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Occurrence of fire foci under different land uses in the State of Amazonas during the 2005 drought

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Abstract   The objective of this work is to evaluate the occurrence of fire foci during the severe drought that occurred in 2005 in the State of Amazonas. The study was conducted in the State of Amazonas, which is inserted in the northern region of Brazil. The main types of vegetation are Igapó Forest, Várzea Forest and Terra Firme Forest. Kernel density was used to spatialize fire foci to quantify them in seven classes of land use and cover (forest, pasture, exposed soil, urban area, pastoral agroforestry system, agroforestry system and agriculture). Through the regression analysis, the relation among the number of fire foci and four meteorological variables was obtained: rainfall, evapotranspiration, relative humidity and average air temperature. Forest and pasture classes were those with the highest number of fire foci corresponding, respectively, to 58 and 37% of the total number of foci. This can be explained by the greater representativeness of these classes in the State and by the high degree of soil exposure in the case of pasture. The number of fire foci was higher in the dry season, covering approximately 85% of the total fire foci. The variable that had the greatest influence on the occurrence of fire foci in the dry season was evapotranspiration. The study puts on alert the vulnerability of the State of Amazonas to the

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occurrence of fires and may also suggest actions to mitigate carbon emissions and biomass stock. Research like this one may provide subsidies to region's managers in an attempt to preserve forest areas and a greater controlling in priority areas considered very high.

Keywords Fire foci · Amazonas · Kernel density · Multiple linear regressions · Land cover · Climate change

1 Introduction

Fires occur commonly in several ecosystems, and in the Amazon, they correspond to an important source of disturbances due to the interrelationships among climatic conditions, the global carbon cycle and the different land use activities, which can be potentiated by future drought events (Morisette et al. 2005; Duffy et al. 2015). In recent years (1983, 1998, 2005 and 2010), drought events in the Amazon occurred with high frequency (de Oliveira-Serrão et al. 2015; Souza et al. 2013). The drought of the years 1983 and 1998 was associated with the El Niño phenomenon (Souza et al. 2013), while in 2005 and 2010 the main cause was the abnormal warming of the tropical North Atlantic Ocean surface (Marengo et al. 2008, 2011).

In addition, studies show that the Amazonian vegetation coverage is highly sensitive to changes in rainfall patterns and that the reduction of rainfall since 2000 has dramatically decreased the green cover of the forest (Hilker et al. 2014). In a typical year, the Amazon region receives about 2500 mm year^{-1} of rainfall. However, in 2005 the region was affected by a severe drought, the worst in 40 years (Marengo et al. 2008). These conditions of higher temperature and low humidity in years of severe drought provide an increase in the area with favorable weather conditions to fire and potentiate the susceptibility of the vegetation to forest fires in this region (Vasconcelos et al. 2015).

Brown et al. (2006), in a study on fire monitoring in southwestern Amazonia in 2005, found that more than 200×10^3 ha of pasture areas and agricultural activities were accidentally burned and more than 360×10^3 ha of standing forest were affected by fire on the tri-border of the States of Madre de Dios/Peru–Acre/Brazil–Pando/Bolivia. Moreover, the Center for Weather Forecasting and Climate Studies, of the National Institute for Space Research, in its Fire Database (https://prodwww-queimadas.dgi.inpe.br/bdqueimadas; INPE 2017) reported that in the State of Amazonas, the number of fire pixels detected by the NOAA12 satellite almost tripled in 2005 when compared to the previous year. 760 pixels were detected in September 2004 and 2166 in September 2005. Among the consequences of the 2005 drought, we can highlight the drastic decrease of the Solimões river basin reported by de Oliveira-Serrão et al. (2015). In addition, the socioeconomic impacts are evident, since for riverside population the rivers are the main transportation routes, as well as sources of labor, food and health.

Given this scenario, extreme climatic events assume great importance in the social, economic and environmental context. Therefore, temporal and spatial information on fire foci are a priority for a better understanding of their causes and to ensure improvement in fire monitoring, combat and fire control. In this context, the present work aims to evaluate the occurrence of fire foci during the severe drought that occurred in 2005 in the State of Amazonas.

2 Materials and methods

2.1 Study area

State of Amazonas (Fig. 1) is inserted in the northern region of Brazil, has 62 municipalities, in an area of 1,559,148.890 km^2 and population of 3,938,336 habitants (IBGE 2017a, b). It is the largest Brazilian State, and its capital Manaus is the most populous city in the North and the seventh most populous municipality in Brazil (IBGE 2017a, b). The State is inserted in the Amazon biome, and the main types of vegetation are Igapó Forest, Várzea Forest and Terra Firme Forest. The Igapó forests are located in low lands, near rivers and are often flooded, whereas the Várzea areas are regions that are subjected to floods mainly in the rainy period. Terra Firme are forests located at higher regions where there are no floods (Lopes et al. 2016; IBGE 2018).

In addition, 98% of its area still maintains its original forest cover (FAS 2011) and approximately 50% of its area consists of conservation units, such as sustainable development reserves, national forests, as well as indigenous lands (Campos and Higuchi 2009).

2.2 Fire foci

Fire foci data for the year 2005 were obtained, in shapefile, on the website of the National Institute of Space Research—INPE (2017). This INPE database identifies the fire foci, among other information, by a set of satellites, and they are: NOAA, TERRA, AQUA, GOES and METEOSAT02. According to INPE (2017), a fire focus indicates the existence of fire in an image resolution element (pixel), which ranges from 1 km×1 km to 5 km×4 km. The ArcGIS 10.5 software was used to access the database and perform the
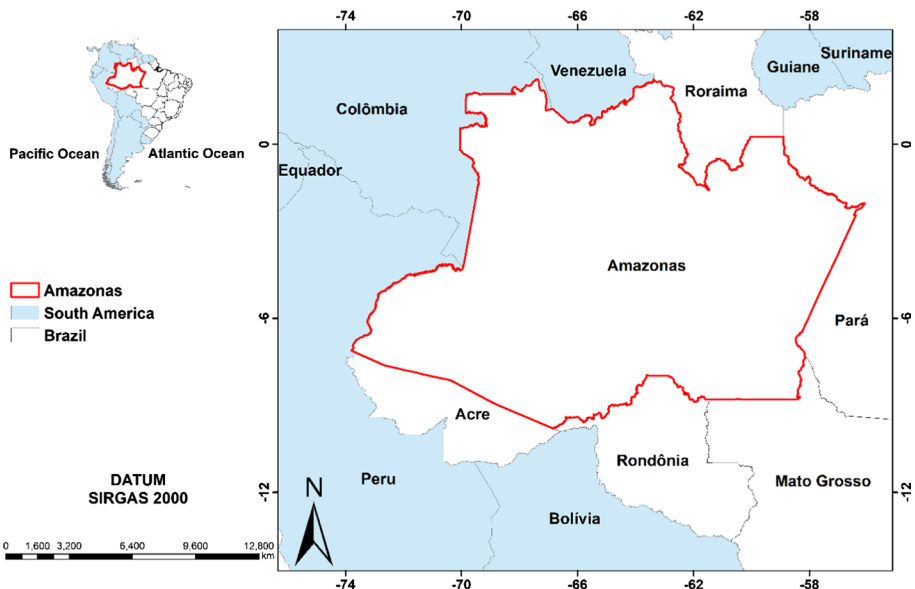

Fig. 1 Geographical location of the study area

counting of monthly number of fire foci. These data were transferred to spreadsheets and transformed into two charts: one for the dry season (April to September) and one for the rainy season (October–March).

2.3 Weather data

In studies on susceptibility of vegetation to fire, meteorological variables on a monthly timescale are commonly used. In addition to these variables, other environmental, economic and infrastructure components may also be relevant. In this work, we used data from four meteorological variables, in NetCDF format, validated by Xavier et al. (2015), which are: average air temperature (°C), rainfall (mm), relative air humidity (%) and evapotranspiration (mm). These data cover all Brazilian States in the period 1983–2013, and therefore, it was necessary to extract only the data for the year 2005 from the State of Amazonas. The extraction of the 2005 data was done using the ArcGIS 10.5 software, through the *multidimension tools* and *make NetCDF raster layer*, in which, besides the extraction, the file was transformed into *raster*. Aiming at obtaining the data from the Amazon, the *extract by mask* tool of the ArcGIS 10.5 was used. Lastly, the average monthly value of each variable was transferred to spreadsheets in tabular form.

2.4 Land cover

The State of Amazonas has a wide diversity of land use. According to the Brazilian Institute of Geography and Statistics—IBGE (2017a, b), there are 55 different forms of land use or land cover in the State. In the present study, these data were clustered into 7 classes according to their similarity (Table 1). In this case, the ArcGIS 10.5 software was also used to read the data, and using the select by attributes tool, the number of areas in each class was quantified.

2.5 Kernel density

After obtaining the fire foci, their densities within the study region were calculated using the kernel density estimator, present in the extension *Spatial Analyst tools* of the ArcGis 10.5 software. Kernel density estimator plots the point intensity of a given phenomenon, corresponding to the radius of its influence. The results generated by Kernel density range from 1 in the position of the point to 0 in the edge of the influence radius,

Table 1 Land cover/land use for the State of Amazonas

Land cover/land use	Abbreviation	Area (km^2)
Forest	A	278,195
Pasture	B	10,646
Exposed soil	C	36
Urban area	D	922
Pastoral agroforestry system	E	1000
Agroforestry system	F	3924
Agriculture	G	2691
Total area		297,414

facilitating the identification of areas with higher incidence of fire foci and their spatial behavior. This method was used to spatialize the fire foci and allow a more accurate analysis of the size and concentration of the fires occurrence.

From the kernel density, maps for each month of the year 2005 were created, which were classified according to their color and tonality, as follows: red indicates very high density; orange indicates high density; yellow medium density; green with lighter shade means low density and green with darker shade indicates very low density. In addition to the monthly maps, a map with the average of the dry season and one of the rainy season was generated. The maps interpolated through kernel density have a resolution of 1 km.

Mathematical formula of the kernel density method is expressed in Eq. (1) by (Smith et al. 2015):

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

wherein n = total number of observations; b = smoothing parameter (i.e., the bandwidth), which can be varied by the user; s = coordinate vector that indicates where the function is being estimated; s_i = coordinate vector representing each observation; K = density function that satisfies the following condition given by Eq. (2):

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

2.6 Multiple linear regression

To determine if the meteorological variables have predictive values for designing the occurrence of fire events, a simple linear regression for each variable was applied in Excel, where the number of foci was the dependent variable and the rainfall, average air temperature, relative air humidity and evapotranspiration were the independent variables. Regression was applied separately for the dry and rainy seasons and, in addition, the coefficient of determination (R^2) was calculated for determining the degree of correlation among the variables and the number of fire foci. Frequency percentage of the fire foci in the different classes (forest, pasture, exposed soil, urban area, pastoral agroforestry system, agroforestry system and agriculture) was also calculated aiming at determining what classes had the highest number of fires. The overall regression model is given by Eq. (3):

$$Y = \beta_0 + \beta_1 x + \varepsilon \tag{3}$$

wherein Y indicates the dependent variable, in this case the total number of fire foci; β_0 = angular coefficient; β_1 = linear coefficient; X = represents the independent variables (evapotranspiration, relative air humidity, average air temperature and rainfall).

Subsequently, the rainfall deviation was calculated in the study period of each month in relation to the historical climate of the region from 1961 to 1990 (Eq. 4).

$$\frac{1}{n}\sum\left(X - \bar{X}\right) \tag{4}$$

wherein X = rainfall (mm) for each month of the year 2005; $\bar{X}$ = rainfall (mm) during the normal period from 1961 to 1990; n = number of years of rainfall (mm) series analyzed.

3 Results

3.1 Kernel density

According to the maps generated after applying the Kernel spatial analysis technique, the highest occurrence of fire foci in the State of Amazonas was from July to November, corresponding to the second half of the dry season and the beginning of the rainy season. For the full year 2005, 30,065 fire foci were recorded (Table 2), of which 97% occurred in this period.

According to the maps, fire foci were more intense in the south and central regions of the State; however, in November the fire foci also concentrated in the north region and in September there was intense record throughout the State. According to the average kernel density maps (Fig. 2), during the rainy season, fire foci spread throughout the State, highlighting the northern and northeastern regions that showed more areas with high (orange and red) concentration of fire foci. During the dry season, it is possible to observe a concentration of foci in the south and central regions of the State, emphasizing the presence of red areas that indicate very high intensity of fire foci. The high intensity in these areas can be explained by the high presence of roads and proximity to the Amazon deforestation arc. In regions with more intense colors, i.e., high density areas, it can be inferred that there is a greater concentration in the number of foci and the regions with low density indicate lower concentrations (Fig. 2).

3.2 Fire foci and meteorological variables

Figure 3 presents the graphs of rainfall and climate for the year of 2005 and the rainfall deviation in relation to the climatology of the State of Amazonas. Observe a rainfall downward trend especially in January (rainy season) and a sharp drop of the rainfall at the beginning of the dry season (May and June). This negative deviation trend for the State of Amazonas shows the prolongation of the drought in the dry period and the decrease in rainfall during the rainy season. Rising population density and the opening of new frontiers for trade and timber exploitation in this region can contribute positively to a change in the regional climate.

The number of fire foci detected in the dry season was 25,169 (Table 2). Of these, 98% (24,802) occurred in months with monthly rainfall less than or equal to 100 mm and 86% of the fire foci occurred in August and September (Table 2). In the rainy season, the total

Table 2 Number of monthly fire foci in 2005 for dry and rainy seasons and frequency (freq.), in percentage (%)

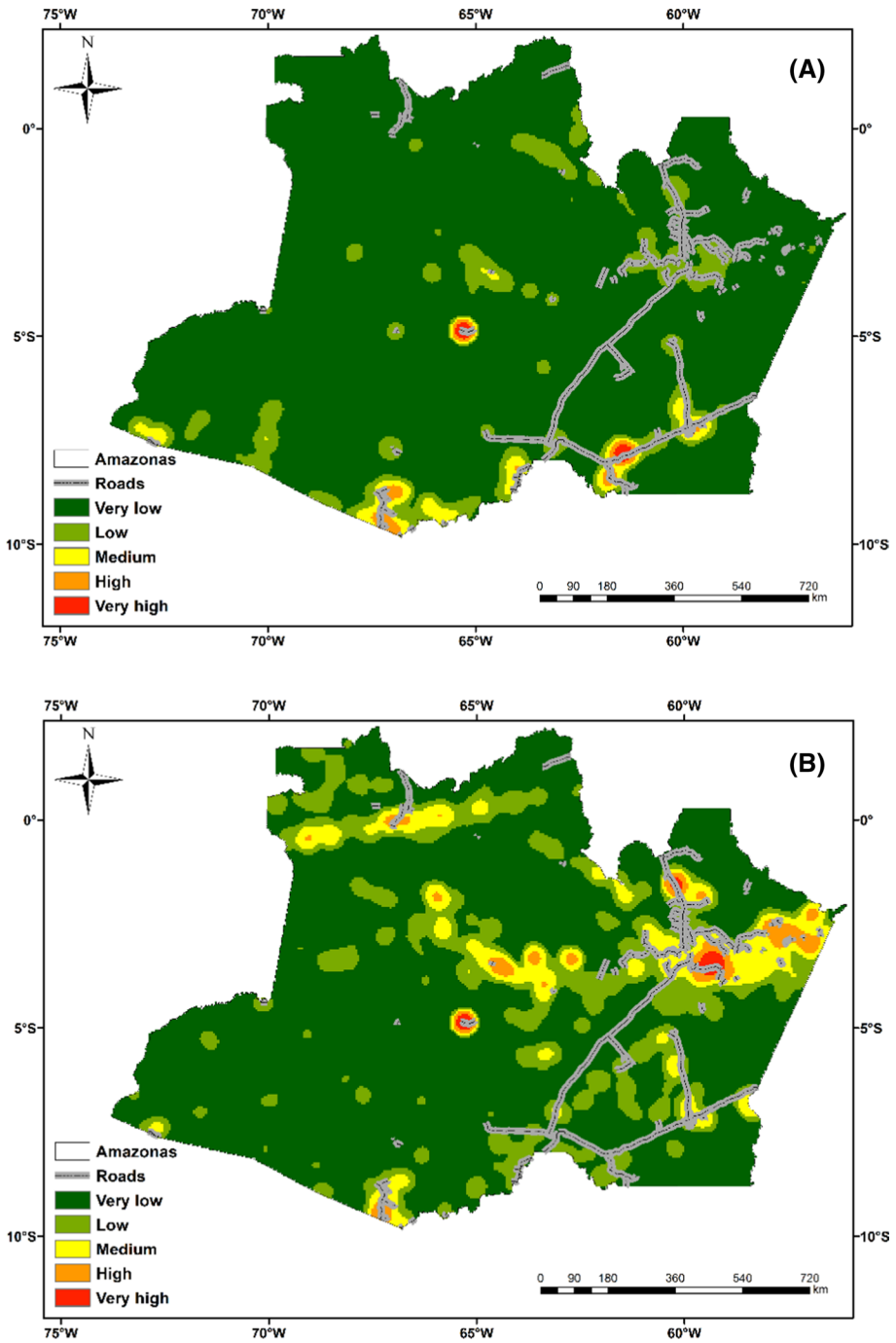| Dry season		Freq. (%)	Rainy season		Freq. (%)
April	34	0.14	October	3391	69.26
May	94	0.37	November	1075	21.96
June	239	0.95	December	67	1.37
July	2.956	12	January	172	3.51
August	11,049	43.9	February	90	1.84
September	10,797	42.9	March	101	2.06
Total	25,169		Total	4896	
Total			Total	30,065	

Total foci throughout the year

Fig. 2 Kernel density for the dry (**a**) and rainy (**b**) stations
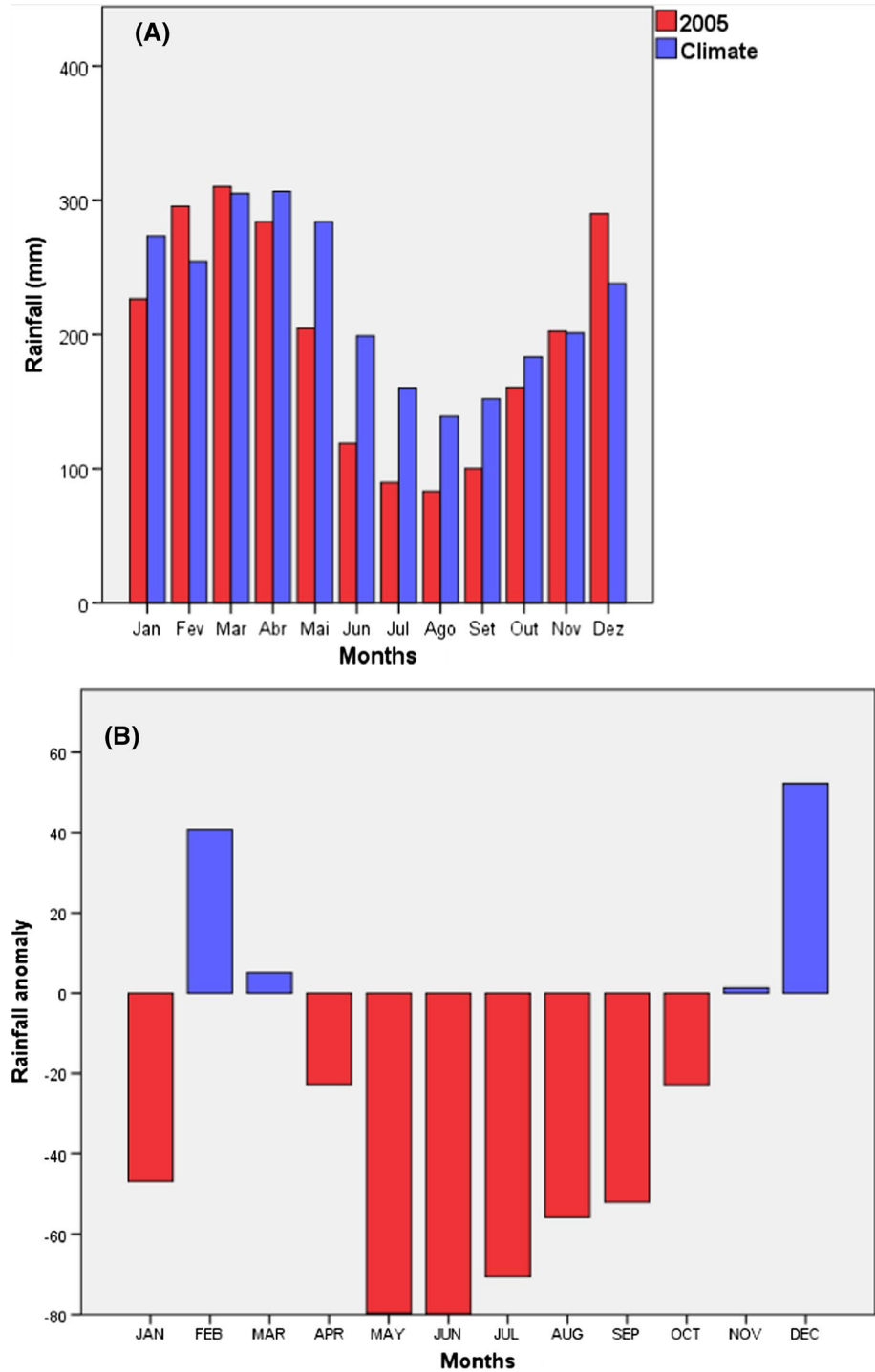
Fig. 3 Monthly rainfall for 2005 and the climatology from 1961 to 1990 (**a**) and rainfall deviation (**b**) for the State of Amazonas

Table 3 Environmental variables for the rainy (gray) and dry (white) seasons: evapotranspiration—ET_o (mm), average temperature—T_{av} (°C), rainfall (mm) and relative air humidity—RH (%)

Months	ET_o (mm)	T_{av} (°C)	Rainfall (mm)	RH (%)
October	126.99	28.87	160.53	81.11
November	114.08	28.48	202.42	84.03
December	104.41	27.84	290.19	86.13
January	119.08	28.5	226.5	84.32
February	90.36	27.75	295.46	86.71
March	101.54	27.84	310.38	86.69
April	97.37	27.8	284.14	86.32
May	102.41	27.98	204.58	84.84
June	104.11	27.77	119.1	83.61
July	110.73	27.14	89.65	81.61
August	121.42	28.24	83.24	81.68
September	122.84	28.33	100.17	78.62

Table 4 Coefficient of determination (R^2), in percentage, for dry (white) and rainy (gray) seasons

Climate variables	R^2 (%)	R^2 (%)
ET_o (mm)	93.24	52.86
T_{av} (°C)	34.97	64.35
Rainfall (mm)	40.86	70.63
RH (%)	67.95	84.41

number of foci was 4896, representing approximately 16% of the total number in the year. The beginning of rainy season, i.e., October and November, comprised 91% of the season fire foci (Table 2) and presented the lowest rainfall values in the rainy season: 160 and 202 mm, respectively (Fig. 3 and Table 3). The month of August presented the highest number of fire foci (11,049), equivalent to approximately 44% of the total.

The average temperature in the dry and rainy periods varied between 27 and 29 °C reaching the highest values in the months of October and November (Table 3). The relative air humidity in the dry season showed its lowest value in September (78%), followed by July and August, both with 81% (Table 3). The other months of the dry season varied between 83 and 86%. In the rainy season, the minimum value was 81% in October and the maximum was almost 87% in February.

Evapotranspiration in the dry season reached its maximum in September (122.84 mm), which corresponds to the month with the lowest relative air humidity of the whole year and the highest average temperature for the dry period. The month of August was the second largest with 121.42 mm, and months from April to July ranged from 97 to 110 mm. The month of October presented the maximum value (126.99 mm) of evapotranspiration during the whole the year, being the month that shows higher average temperature of the year and one of the lowest of a decade. From November to March, values ranged from 90 to 114 mm.

The values of the coefficients of determination for each variable are presented in Table 4. Overall regression model showed a correlation among the observed data, with coefficients significant for all variables. In the dry season, the variable that presented the highest correlation with the number of fire foci was evapotranspiration with a R^2 of 93.24%, which is directly influenced by solar radiation, wind, temperature and relative air

humidity. Nevertheless, the average temperature showed the lowest correlation, with R^2 of 34.97%. In the rainy season, the relative air humidity presented a higher relation with the number of fire foci ($R^2 = 84.41\%$), and evapotranspiration obtained the lowest R^2, which was equal to 52.86%.

3.3 Fire foci and land use

The results indicate that the forest and pasture classes were those with the highest number of fire foci corresponding, respectively, to 58 and 37% of the total fire foci (Fig. 4). The highest number of fire foci found in this study in forest and pasture areas is correlated with the area size (94 and 4%). The areas covered by forest were the only areas where fire foci were detected during all months of the year with a total of 16,525 foci. In these areas, during the dry season, 83.45% of the fire foci were recorded and of these, 88.32% were detected during the months of August and September. The month of April presented the lowest number of all year with a total of 29 foci, being this the month of the dry period with the highest rainfall index and relative air humidity.

In the rainy season, October had the highest fire foci record, with 1733 foci from a total of 2734, which is the equivalent to 63.38% of the total. The month of November presented 699 foci followed by a representative drop to 49 foci in December, which was the month with the lowest record for the period. For the pasture class, in the dry period, the dynamics was like the forest, i.e., the months of August and September reached the maximum, which
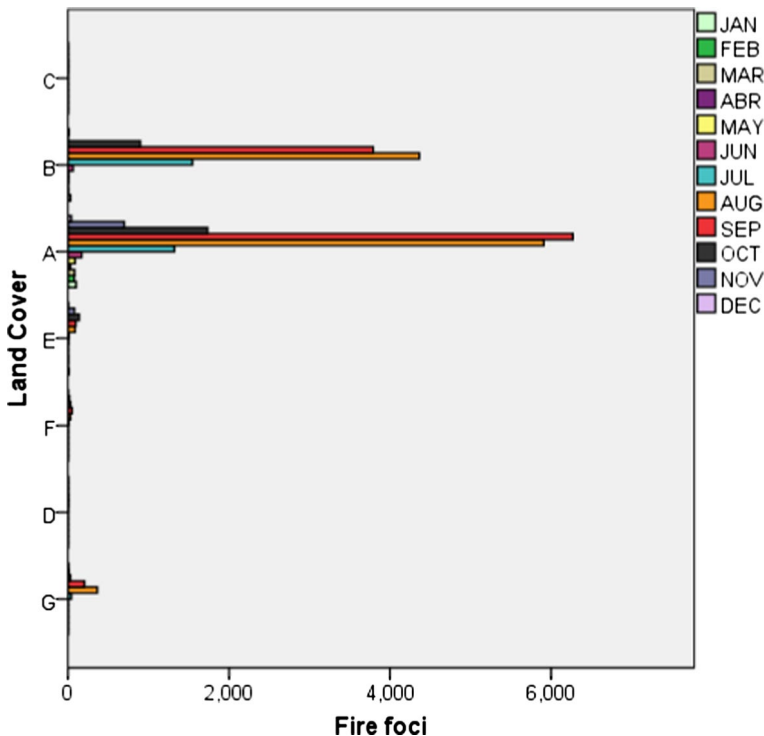

Fig. 4 Land cover versus fire foci in the State of Amazonas in 2005

was the equivalent to 59.15% of the total period. However, May reached the lowest value with only 3 foci for the whole month, followed by April, which showed 4 fire foci.

In the rainy season, the months of March and November did not show fire foci and in February was recorded only 1. In this period, the fire foci were concentrated in October where 95% of the total foci were recorded. Agriculture class had a total of 652 fire foci, mostly concentrated in the dry period (August and September). From January to June, there were no records of fire foci in this class. In areas with a predominance of agroforestry activities, the number of fire foci in the year was 139, occurring between July and November with a maximum in September (51). Pastoral agroforestry class showed 434 foci during the year where the maximum value was recorded in October (140). In this class, February, April and May did not present fire foci. The urban areas recorded 15 fire foci during the year, distributed from July to December with predominance in August and September. The class of exposed soil practically did not present fire foci, with a total of 2 records, being 1 in August and 1 in September, throughout the year.

4 Discussion

4.1 Fire foci and climate in Amazon region

One of the ways for reducing the risks of forest fires in protected areas is to spatially evaluate fire foci using spatial methods such as Kernel Density (Bacani 2016; Tien Bui et al. 2016). Results found by Wu et al. (2014), Ganteaume and Long-Fournel (2015) and Bacani (2016) are like those found in this study, where the areas with the greatest risk are close to the urban area edges, rural settlements and main roads. Studying the droughts that occurred in the 1990s (1997 and 1998) and the drought of 2005 and its relationship with the number of fire foci in the Amazon region, Aragao et al. (2007) found similar results and showed that despite the year showing a decline in deforestation rates, the number of fire foci was higher in 2005, indicating the intense drought occurred at that year as main cause.

Climatic conditions play an important role in the incidence of fire foci, and the year analyzed in this study was characterized by a severe and persistent drought in the State of Amazonas. In some climate change papers with future projections on some models such as that presented in the fifth report of the Intergovernmental Panel on Climate Change (IPCC 2014), some models underestimate the variability of the dry season length and the risk of deforestation may be much higher in this region (Fu et al. 2013). The results found in this study regarding the reduction of the rainy season and the prolongation of the dry period as the year of 2005 show that the forecast models should be updated periodically.

Relative air humidity, which is influenced by rainfall, also affects the moisture content of the combustible material and maintains relation with its flammability (Ray et al. 2005). Furthermore, Mendoza (2003), by conducting experimental fires in Acre, found strong relationship with relative air humidity and fire propagation speed, where the higher the humidity, the lower the fire propagation speed. Torres (2006) carried out an analysis of the relationship among the meteorological data and the fire incidence in the municipality of Juiz de Fora, MG, in the period 1995–2004 and found an inverse relationship between air humidity and number of fires. Machado et al. (2014) found similar results in Mato Grosso, corroborating the results already expected and found in the present study.

In the present study, more than 93% of the fire foci comprised the months with lower rainfall rates, a similar result was found by Vasconcelos et al. (2015) that identified more than 95%

of the fire foci in the driest months. Average air temperature kept little variation throughout the year, being close to 28 °C. Even so Ray et al. (2005) showed that in the Amazon, depending on the type of vegetation, fire events can occur at temperatures above 24 °C. Vasconcelos et al. (2015) compared a year of normal drought (2004) with a year of severe drought (2005) and found greater susceptibility to fire in 2005, as well as greater number of fire foci.

Overall, climatic conditions in which the highest incidence of fire foci occurred in the present study are correlated with years of droughts like 2005 and 2010, where water levels dropped significantly from the Amazonian rivers, isolating populations that are at riverbanks. Furthermore, dry season is more prolonged, being dry period worsened by a decline in rainy period (Espinoza et al. 2011; Marengo et al. 2011; Xu et al. 2011; Frappart et al. 2012).

Results found in this study are important for the knowledge of local relationships with climate, fire and land use and cover. Similar results of local character have been addressed, leading to the hypothesis that individuals, sectors and systems are affected to varying degrees and, moreover, may be impaired to a greater or lesser degree. These impacts range in magnitude and intensity according to certain aspects, such as geographic location, weather, prevailing social, economic and environmental conditions and the infrastructure of a given location (Sena et al. 2012).

Another important point raised in this study is that fire foci concentrated in some regions may increase respiratory diseases, such the 2005 drought, which was geographically more concentrated (Smith et al. 2014). The increase in forest fires and other uses as found in this study and the change in land cover over the years may reduce rainfall and increase the drought amplitude in the region (Bagley et al. 2014). Similar results found in this study were approached with the same perspective, where the authors explored the climatic factors in the last two more extreme droughts in the Amazon region (2005 and 2010) to show the decline of vegetation in this period (Zhao et al. 2017).

5 Conclusions

The hot spots were concentrated near the roads in the south and central regions of the Amazon. Although forests contribute to reducing the effects of climate change, it is a class that suffers from a high number of fire foci, especially in drought years in this region. Furthermore, temperature, represented by evapotranspiration, and relative air humidity had the greatest influence on the occurrence of fire foci, indicating the direct relationship between the results and the drought event of 2005.

The study is useful, since it puts in alert the vulnerability of the Amazon ecosystem in the face of the occurrence of fires, and it can also subsidize actions of mitigation of carbon emission and biomass stock, thus collaborating for more sustainable practices in one of the biomes of greater biodiversity in the world.

By monitoring fires by kernel density associated to meteorological variables, research like this one may provide subsidies to region's managers in an attempt to preserve forest areas and a greater controlling in priority areas considered very high.

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