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ORIGINAL PAPER

Fire foci assessment in the Western Amazon (2000–2015)

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Abstract

Burning is a practice widely used by rural producers in Brazil, mainly in the Amazon region, as the main instrument to prepare the land for agriculture. In this study, we used the data of all heat foci in the Western Amazon, Brazil, provided by the National Institute for Space Research through its Database of Burns (*BDQueimadas*). This database often has some redundancies owing to the detection of the same burn more than once or capture of the same fire focus by different environmental satellites, resulting in an overestimation of data. In the present study, we optimize a method to reduce redundancies in an extensive database for the Western Amazon for the time period of 2000–2015, using a model for the identification and exclusion of duplicate heat foci, utilizing the ArcGIS 10.2 software. Kernel density estimates were used and correlated with average precipitation of each year obtained from Tropical Rainfall Measuring Mission (TRMM) satellite (product 3B43). From a total of 1,273,971 heat foci obtained from all environmental satellites, only 433,267 were maintained for the whole period of study (2001–2015), indicating a reduction of approximately 66%. NPP-375 (Suomi National Polar-orbiting Partnership, 375 m of spatial resolution) was the most redundant environmental satellite. The fire foci occurrence showed high correlations with rainfall as well as El Niño events. This work could also delineate areas in the Western Amazon that are most vulnerable to drought and resulting fires.

Keywords Amazon forest · Forest fires · Heat foci · Kernel density

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1 Introduction

The Amazon is the largest tropical rainforest in the world, with approximately 7 million km^2 of forest, representing 56% of the tropical rainforest area of the planet. It is also the largest river network in the world and contributes 20% of the total freshwater (Correia et al. 2007) flowing into the oceans. The Amazon rainforest has been the focus of world attention because of its mineral wealth, great diversity of flora and fauna, and also due to the effects of large-scale deforestation of the region on regional and global climate (Marengo 2007; Almeida et al. 2016). The Legal Amazon can be divided into two large portions, the Western and the Eastern Amazon. According to Brasil (2017), Western Amazon has 42.97% of the Legal Amazon's territorial extension and includes approximately 57% of the region's forests. Therefore, in addition to representing the most preserved part of the Amazon rainforest, it is also a unique stock of biodiversity of the planet, with the presence of several species still unknown.

Naturally, fire is a rare event in the Amazon rainforest, but it is growing in size and frequency across the tropical region, where the slash-and-burn farming methods are used to convert rainforests into agricultural lands (Cochrane 2003). Generally, in the Amazon, forest fires are most observed during periods of drought, which begin in July (Caúla et al. 2016). They also show an increase during drought years (Barbosa et al. 2018), which could be related to the annual rainfall variations. During this time, highest peaks of deforestation occur and the use of fire constitutes a practice rooted in the culture of the Brazilian Amazon. According to Martinez et al. (2007), fires are largely used in the productive process of the region and correspond to one of the factors that drive its agricultural expansion. Each year, farmers and ranchers burn their lands to convert forests into cropland and/or to control the proliferation of invasive plants (Alencar et al. 1997).

Some of these fires end up out of control and enter the forest; the effects of these fires could reach a global scale as they influence the chemical composition of the atmosphere and phenomena that are strongly linked to climate (Nepstad et al. 1999). Changes in Amazonian ecosystems could have an impact on the general circulation of the atmosphere, on the transport of moisture, and therefore on the hydrological cycle (Correia et al. 2007). According to Cândido et al. (2007), future climate projections show a drier climate trend in the Amazon, which would lead to a decrease in humidity in the atmosphere and soils, followed by a reduction in the river flow, and an increased risk of fire in the region. There is also an indication that the climate of the eastern part of the Western Amazon and the states of Rondônia and Acre will become drier because of an increase in aridity of the region (Liberato and Brito 2010), and consequently, forest fires will become more common, especially in more vulnerable areas.

The National Institute for Space Research (INPE) monitors forest fires in South America via environmental satellites through the detection of heat focus, using a thermal infrared sensor (approximately 4 μm) (INPE 2017). Each polar-orbiting satellite produces at least two sets of images per day and geostationary satellites produce several images per hour, with a total of more than 200 images per day being processed specifically to detect foci of burning vegetation (INPE 2017). INPE provides a broad database of heat foci, and for using all the available data it needs some preprocessing, in order to avoid overestimation of fire foci. Overestimation usually happens when different satellites detect coincident heat spots or detect the same burn more than once, which could then lead to redundancy in the number of heat foci. In this sense, the present study aims to elucidate such issues in the obtained dataset for the period from 2001 to 2015 in the Western Amazon, in addition to performing an assessment of fire foci distribution and comparatively analyzing the data detected after reducing redundancy using meteorological data from the region. Thus, with the calibrated fire foci data, we analyzed the relationship between fire foci distribution and rainfall and highlight the vulnerability of the Western Amazon ecosystem to the occurrence of fires.

2 Materials and methods

2.1 Study area

The present study was carried out for the Western Amazon, located in the geographical center of the continental Amazon, in the northern region of Brazil and included the states of Amazonas, Acre, Rondônia, and Roraima (Fig. 1). It occupies approximately 2,194,599 km^2, covering about 42.97% of the Legal Amazon's territorial extension that includes approximately 57% of the region's forests (Brasil 2017) and has 7.4 million inhabitants (IBGE 2019). According to Alvares et al. (2013), the Köppen classification of the study area is Af and Am, tropical climate without a dry season and with the monsoon, respectively. The annual rainfall of the region is in the range from 2200 mm to above 3300 mm, and annual mean temperatures are in the range of 22 °C to above 26 °C. The main soils are Latosols (Oxisols), Spodosols, Argisols (Ultisols) and Cambisols (Inceptsols), forming many different soil associations, and the main vegetation types are dense and open lowlands and dense submontane ombrophilous forest (Schaefer et al. 2008). The main economic activities are vegetable extractivism and agriculture (MMA 2003).

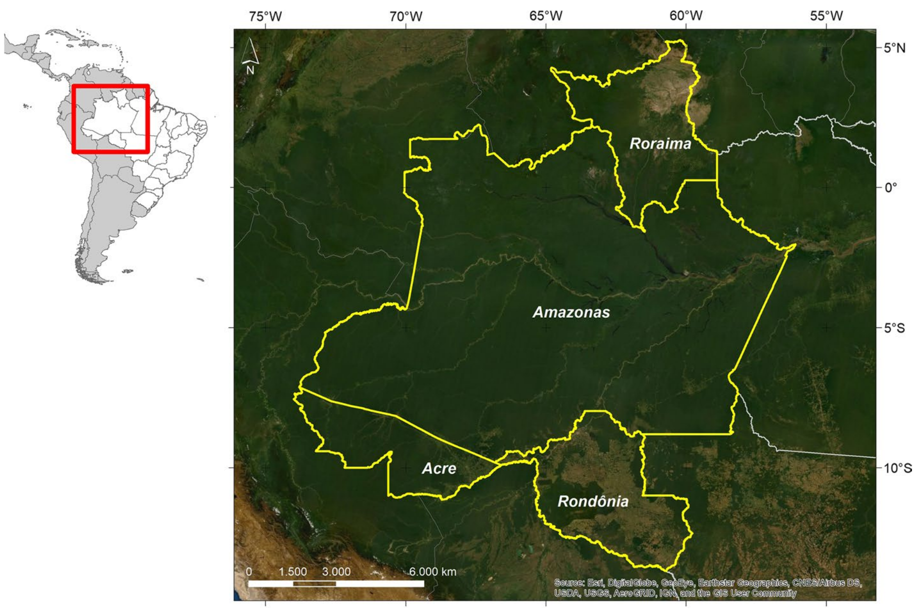

Fig. 1 Map of the study area (Western Amazonia) and its location in the Brazilian states

2.2 Database

2.2.1 Fire Foci

Data of the heat foci for the time period from 2001 to 2015 were obtained in a shapefile format from the Web site of INPE and included data from all the satellites that operate with a thermal infrared sensor (about 4 μm) (Table 1). This INPE database identifies the point heat foci (shapefile), using an algorithm obtained from National Aeronautics and Space Administration (NASA) projects (Giglio et al. 2016; Schroeder et al. 2014). ArcGIS 10.2 software was used to access the database and to count the annual number of heat foci. The number of satellites and sensors from the INPE database, used in this study period (2000–2015), is listed in Table 2.

2.2.2 Rainfall data

We used raster files of the rainfall data from the Tropical Rainfall Measuring Mission (TRMM) satellite product 3B43, in NetCDF format (TRMM 2014), and later the units were converted from mm h^{-1} to mm $month^{-1}$ in the ArcGIS version 10.2 software. The

Table 1 Basic characteristics of satellites and sensors used in this study for Western Amazon

Satellite	Sensor	Launch (dd/mm/yyyy)	Current situation	Spatial resolution (km)	Temporal resolution
NPP-375	VIIRS	28/10/2011	Active	0.375	Daily
NPP-750	VIIRS	28/10/2011	Active	0.75	Daily
TERRA	MODIS	18/12/1999	Active	1.0	1–2 days
AQUA	MODIS	04/05/2002	Active	1.0	1–2 days
ATSR	IRR	01/06/1991	Inactive	1.0	
NOAA-12	AVHRR/2	14/05/1991	Inactive	1.1	Daily
NOAA-14	AVHRR/2	30/12/1994	Inactive	1.1	Daily
NOAA-15	AVHRR/3	13/05/1998	Active	1.1	Daily
NOAA-16	AVHRR/3	21/09/2000	Inactive	1.1	Daily
NOAA-17	AVHRR/3	24/06/2002	Inactive	1.1	Daily
NOAA-18	AVHRR/3	20/05/2005	Active	1.1	Daily
NOAA-19	AVHRR/3	06/02/2009	Active	1.1	Daily
METOP-B	AVHRR/3	17/09/2012	Active	1.1	Daily
TRMM	VIRS	01/11/1997	Active	2.1	3 h
MSG 02	SEVIRI	25/12/2005	Inactive	3.0	15 min
MSG 03	SEVIRI	05/07/2012	Active	3.0	15 min
GOES 08	I-M	13/04/1994	Inactive	4.0	40 min
GOES 10	I-M	25/04/1997	Inactive	4.0	15 min
GOES 12	I-M	23/07/2001	Active	5.0	30 min
GOES 13	I-M	24/05/2006	Active	6.0	30 min

VIIRS visible infrared imaging radiometer suite, *MODIS* moderate-resolution imaging spectroradiometer, *AVHRR/2* advanced very high-resolution radiometer with five channels, *AVHRR/3* advanced very high-resolution radiometer with six channels, *VIRS* visible and infrared scanner, *IRR* infrared radiometer, *SEVIRI* spinning enhanced visible and infrared imager, *I–M* Imager instruments

Table 2 Number of satellites and sensors used to acquire fire foci in each study year for the Western Amazon

Years	Number of satellites	Sensor used
2001	4	IRR, I-M, AVHRR/2, MODIS
2002	5	IRR, I-M, AVHRR/2, MODIS
2003	7	IRR, I-M, AVHRR/2, MODIS
2004	6	IRR, I-M, AVHRR/2, MODIS
2005	11	IRR, I-M, AVHRR/3, MODIS
2006	11	IRR, I-M, AVHRR/3, MODIS
2007	12	IRR, I-M, AVHRR/3, MODIS, SEVIRI
2008	11	IRR, I-M, AVHRR/3, MODIS, SEVIRI
2009	11	IRR, I-M, AVHRR/3, MODIS, SEVIRI
2010	11	IRR, I-M, AVHRR/3, MODIS, SEVIRI
2011	11	IRR, I-M, AVHRR/3, MODIS, SEVIRI
2012	13	IRR, I-M, AVHRR/3, MODIS, SEVIRI
2013	13	VIIRS, I-M, AVHRR/3, MODIS, SEVIRI
2014	10	VIIRS, I-M, AVHRR/3, MODIS, SEVIRI
2015	11	VIIRS, I-M, AVHRR/3, MODIS, SEVIRI

resolution of 3B43-TRMM data is about 30 km and was validated for the Amazonas state by Almeida et al. (2015), indicating that the TRMM data are an alternative source of quality data for rainfall estimates. The data have monthly rainfall information for all states of the Legal Amazon for the period from 2001 to 2015, and therefore, it was necessary to use the Map Algebra tool in the ArcGIS 10.2 software to obtain the sum of the annual precipitation for Western Amazon. Finally, the annual mean values were transferred to Microsoft Excel in tabular form.

2.3 Analysis of the data

2.3.1 Exclusion of multiple heat foci

For the validation of heat foci, a methodology developed by Santos (2015) was used. The redundancy of the fire foci was mitigated in the ArcGIS 10.2 software through the processes of identification, grouping, and exclusion of repeated points. The flowchart below represents the tools used in the processing performed for the elimination of redundancy points; we used the ModelBuilder tool that allows automation of the process (Fig. 2).

In the execution of the exclusion model of heat foci, the input file is the heat foci as indicated in Fig. 2 as "Focus." Subsequently, the *Find Identical* tool identifies foci with the same date and includes its attribute table to the original table of the heat foci file. Buffers are generated from the spatial resolution of each sensor previously defined in the attribute table of the foci file. Polygons of the same date that are within the range of the spatial resolution of the sensor are joined in the same polygon. The *Multipart to Singlepart* tool performs the function of dismembering the information of each polygon in the attribute table. Finally, with the *Feature to Point* tool, a central point is created for each polygon, thus generating a new vector file that will be the new fire foci without duplication of information.

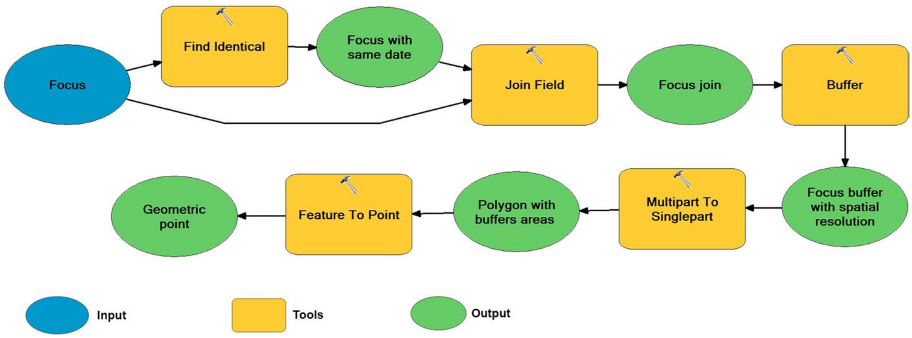

Fig. 2 Workflow of the process of elimination of duplicate heat foci, using the ModelBuilder tool that allows automation of the process in ArcGIS 10.2

After obtaining a new vector file with the exclusion of repeated points, we performed the analysis of fire foci over the years in Microsoft Excel, with and without the removal of duplicate points.

2.3.2 Kernel density

After obtaining the fire foci, their densities within the study region were calculated using the Kernel estimator, using the *Spatial Analyst* tool of ArcGIS 10.2 software. The kernel density estimator plots the point intensity of a given phenomenon, corresponding to the radius of its influence. The results have values varying from 1 at the position of the point to 0 at the edge of the influence radius, which contributes to the identification of areas with a higher incidence of fire foci and their spatial behavior (Silva Filho et al. 2009; Clemente et al. 2017).

This method was used to spatialize the fire foci for a more precise analysis of the concentration areas of the occurrence of the fire. From Kernel density, maps were created for each year of the study period and were classified according to their color, as follows: Red indicates very high density; orange indicates high density; yellow shows medium density; green means low density; and white denotes very low density. This color classification is commonly used and can be seen, for example, in Souza et al. (2013) and Barbosa et al. (2018). The Kernel density method was based on Smith et al. (2015) and expressed by Eq. (1):

$$\hat{f}(s,b) = n^{-1}b^{-2}\sum_{i=1}^{n} K\left\{\frac{(s-s_i)}{b}\right\} \tag{1}$$

where n is the total number of observations; b is the smoothing parameter; s is the coordinate vector; s_i is the coordinate vector representing each observation; and K is the density function that satisfies the following condition given by Eq. (2):

$$\int K(s)ds = 1 \tag{2}$$

2.3.3 Statistical analysis

In order to analyze the influence of the meteorological variable on the number of fire foci, the Pearson correlation coefficient (r) and the coefficient of determination (R^2) were used, where the number of fire foci was the dependent variable (x) and rainfall the independent variable (x). The analysis was performed in Microsoft Excel. The coefficient R^2 was calculated in order to determine the quality of the regression fitting and the ratio in which the variable × explains the variable y; its value varies from 0 to 1. The coefficient r was calculated to indicate how the two variables are related and their degree of correlation; the result ranges from − 1 to 1.

3 Results

During the study period from 2001 to 2015, before the application of the method of exclusion of multiple foci, there were 1,273,971 occurrences of heat foci in the Western Amazon. After the complete exclusion of the redundant foci, the numbers were reduced to 433,267 fire foci, totaling in a reduction of approximately 66% of the data. Table 3 indicates the reduction in the numbers after the exclusion of redundant fire foci in each year and also the number of environmental satellites and sensors used.

Figure 3 shows the annual variation in the fire foci during the study period and the corresponding average annual rainfall. The years 2001, 2008, and 2009 recorded higher amounts of rainfall (Fig. 3).

For a majority of the cases, the variables showed an inversely proportional correlation, i.e., the higher the amount of rainfall, the lower the number of heat sources. The exception was the year 2005, which showed a small increase in the average annual rainfall in comparison with 2003 and 2004, but there was an increase in the number of heat sources.

Table 3 Percentage (%) of reduction in the number of fire foci before and after the exclusion of redundancy in each year

Years	Before	After	Reduction (%)
2001	20,811	11,648	44.03
2002	61,262	28,526	53.44
2003	110,911	41,453	62.62
2004	109,704	37,163	66.12
2005	165,825	42,932	74.11
2006	100,130	27,114	72.92
2007	83,374	27,753	66.71
2008	47,128	19,473	58.68
2009	36,158	19,343	46.50
2010	87,062	28,998	66.69
2011	38,657	16,995	56.04
2012	77,055	22,216	71.17
2013	35,732	16,999	52.43
2014	80,233	34,765	56.67
2015	219,929	57,889	73.68
Total	1,273,971	433,267	65.99

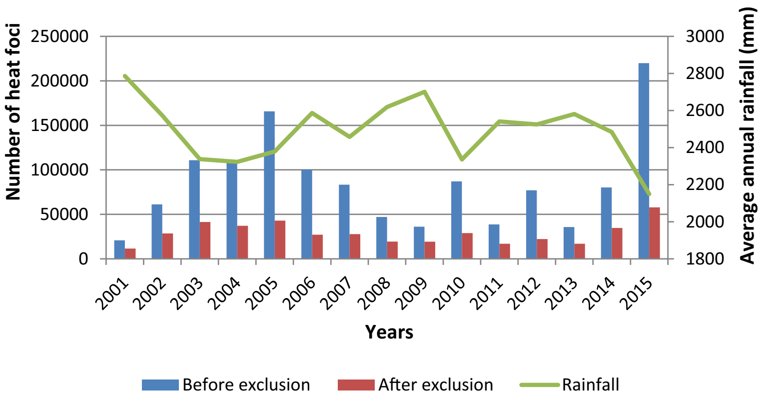

Fig. 3 Distribution of fire foci and mean rainfall (mm) for the study period, before and after the exclusion of redundant heat foci

The coefficient r indicated a strong and negative correlation between the number of fire foci and annual rainfall; the value found was $r = -0.89$ (Fig. 4). The value of the coefficient R^2 indicated that 79% of the variability in the number of fire foci could be explained by the variability in annual mean rainfall (Fig. 4).

The Kernel maps of fire foci of the Western Amazon area show that the areas where there was a higher density of fire foci are also the areas where low rates of average precipitation were recorded (Figs. 5 and 6).

4 Discussion

The analysis revealed a considerable variation in fire foci over the years considered for the study, indicating the important role of rainfall conditions in controlling the fires in the Amazon rainforest region; this is reported in others studies too (Morton et al. 2013; Caúla

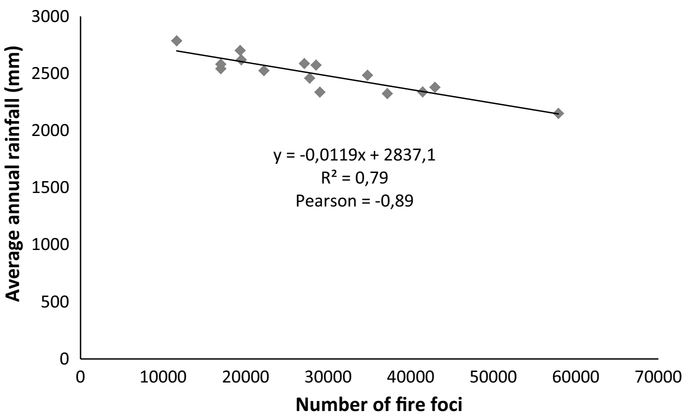

Fig. 4 Scatter plot of the total number of fire foci (after exclusion) and the average annual rainfall (mm. year^{-1})

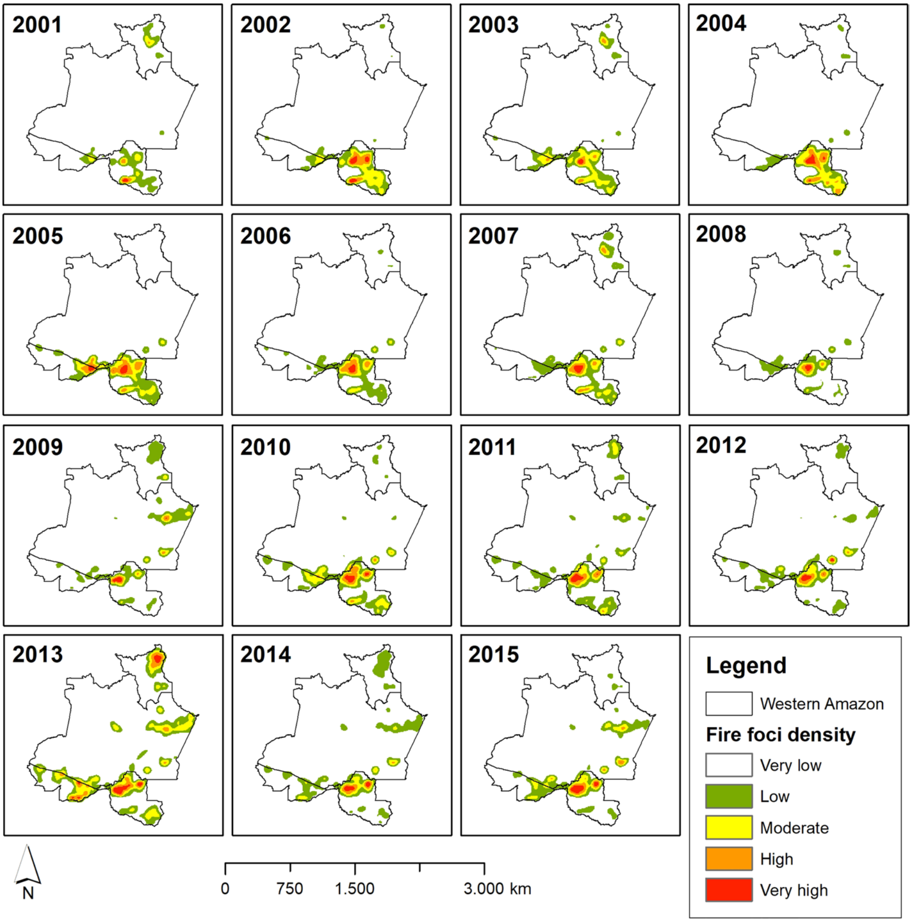

Fig. 5 Kernel map of fire foci density for the Western Amazon during the period from 2001 to 2015

et al. 2015, 2016). The periods of highest annual average rainfall rates (2006–2009 and 2011–2013) coincided with periods of lesser occurrence of fire foci. In this sense, the number of fire foci shows a relation to the annual average rainfall, in terms of density intensity.

This is especially seen in the year 2009, with the number of fire foci being much reduced compared to previous years, due to the fact that 2009 received rains well above the average of previous years. Assessing the rainfall and the fire foci for these 15 years, we could observe a cyclical behavior, except for 2015, which was an atypical year. The high interannual rainfall variability showed many dry years, which were preceded by wet years or the reverse. Hence, if an event has ever happened in the past, from the cyclical processes of nature one could expect that similar events may occur again in the present (Ramos et al. 2011).

The high number of heat foci in 2005 could be explained by the fact that there was a considerable increase in the number of environmental satellites in 2005 (Table 2) compared with previous years, which could have resulted in better detection of foci, thus explaining the increased number of heat foci.

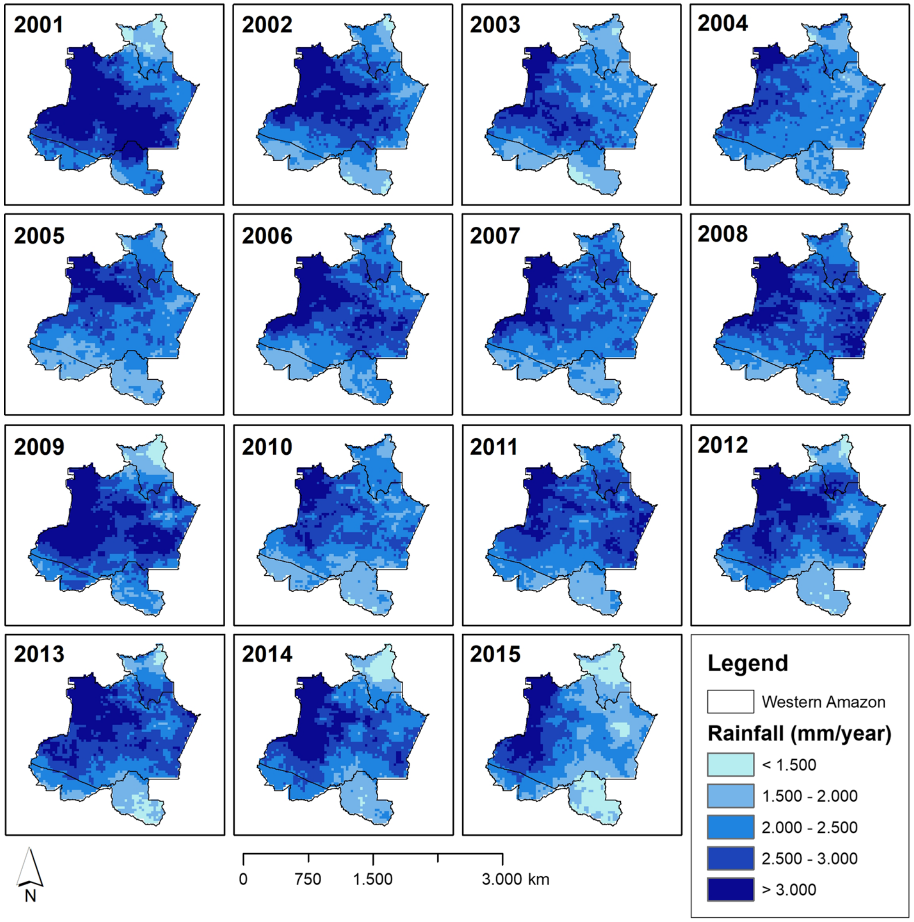

Fig. 6 Average annual rainfall (mm.year^{-1}) maps for the Western Amazon during the period from 2001 to 2015

For the year 2015, an increase in the redundancy was found due to the inclusion of data from satellites with higher spatial resolution, as in the case of NPP-375 (Suomi National Polar-orbiting Partnership, 375 m of spatial resolution), which has a spatial resolution of 375 m and can identify more than one heat foci in the same large fire. In addition, it was a year preceded by two wet years, which not only prevented the occurrence of fires, but also induced the growth of more vegetal biomass. It was also identified as an atypically dry year, favoring with greater ease, the burning of the accumulated biomass in the following 2 years.

We also observed that the periods of lesser rainfall coincide with the periods of El Niño, in 2002/2003 (moderate), 2004/2005 (weak), 2006/2007 (weak), and 2009/2010 (weak) (INPE 2017), indicating a strong cause and effect relationship between the droughts caused by El Niño and the occurrence of fire foci. Marengo et al. (2008) and Lewis et al. (2011) show that similar to 2005, the 2010 drought was also related to the occurrence of large-scale ocean–atmosphere coupled systems (El Niño and Atlantic Dipole), which influenced the rainfall over Amazon in 2010 to reduce, especially in the Western Amazon. In general, the climatic conditions associated with a higher incidence of fire foci in the present study are similar to those found in other studies (Gatti et al. 2014; Ray et al. 2005; Caúla et al. 2015).

Several studies have shown that weather plays an important role in the occurrence of fire foci. Torres et al. (2010) analyzed the relationship between meteorological data and fire foci in Juiz de Fora, Minas Gerais, for the period of 1995–2004 and found a negative correlation (− 51%) between rainfall and the number of foci, indicating that the amount of rainfall directly affects the number of fire foci in vegetation. Lower levels of correlation (40–70%) were also found for the state of Amazonas (Barbosa et al. 2018). This negative correlation between rainfall and fire foci reveals a representative increase in fire risks, when severe droughts provoke greater forest flammability, reduction in moisture content in the combustible material, and increased leaf loss as a result of adaptation to stress (Nepstad et al. 1999, 2004; Alencar et al. 2011).

Kernel maps are useful to assess a large concentration of points when the visual analysis is impaired. The maps of average annual rainfall and Kernel density showed that the most intense fire foci occurred in the states of Roraima and Rondônia, precisely in the areas, where the lowest mean annual rainfall was recorded (Figs. 5 and 6). The high intensity of forest fires in these areas is also related to the proximity of the state of Rondônia to the Amazon deforestation arc and the presence of the Cerrado biome in both the states (Chen et al. 2013). In terms of ecological aspects, fire is an essential element of the Cerrado biome and when there is the increased number of fires in the forest areas, there is a tendency of savannization of the area (Cochrane and Schulze 1999; Cochrane 2003; de Liesenfeld et al. 2016; Silva Junior et al. 2019). These aspects indicate high vulnerability areas with the increasing number of forest fires in the Western Amazon.

According to Maeda et al. (2009, 2011), the use of remote sensing and Geographic Information System (GIS) technique could be considered as an additional alternative for supporting forest fire prevention policies. Other studies have also used numerical simulation with GIS approach, for predicting the rate of spread of forest fire or the probability of wildfire (Bufacchi et al. 2016; Ramirez et al. 2019). Thus, identifying the areas that are most vulnerable to forest fires, especially using GIS, could help in implementing policy decisions to reduce the rate of deforestation, which would also potentially help in reducing the net emission of greenhouse gases from Amazonia (Fearnside 2000).

5 Conclusions

The point exclusion method used in this study proved to be efficient in eliminating duplicate fire foci in the data obtained from different satellite sensors. The data for the study period were obtained from INPE and included data from different satellites. Approximately, 66% of the fire foci analyzed for the study were redundant and it revealed the importance and influence of the different satellites used in this type of analysis. The NPP-375 satellite has great potential in such analysis, because of better spatial resolution of the VIIRS sensor; however, it also showed that the redundancy calibration is necessary or it could overestimate the number of fire foci. The number of fire foci showed a significant correlation with the annual average rainfall and also indicated a relation with El Niño events. This work could delineate the areas in the Western Amazon that are most vulnerable to drought and resulting fires.

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