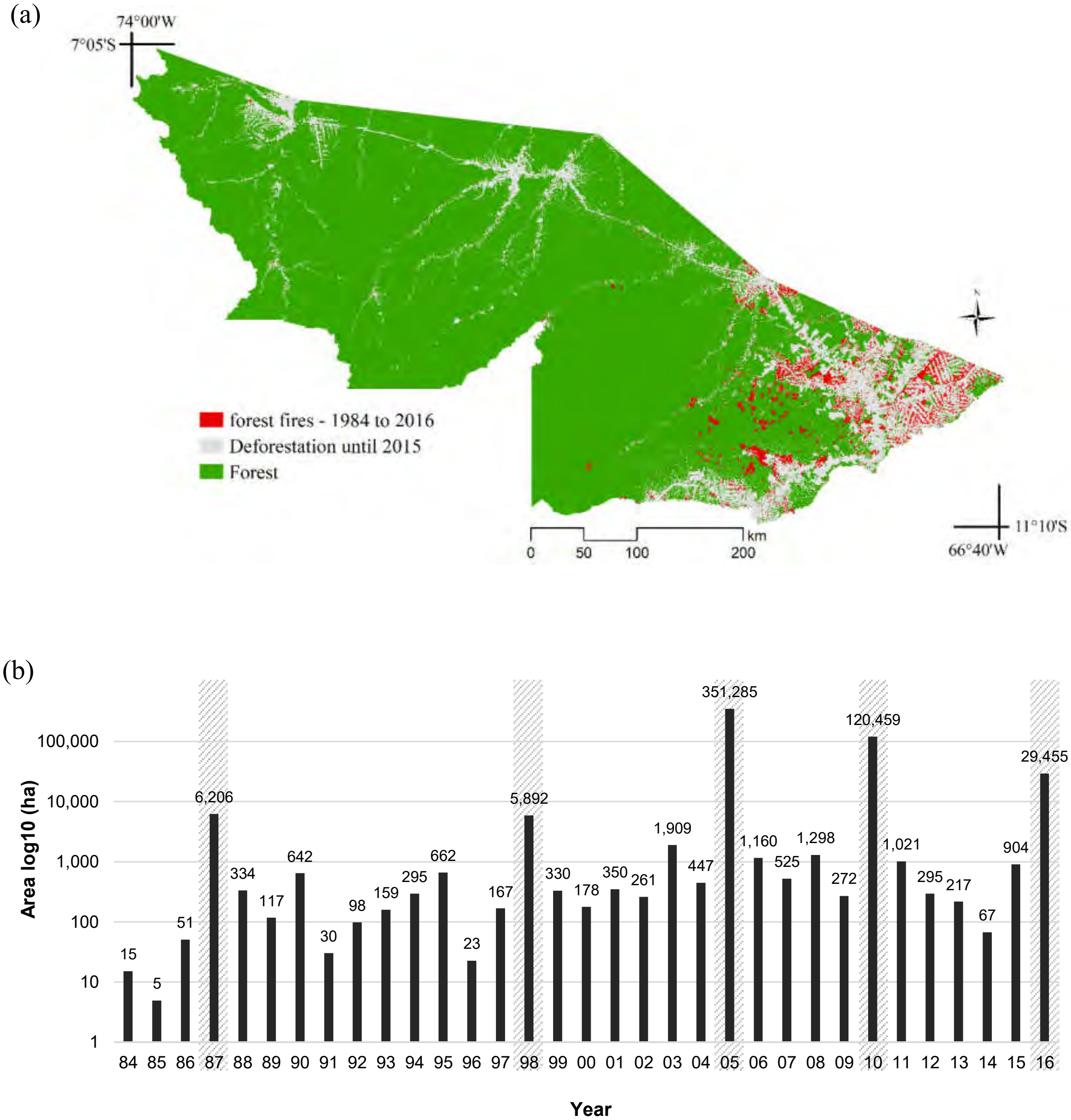


Figure 4. Historical series of forest fires for the state of Acre for the period from 1984 to 2016. (a) Spatial distribution of fires and (b) Temporal distribution of the annual area of occurrence of forest fires, where the cross-hatched bars indicate years of extreme drought from El Niño and/or anomalous warming of the tropical North Atlantic Ocean (Atlantic dipole).

Over the 33-year period there was an average of one large fire every seven years (1987, 1998, 2005, 2010 and 2016). With the shortening of the recurrence time of forest fires, the area of forest impacted by fire increased over time. The burn-scar area in the second half of the study period (2001 to 2016) was 36 times greater than the area burned in the first half (1984 to 2000) (Figure 4b). More detailed information on the total, maximum and average area of forest fire scars is provided in the Supplementary Material (Table S2).

3.2. Extreme drought

The years with extreme droughts recorded by both the MCWD anomaly analysis (Figure 5; Annual maps are provided in the Supplementary Material, Figure S3) and the maximum number of consecutive days without rainfall and with high temperatures (Figure 6) were: 1987, 1998, 2005, 2010 and 2016, which concentrated 98% of the forest fire scars. These years coincide with the years with areas of forest-fire-scars greater than 6000 ha. The MCWD anomaly in all extreme-drought years was greater than -1.96, which is compatible with periods longer than 43 consecutive days without rainfall and 35 days with temperatures > 35 °C. The droughts of 2005 and 2010 were stronger, with a further 62 consecutive days without rainfall, reflecting anomaly values below -3. Unlike 1987 and 1998, when forest fires affected less than 6000 ha and were restricted to the eastern region of Acre, the El Níño of 2016 impacted four times more area and affected parts of Acre that had never been impacted since the beginning of our monitoring, as in the municipality of Feijó in central Acre. In 2016 there was a record number of days with high temperatures (66 days), which may have aggravated the effect of the rainfall deficit.

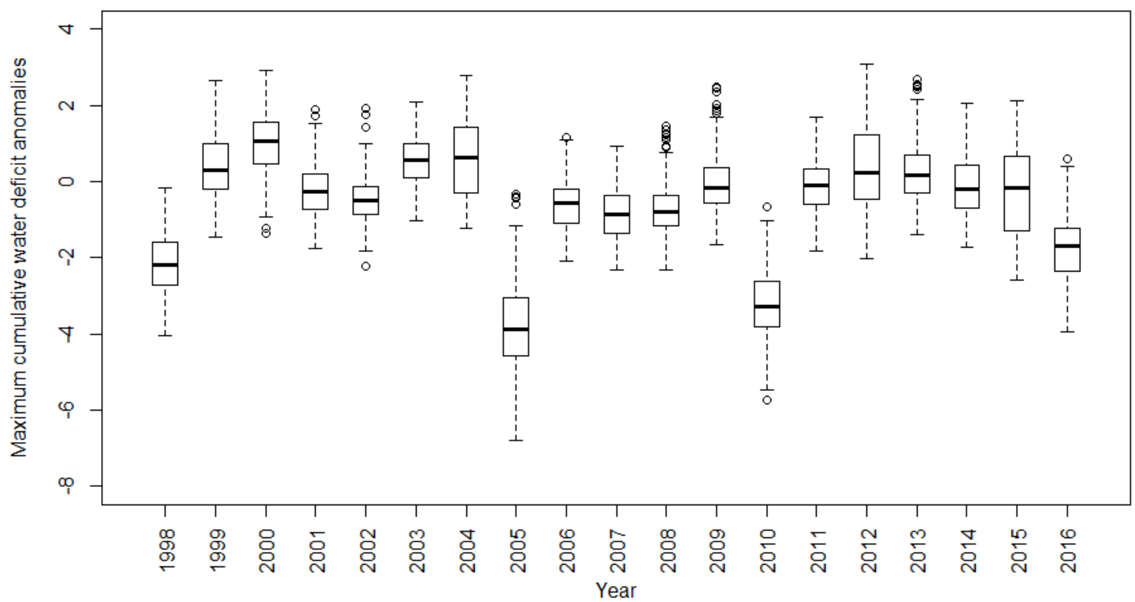


Figure 5. Boxplots of MCWD (maximum cumulative water deficit) for the state of Acre from 1998 to 2016.

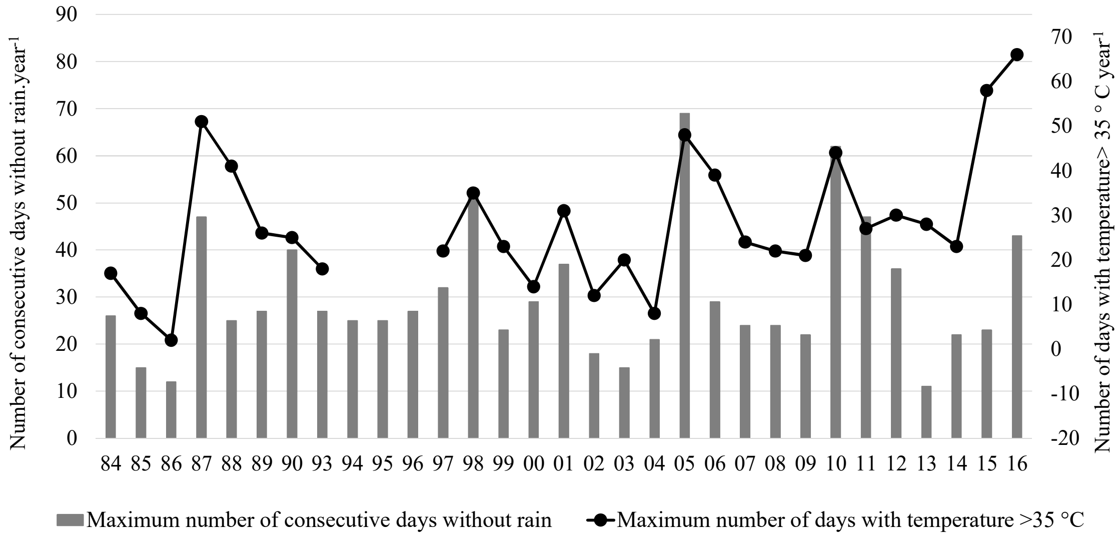


Figure 6. Maximum numbers of consecutive days without rain each year and total number of days with temperature above 35 °C in the months from July to October, based on data from the conventional meteorological station in Rio Branco from 1984 to 2016.

Analyzing the sequence of Landsat images for 2005, 2010 and 2016 every 15 days for scenes 001/067 and 002/067, we observed that the cumulative daily water deficit (CWD) for the first visualization of forest-fire scars was from -174 mm to -200 mm in the most-fragmented area (scene 001/067). The CWD ranged from -220 mm to -230 mm in the least-fragmented area (scene 002/067). For forest-fire scars in large non-fragmented forest blocks, the CWD was -319 mm. This information can be of key importance as a basis for issuing alerts.

3.3. Fire and deforestation

There was no relation in the time series between fires and deforestation in the state of Acre (Figure 7). However, 88% of the forest-fires scar area was in the eastern portion of Acre, where there is more deforestation and greater forest fragmentation (Figure 5a). Another interaction observed was that 27% of the area affected by forest fires was deforested in the years following the occurrence of the fire, leaving 349,760 ha of forests in Acre still standing in 2015 that had been degraded by fire (Table 2). The smaller the area of a forest fragment affected by fire, the greater the chance of this area being subsequently. In years of normal drought, fires affect small areas as compared to extreme-drought years; however, the percentage of the area of the scars that is subsequently deforested is higher (average 68%) for scars formed in years without extreme drought than in other years (average of 30%). The time course for this deforestation also changes, and in the period from 1984 to 2001 the time for deforestation of at least 60% of the forest-fire scars area averaged 14 years, and for the subsequent period (2002-2015) the time to reach this percentage averaged six years. Up to 2016 the percentages of the burned area that had been deforested were 44% for polygons up to 50 ha in area, 26% for polygons 50 to 1000 ha in area and 16% for polygons greater than 1000 ha in area.

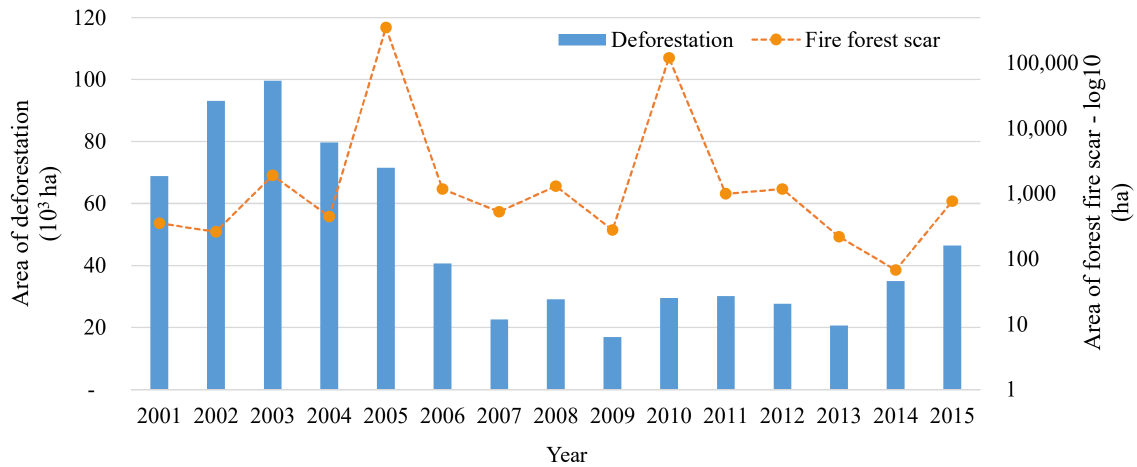


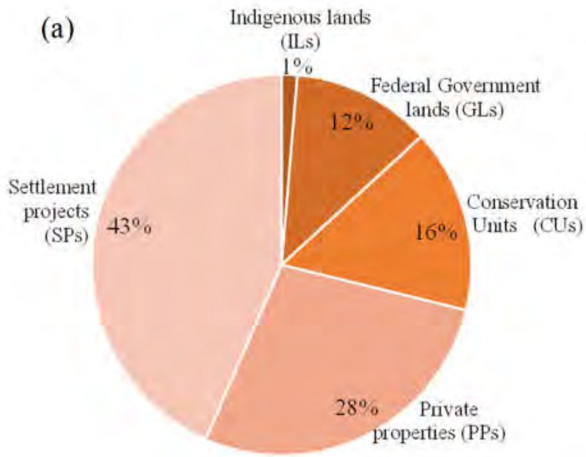
Figure 7. Annual rates of deforestation from PRODES (INPE's Amazon Monitoring Project) and area of annual forest fires in the state of Acre. Note that the "year" for PRODES is from 1 August of the previous year to 31 July of the reported year, while the "year" for forest fires is from 1 January to 31 December.

Table 2. Forest area burned one, two or three times and its subsequent conversion to deforestation in the state of Acre.

Number of times burned	Area burned (ha)	% of total area burned	Maximum polygon area of burned forest (ha)	Burned forest area subsequently deforested (ha)	% Deforested of burned forest area
1	388,350	86	14,840	105,900	27
2	59,800	13	3,230	15,600	26
3	5,730	1	490	1,380	24
Total	453,880	100		104,120	27

3.4. Location of forest fires by land-tenure categories and geopolitical boundaries

Renovation and management of pastures with the use of fire were the activities found at deforested locations near 95% of the forests points visited in the field in the process of validating the mapping. Pasture burning is the main source of ignition for fires that escaped in 2005 and 2010. The type of agricultural activity is closely related to land-tenure categories. In 2005 and 2010, settlement projects had the highest percentage of forest-fire scars (43% of the total area of scars: 156,600 ha in 2005 and 50,960 ha in 2010: Figure 8). Settlement projects represented the land-tenure category with the greatest use of land for agriculture and livestock. The private property category had forest fire in 28% of the total area of fire scars (95,068 ha in 2005 and 33,538 ha in 2010), conservation units had 15% (52,522 ha in 2005 and 19,645 ha in 2010), federal government lands had 12% (42,626 ha and 13,960 ha) and indigenous lands has 1% (2535 ha in 2005 and 2339 ha in 2010).



(b)

Categories Land	**% forest area remaining**	
	2005	**2010**
SPs	16	5
PPs	4	1
GLs	1	<1
CUs	1	<1
ILs	<1	<1

Figure 8. Contribution of land-tenure categories to the area of forest fires in the state of Acre between 1984 and 2015: (**a**) forest area affected by fires in five land categories and (**b**) forest area remaining by 2016 affected by forest fires in each land-ownership category.

The absolute extent of the forest area affected by fire in conservation units is of concern. In the Chico Mendes Extractive Reserve alone, fires affected an area of 50,470 ha between 1984 and 2016, 42,700 ha of which was in 2005. Of the 19 conservation units in Acre, nine had forest-fire scars from the 2005 fires and 12 from the 2010 fires (Supplementary Material, Table S4). In years of extreme drought, even burning in small agricultural areas can get out of control and turn into large forest fires. For example, in the Chico Mendes Extractive Reserve, which is an area with little forest fragmentation, eight polygons of burned forest larger than 1000 ha had their probable sources of ignition in deforested areas averaging 30 ha in size.

The vulnerability of the landscape to forest fires is most evident when the analysis covers the total area of forest remnants affected by fire within the municipal boundaries. The municipalities of Plácido de Castro and Senador Guiomard had more than 50% of their area of forest remnants burned in 2005 (Supplementary Material, Table S3. Of the total area affected by forest fires in the 1984-2015 period, Rio Branco (26%), Senador Guiomard (11%), Sena Madureira (10%), Xapuri (10%), Placido de Castro (9%) and Acrelândia (9%) had the greatest areas of forest impacted by fire (Supplementary Material, Table S3). In both analyses, all of the municipalities are in the portion of the state with the most fragmented forests (Figure 9).

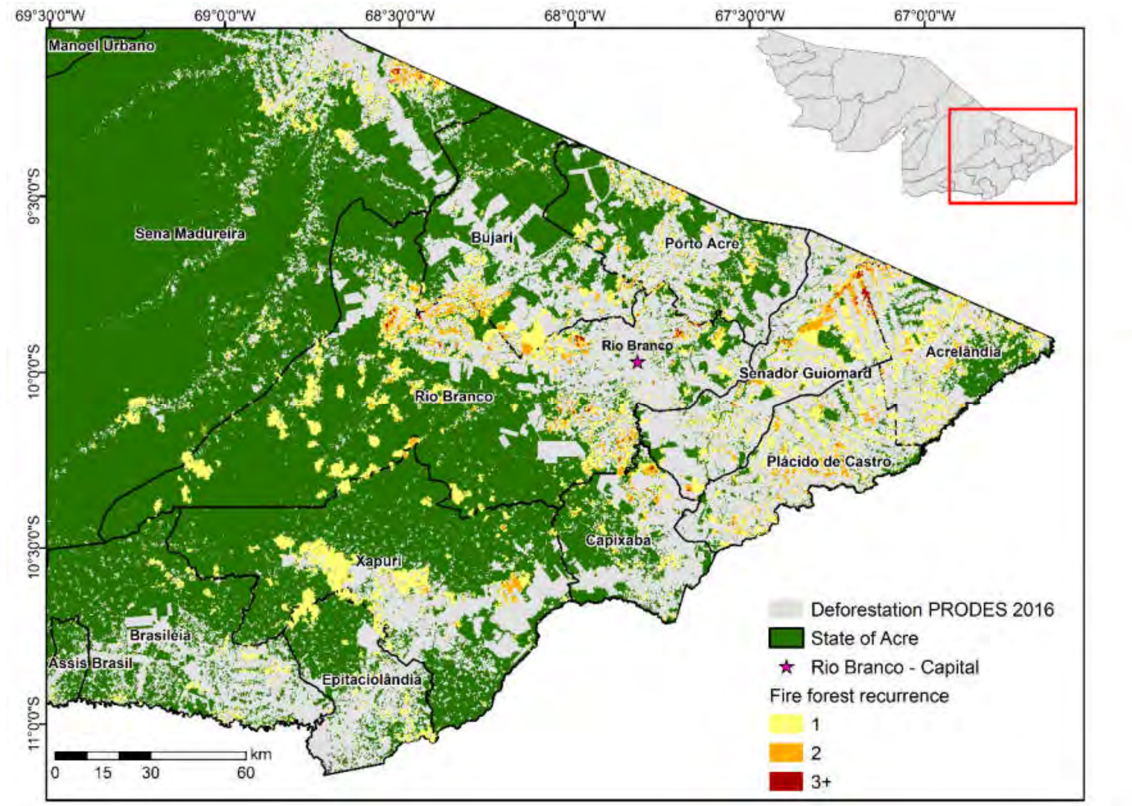


Figure 9. Forest-fire scars of areas burned one, two and three or more times in eastern Acre, Brazil between 1984 and 2016.

3.5. Logging

Using both systematic and visual methods, we identified 181 areas (polygons) with logging between 1984 and 2016. Of these, 45% coincided with areas of forest-fire scars and 55% had no spatial coincidence. Among the coincident areas, 56% had logging was done before the fires (about 8 years earlier), 37% were logged after the occurrence of the fires (on average 4 years later) and only 7% were made in the same year of fire.

4. Discussion

The history of forest fires in Acre between 1984 and 2016 shows an almost binary behavior: in the normal climate years there is little occurrence of forest fires, while in the years of extreme drought several thousands of hectares of forest areas are burned. This binary behavior of forest fires demonstrates the importance of extreme droughts as a key factor driving the occurrence of fires. The years with the greatest area of forest-fire scars are associated with extreme droughts related to the anomalous surface warming of the tropical North Atlantic, especially in 2005 and 2010 (Lewis et al., 2011; Zeng et al., 2008).

Mapping the extent of forest fires can be affected by the spatial resolution of the satellite image used. For 2005, Shimabukuro et al. (2009) estimated 2800 km^2 of forest-fire scars in Acre using MODIS images, a difference of 700 km^2 in relation to the present study (3513 km^2 of forest-fire scars in 2005). Mapping with the MODIS satellite does not allow identification of areas smaller than 25 ha (Anderson et al. 2015). In the present study, areas smaller than 30 ha in 2005 represented 3470 polygons, adding an area of 253 km^2 (7% of the total area mapped for that year).

In absolute terms, the impact of fire in years of extreme drought was higher in other Amazon states than it was in Acre. During the El Niño of 1997-1998 in Roraima, 11,394-13,928 km^2 of forest was impacted by fires (Barbosa and Fearnside, 1999). In Mato Grosso in 2010 12,776-13,011 km^2 was impacted by fires caused mainly by the Atlantic dipole (Anderson et al., 2015). In Roraima, forest fires in 1997-1998 accounted for 7% of the state's forest area, followed by Mato Grosso in 2010 with 4% and Acre in 2005 with 3%.

Toomey et al. (2011) reported daytime warm anomalies of 3 °C in 2005 and 2010 in Acre, which, associated with water deficiency, explain the reduction of forest biomass. This association highlights the catastrophic effect of climate change on the dynamics of forest fires in Acre. In 2016, we appear to have experienced the limit of the forest's tolerance to drought when a large number of days with high temperatures associated with a period of 40 consecutive days without rainfall was enough to make the forest flammable and impact 29,455 ha of forests in the state. In periods of severe droughts trees lose more leaves, thus accumulating more litter. This, together with high temperatures and an open canopy due to the greater number of trees without leaves, changes the microclimate in the forest. Direct sunlight enters the forest interior, drying out the litter and making it highly combustible (Nepstad et al., 1999a).

The recurrence of forest fires accelerates forest degradation, especially when combined with fragmentation and logging, which cause drastic depletion of biodiversity and carbon stock (Barlow et al., 2016; Laurance et al., 2018). In the Acre River Valley, the recurrence of fire was greater than in other parts of the state, with forests burning as many as three times. This is a feature of fires throughout the arc of deforestation, with forests burning as many as five times, as observed in the state of Mato Grosso (Morton et al., 2013).

There was no relationship between the interannual variability of forest fires and deforestation, unlike the relationship observed by Barni et al. (2015) and Morton et al. (2013) (Figure 7). However the results presented differ from Morton et al. (2013) in relation to the conversion of burned forest to deforestation in the years following the fire, with a conversion percentage of 27% for Acre and an average of 8% for Southern Amazonia. This difference may be due to the size of the forest fire polygons mapped, Morton et al. (2013) mapping areas larger than 25 ha and our study in Acre mapping areas mapping areas larger than 1 ha. Van Marle et al. (2017) found that in part of the arc of deforestation only 31% of the fire events were explained by deforestation. Aragão and Shimabukuro (2010) showed that the growth of the number of ignition sources in the Amazon followed the inverse of the deforestation trend during the period of falling deforestation rates that occurred between 2004 and the time of their study, with serious implications for goals for reducing greenhouse-gas emissions.

In Acre, however, the portion of the state with the greatest extent of forest fires was also the area with the greatest deforestation. This deforestation left the remaining forests more vulnerable to fire entry due to fragmentation and due to more extensive forest edges. Forest fires are concentrated in the Acre River Valley, accounting for 88% of all forest areas affected by fire in the state of Acre. This is the region with the greatest consolidation of agricultural activities and a high level of forest fragmentation, and it has the main terrestrial connections to other parts of Brazil and to Peru and Bolivia: Highways BR-364 and BR-317.

Protected areas for forest conservation are affected by fire in the Acre River Valley. Fire scars in protected areas accounted for 14% of the entire forest-fire area between 1984 and 2016. The Chico Mendes Extractive Reserve was especially affected, with forest fires in isolated areas with continuous-forest polygons greater than 1000 ha in area impacted by fire, especially in 2005 (Figure 10). Vasconcelos et al. (2013) also reported the occurrence of forest affected by fire in indigenous lands in the southern Amazon. Human pressure from settlement projects and roads around protected areas increases the likelihood of uncontrolled fire reaching large areas of forest (Fearnside, 2009).

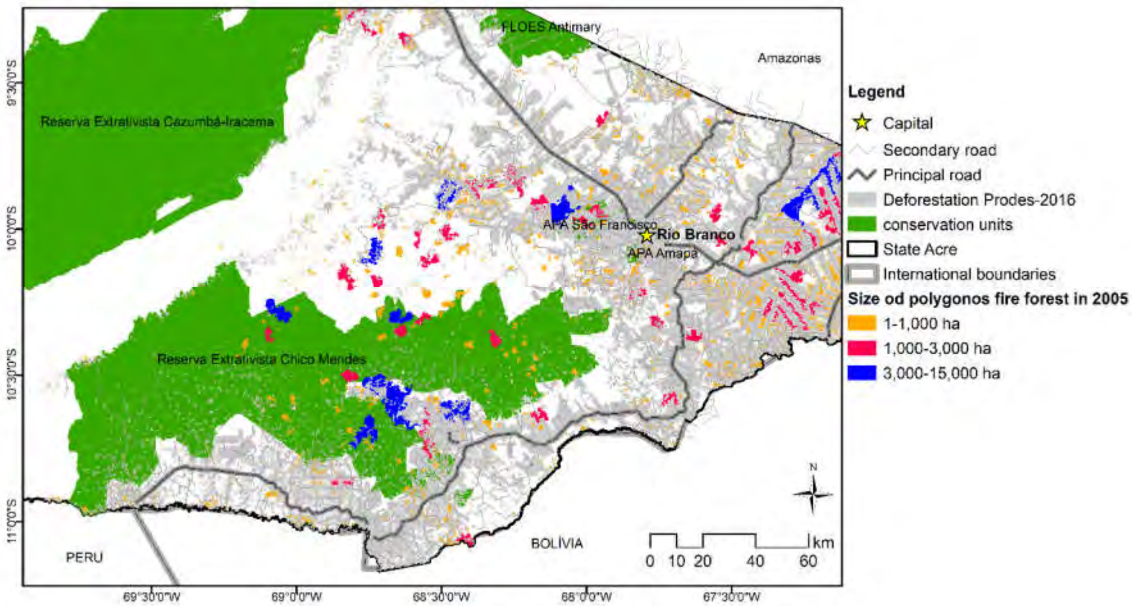


Figure 10. Example of the fires of 2005, size of polygons of forest fires in conservation units under strong anthropic pressure, eastern Acre state, Brazil.

Logging is well known as a factor that increases the vulnerability of Amazonian forests to subsequent fires (e.g., Nepstad et al., 1999b). Here we show that the inverse relationship can also apply: forest fire can be associated with subsequent logging. These results show the importance of improving and expanding the mapping of the logging in the whole state of Acre and elsewhere in Amazonia.

Forest fires will likely be more frequent and more intense with further lengthening of the dry season, which is already occurring in southwestern Amazonia (Fu et al., 2013). This effect, which is linked to global climate change, would be worsened by the effect of continued deforestation in further reducing rainfall in the dry season (Spracklen and Garcia-Carreras, 2015). These effects can be expected to cause an even more drastic impoverishment of forest carbon stocks and biodiversity, as well as compromising policies for rewarding ecosystem services.

With the advancement of mapping fire impact based on field data, it will be possible to better understand the impact from climate change on forest degradation by fire, adaptation of forest to new drought and/or fire regimes and of recovery of forest-carbon stocks (Berenguer et al., 2014; Bustamante et al., 2016). By reducing uncertainties through monitoring with remote sensing, it will be possible to improve carbon-cycle models and estimates of impacts on biodiversity and climate, supporting social, economic and political decision-making (Bustamante et al., 2016; Olofsson et al., 2013).

Maintaining the goals of reducing deforestation does not guarantee the maintenance of forest ecosystem services, since forest degraded by logging and fire retains only 46-61% of its potential conservation value (Barlow et al., 2016). We observed two situations combining logging and forest fires, pre-fire exploration and post-fire exploration. The first is more common in most of the Amazon (Barlow et al., 2006; Berenguer et al., 2014). In Acre the most common situation is the second. Through rapid assessment of Landsat-TM scene 002/067, 26% of the identified logging occurred up to three years after the fires of 2005 or 2010, unleashing a new mode of forest degradation that could further hamper forest recovery after the fires.

Public policies for reducing greenhouse-gas emissions have so far only considered the impact of deforestation, s in the Acre state government's program to reduce greenhouse-gas emissions (Neves et al., 2013). We recommend that future studies include calculation of emissions from forest fires over a historical series, as these fires can be a significant emissions source, especially in drought years.

Conclusions

Monitoring of forest fires in the state of Acre over a 33-year period (1984-2016) shows that higher frequencies and area of forest-fire scars are concentrated in the last 12 years, when 95% of the area burned over the entire period was in the years 2005, 2010 and 2016.

Forest fires are responses to drought events, increased fragmentation, and the use of fire in agricultural practices. In the eastern portion of Acre, the municipalities of Acrelândia and Senador Guiomard had more than 50% of their remaining forests affected by fire in 2005.

The impact of humans on initiating forest fires is decisive: 42% of forest fires occurred in INCRA settlement projects and 87% of the fires occurred in the eastern portion of the state, which is the most densely populated region and accounts for 65% of deforestation in Acre. Conservation units accounted for 14% of the entire forest-fire area in Acre, showing the fragility of the landscape even with low deforestation pressure.

The implications of forest fires for policies to reduce carbon emissions and pay for environmental services are enormous. The area affected by forest fires in Acre in the period from 2004 to 2015 is equal to the entire area deforested in the state over the same period.

The joint analysis of timber extraction on increasing susceptibility of the forest to fire and of predicted increases in climatic extremes will be important to understanding the future evolution of forest fires in southwestern Amazonia.

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Supplementary Material

Dynamics of forest fires in the southwestern Amazon

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Table S1. Data for the Landsat images used in this study for the mapping of forest fires in the state of Acre

Year	**001/067**	**002/066**	**002/067**	**002/068**	**003/066**	**003/067**	**004/065**	**004/066**	**004/067**	**005/065**	**005/066**	**006/065**
1984	15-Dec	17-Sep	01-Sep	06-Dec	cloud	10-Oct	15-Sep	01-Oct	01-Oct	06-Sep	cloud	cloud
1985	16-Nov	04-Sep	06-Oct	06-Oct	cloud	30-Nov	cloud	cloud	cloud	09-Sep	09-Sep	cloud
1986	cloud	10-Nov	10-Nov	25-Oct	30-Sep	30-Sep	07-Oct	07-Oct	07-Oct	14-Oct	14-Oct	cloud
1987	05-Oct	12-Oct	12-Oct	12-Oct	cloud	03-Oct	26-Oct	cloud	cloud	15-Sep	01-Oct	cloud
1988	05-Set	14-Oct	01-Oct	30-Oct	cloud	cloud	10-Sep	10-Sep	cloud	cloud	cloud	26-Oct
1989	24-Sep	15-Sep	cloud	15-Sep	22-Sep	22-Sep	13-Sep	cloud	cloud	25-Dec	04-Sep	30-Nov
1990	14-Nov	cloud	18-Sep	18-Sep	cloud	cloud	cloud	16-Sep	16-Sep	cloud	07-Sep	cloud
1991	30-Sep	10-Dec	10-Dec	10-Dec	15-Oct	14-Oct	cloud	05-Oct	05-Oct	cloud	cloud	cloud
1992	02-Oct	10-Nov	23-Sep	23-Sep	30-Sep	30-Sep	30-Sep	30-Sep	05-Sep	28-Sep	28-Sep	cloud
1993	06-Nov	25-Aug	25-Aug	25-Aug	20-Nov	04-Nov	08-Sep	cloud	08-Sep	30-Aug	30-Aug	08-Oct
1994	11-Dec	29-Sep	29-Sep	cloud	cloud	cloud	14-Nov	14-Nov	14-Nov	05-Nov	cloud	25-Sep
1995	cloud	06-Sep	18-Oct	18-Oct	23-Sep	23-Sep	cloud	14-Sep	cloud	05-Sep	07-Oct	27-Aug
1996	16-Dec	cloud	cloud	20-Oct	09-Sep	09-Sep	02-Oct	02-Oct	02-Oct	26-Nov	26-Nov	14-Oct
1997	30-Sep	21-Sep	05-Sep	08-Nov	28-Sep	12-Sep	cloud	19-Sep	05-Oct	12-Oct	12-Oct	17-Sep
1998	15-Sep	10-Oct	29-Dec	24-Sep	30-Aug	30-Aug	22-Sep	22-Sep	22-Sep	13-Sep	13-Sep	04-Sep
1999	16-Sep	05-Oct	05-Oct	05-Oct	18-Sep	18-Sep	11-Oct	11-Oct	11-Oct	03-Nov	03-Nov	23-Sep
2000	16-Dec	24-Nov	18-Dec	18-Dec	04-Sep	cloud	27-Sep	25-Sep	25-Sep	04-Oct	02-Sep	11-Oct
2001	25-Sep	08-Sep	02-Oct	02-Oct	09-Oct	09-Oct	cloud	cloud	cloud	07-Oct	07-Oct	15-Nov
2002	07-Nov	26-Aug	26-Aug	26-Aug	04-Oct	04-Oct	27-Oct	11-Oct	11-Oct	16-Sep	16-Sep	23-Sep
2003	17-Oct	09-Nov	23-Oct	24-Oct	15-Oct	15-Oct	cloud	cloud	cloud	cloud	cloud	25-Feb
2004	01-Sep	08-Sep	24-Jun	26-Oct	15-Sep	17-Oct	09-Nov	09-Nov	09-Nov	31-Oct	28-Aug	23-Nov
2005	20-Sep	13-Oct	11-Sep	13-Oct	05-Nov	05-Nov	25-Sep	25-Sep	25-Sep	16-Sep	16-Sep	23-Sep
	22-Oct	10-Jun	13-Oct	25-May	16-May							
2006	07-Sep	14-Sep	14-Sep	13-Aug	21-Sep	05-Sep	28-Sep	28-Sep	28-Sep	03-Sep	03-Sep	25-Aug
2007	26-Sep	16-Aug	17-Sep	06-Sep	24-Sep	23-Aug	29-Jul	29-Jul	11-Jun	22-Sep	22-Sep	cloud
2008	28-Sep	18-Aug	18-Aug	19-Sep	28-Oct	28-Oct	01-Sep	16-Aug	01-Sep	24-Sep	24-Sep	14-Aug
2009	01-Oct	06-Sep	06-Sep	06-Sep	13-Sep	13-Sep	04-Sep	04-Sep	04-Sep	14-Nov	14-Nov	04-Oct
2010	04-Oct	11-Oct	13-Oct	10-Oct	03-Nov	03-Nov	06-Aug	07-Sep	07-Sep	30-Sep	30-Sep	20-Aug
	01-Jun	24-Jun	24-Jun	24-Jun	30-May	30-May		05-May		15-Jul		
2011	05-Sep	30-Oct	30-Oct	30-Oct	18-Aug	18-Aug	09-Aug	09-Aug	22-Aug	15-Aug	15-Aug	08-Sep
2012	02-Nov	06-Sep	06-Sep	06-Sep	13-Sep	29-Sep		20-Sep	20-Sep	11-Sep	11-Sep	18-Sep

2013	26-Sep	17-Sep	17-Sep	17-Sep	11-Nov	08-Sep	30-Aug	30-Aug	01-Oct	11-Dec	11-Dec	13-Sep
2014	29-Sep	07-Nov	22-Oct	22-Oct	13-Oct	13-Oct	18-Sep	18-Sep	02-Sep	24-Aug	25-Sep	18-Oct
2015	18-Oct	09-Oct	12-Dec	12-Dec	17-Nov	03-Dec	23-Oct	23-Oct	23-Oct	12-Sep	12-Sep	21-Oct
2016	09-Sep	09-Sep	09-Sep	09-Sep	18-Oct	15-Aug	07-Sep	07-Sep	07-Sep	29-Aug	14-Sep	16-Aug
	05-Nov	28-Nov	09-Sep	09-Sep	18-Oct	19-Nov				01-Nov	01-Nov	

Table S2. Total, maximum and average annual area of forest fire scars for the State of Acre from 1984 to 2016.

Year	Total	Maximum	Average
1984	15	8	4
1985	5	4	2
1986	51	22	10
1987	6,206	1,012	14
1988	334	56	7
1989	117	33	10
1990	642	47	12
1991	30	13	10
1992	98	51	24
1993	159	25	11
1994	295	33	7
1995	662	93	12
1996	23	10	8
1997	167	62	12
1998	5,892	215	12
1999	330	29	7
2000	178	28	7
2001	350	142	18
2002	261	70	16
2003	1,909	121	14
2004	447	48	8
2005	351,285	15,040	73
2006	1,160	164	6
2007	525	134	10
2008	1,298	146	10
2009	272	55	6
2010	120,459	4,764	39
2011	1,021	186	16
2012	295	68	11
2013	217	28	6
2014	67	15	6
2015	904	86	7
2016	29,455	3,926	39

Table S3. List of protected areas with forest fire scars in 2005 and 2010.

Conservation Units	**2005**	**2010**
APA Amapá	517	72
APA Irineu Serra	66	120
APA São Francisco	7,609	3,584
Arie Seringal Nova Esperança	20	34
Floresta Estadual do Antimary	176	130
Floresta Estadual do Chandles	18	91
Floresta Nacional Santa Rosa do Purus	47	409
Parque Nacional da Serra do Divisor		12
Reserva Extrativista Cazumbá- Iracema	1,259	583
Reserva Extrativista Chico Mendes	42,795	8,607
Reserva Extrativista do Alto Juruá		206
Reserva Extrativista do Alto Tarauacá		95

Table S4. Areas of forest fires by municipalities in the state of Acre in the 1984 - 2016 period, classified by the number of times each pixel had been burned.

Municipality	**Area burned (ha)**		
	1st time burned	**2nd time burned**	**3rd time burned**
Acrelândia	32,437	5,132	885
Assis Brasil	4,676	36	
Brasiléia	14,222	206	10
Bujari	24,058	4,886	70
Capixaba	12,838	2,600	305
Cruzeiro do Sul	916	11	2
Epitaciolândia	13,934	162	
Feijó	1,180	24	
Jordão	190		
Mâncio Lima	1,161	27	
Manoel Urbano	1,721	5	
Marechal Thaumaturgo	340		
Plácido de Castro	31,500	8,301	280
Porto Acre	23,526	3,410	201
Porto Walter	91		
Rio Branco	96,530	16,997	2,005
Rodrigues Alves	546	13	
Santa Rosa do Purus	2,402	9	
Sena Madureira	42,626	3,960	514
Senador Guiomard	36,915	10,234	1,439
Tarauacá	270	5	
Xapuri	46,107	3,782	16

In Figure S1 one can see that August and September have large spikes of burning (active fire), most of which is in cattle pastures or agricultural fields but that trigger forest fires. This means that the forests are still burning in this period and it is not possible to map the total fire damage at that time. The best images for mapping the total fire damage in the forest are from September to December, when the fires decrease and the rains start.

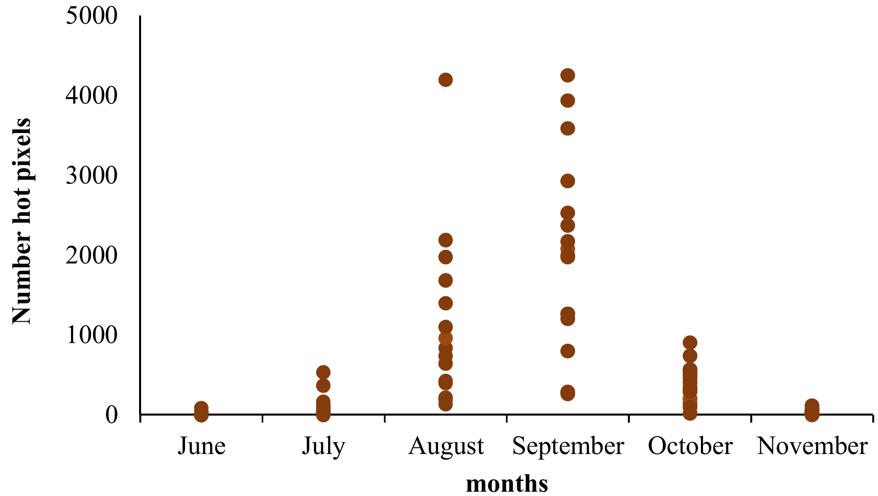

Figure S1. Temporal distribution of hot spots between June and November in the period from 2000 to 2016 using the reference satellite Aqua-TM

The main challenge for mapping forest fires in the southwestern Amazon is confusion of fire scars with areas affected by blowdowns, vegetation under extreme water stress and senescent bamboo populations in open forests (Figure S2). These regional specificities can lead to errors in mapping land-use and land-cover change. In 2003, for example, INPE's PRODES project misclassified patches of senescent bamboo as deforestation (Deus and Mastrângelo, 2016), and, more recently, the MapBiomas project misclassified these same forest formations as secondary forests (MAPBIOMAS, 2016). The interpreter's local experience and knowledge is crucial to producing an accurate map.

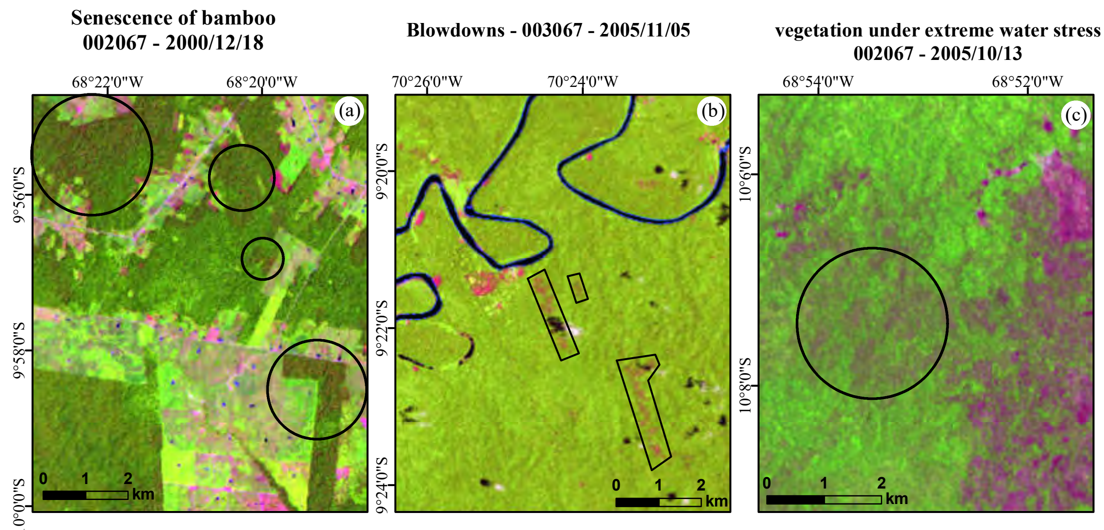

Figure S2. Main types of confusion during the mapping of forest fires. (a) Bamboo senescence demarcated by black circles and (b) blowdowns near areas of fire marked by black rectangles and (c) vegetation under extreme water stress near large areas of forest fire.

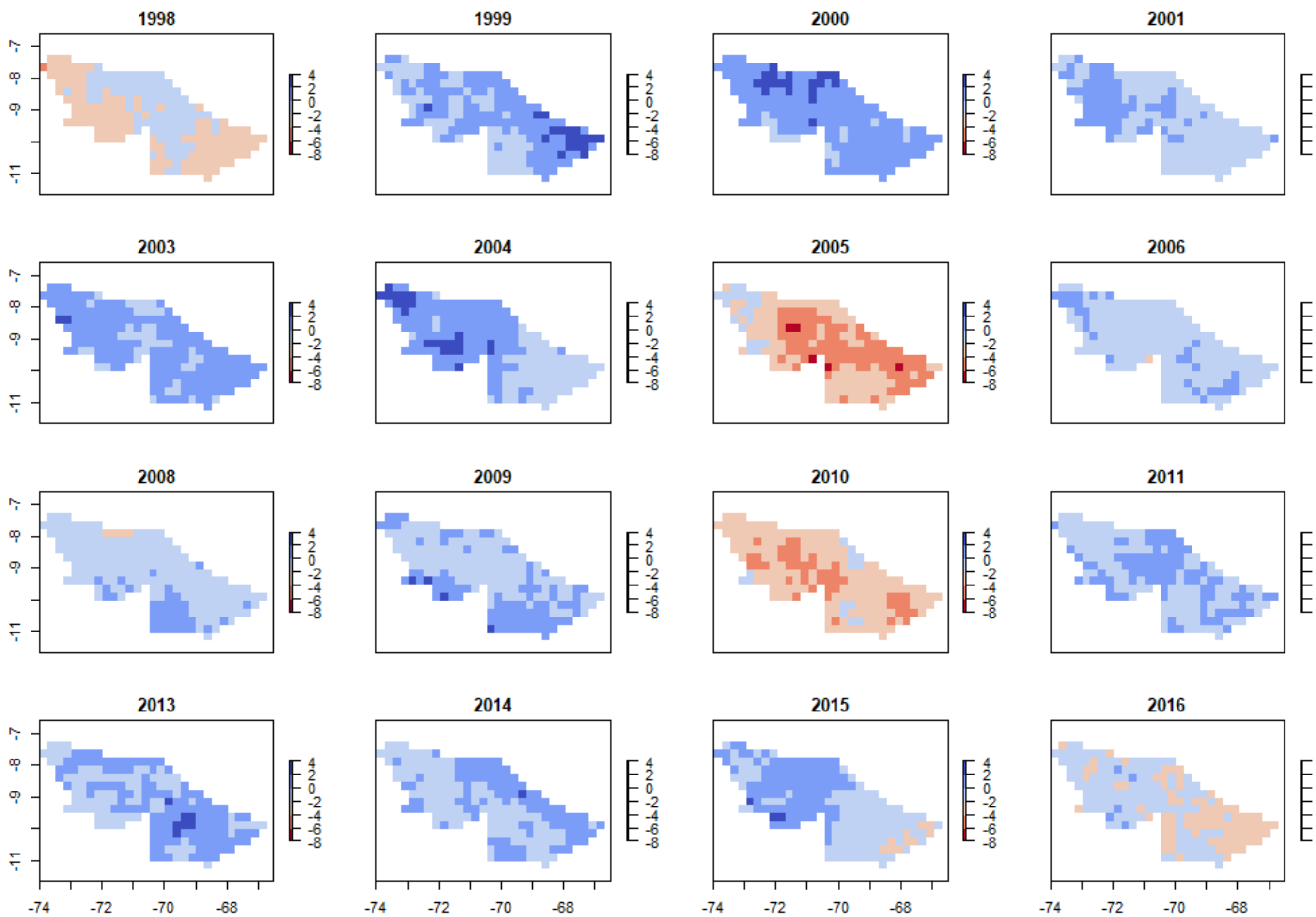

Figure S3. Annual spatial distribution of the Maximum Cumulative Water Deficit (MCWD) anomaly for the State of Acre from 1998 to 2016.