




Fire foci and their spatiotemporal relations to weather variables and land uses in the state of Mato Grosso

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Abstract

We analyzed the occurrences of fire foci between years 2001 and 2015 in Mato Grosso state, Brazil. For this, we used remote sensing data and we correlated fire with surface temperature, rainfall, wind speed, air temperature, relative humidity, and vegetation index. The data were analyzed within the state according to use and cover classes. We also spatialize the fire occurrence using Kernel density and analyze trends with the Mann–Kendall test. The year 2015 was the year with the highest average annual air temperature and lowest annual cumulative rainfall, and wet season with the lowest relative humidity and highest surface temperature. Therefore, it was the year with less difference in the number of fire foci between wet (40.53%) and dry (59.47%) seasons. The period 2002–2005 and the years 2007 and 2010 had the highest fire foci, representing about 66.5% of the total from 2001 to 2015. In these years, 80 to 83% of fire foci occurred in the dry season. The classes with the highest density of fire were Mining Area, Urban Area, Temporary Crops, and Pasture. The fire foci in Urbanized Area, Temporary Crops, Pasture and Forestry classes tended to decrease throughout the 15 years evaluated. Fire foci were negatively correlated with rainfall, relative humidity and soil water and positively correlated with wind and surface temperature. This demonstrates that public policies related to combating fires in Brazil must be intensified especially in years with prediction of extreme drought.

Keywords Tropical forest · Cerrado biome · Agricultural frontier · Remote sensing · El Niño · Dry season

1 Introduction

The Amazon provides essential environmental services, and conserving them requires understanding the interactions between climate and human activities and their effects on forest biomass degradation (Barni et al., 2021). In the last decades, the Brazilian Amazon has been suffering from intensive burning caused by changes in land use and cover, for

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example, to expand the agricultural frontier, and aggravated by climate anomalies, generating significant economic, social and ecosystem services losses (Latorre et al., 2017). Fire is still a widespread instrument in this landscape, often applied by small, medium and large rural producers in agricultural management and in recently deforested areas (Alencar et al., 2020). Generally, fire in forest areas originates from nearby areas being burned, either as part of the initial deforestation or in the subsequent management of agricultural and livestock systems (Barni et al., 2021). Burning of vegetation in tropical ecosystems, directly related to land use, vegetation type, and climate variables, is one of the main factors that impact on regional climate and biodiversity (Panisset et al., 2018).

In the perspective of anthropic influences on climate, possible increases of dry seasons may increase the susceptibility of these areas to fires (Alves & Pérez-Cabello, 2017). Extreme drought events have occurred more frequently and are often related to the El Niño Southern Oscillation (ENSO) which is understood as a sea surface temperature anomaly and can have a large impact on regular rainfall patterns and temperatures on a global scale (Burton et al., 2020; Sousa et al., 2015). During 1997/98 and 2015/16, very high sea surface temperature anomalies were recorded, while the years 2002/03, 2004/05, 2006/07 and 2009/10 also showed higher than average sea surface temperatures (Burton et al., 2020). These anomalies can change the burning patterns in the Amazon but need to be combined with anthropogenic actions for ignition (Alencar et al., 2015; Aragão et al., 2009; Fonseca et al., 2019). Anthropogenic influence in change fire regimes includes suppressing fire, changing the frequency, timing and spatial distribution of ignition sources, changing fuel structure and composition through changing land use and cover, and contributing to greenhouse gases to the atmosphere, which drives climate warming (Fonseca et al., 2019).

The changes in climate and anthropic advancement (Lima et al., 2019; Silva et al., 2018a; Silva Junior & Lima, 2018) promote changes in the region fire dynamics, as they decrease soil water and promote essential effects on the pattern of forests and other vegetation cover (Alencar et al., 2015; Choat et al., 2012; Lewis et al., 2011; Lima et al., 2019; Rowland et al., 2015), triggering a direct influence on economic production and agricultural activities (Arvor et al., 2013). In addition, forests impacted by fires may not recover their original carbon stock, resulting in a net positive carbon contribution to the atmosphere, i.e., fires are important contributors to atmospheric greenhouse gas concentrations (Silva et al., 2018b). Future changes in the behavior of the fire use may have important impacts on many processes, for example, atmospheric emissions, and climate policy, biodiversity conservation, and land use management (Aragão et al., 2018; Barlow et al., 2016; Fonseca et al., 2019). Empirical predictions claim that climate change is the most important driver of increased Amazon understory fire activity by 2080 (Le Page et al., 2017).

Extreme weather events, such as drought in the Amazon Basin in 2005, 2010, and 2015, were responsible for significant changes in carbon stock in the ecosystem, water resource availability, and fire occurrence (Panisset et al., 2018). During long dry seasons, in the Amazon the favoring of natural disasters associated with the use of fire is observed (Latorre et al., 2017), mainly in border areas of this biome (Ramos, 2017). The western and southern regions of the Amazon were the hardest hit by drought in 2005 and 2010 (Santos et al., 2017; Zeng et al., 2008), causing more impacts at these locations. Some impacts were the air temperature in both years higher than average, the surface temperatures higher, and the atmosphere was drier in the year 2010 (Marengo et al., 2011a, 2011b).

In these regions, most affected by the drought in 2005 and 2010 is the state of Mato Grosso. This state includes parts of the Amazon, Cerrado and Pantanal biomes. Among the Brazilian states, Mato Grosso stands out for its extensive territory that provides a diversity of ecological, social, economic, cultural situations, production processes and rural

and agro-industrial development (Souza et al., 2013). The landscapes of this state form a mosaic with different ecosystems, including forest formations, savannas, wetlands, areas with natural and planted pastures, agricultural areas and urban centers. In the state, there is a predominance of megathermal climates, with concentrations of potential evapotranspiration in the summer below 40% and rainfall concentrated in the summer/autumn and water shortages in the winter/spring (Souza et al., 2013).

Mato Grosso is one of the main contributors to Brazilian agricultural production. Between years 2001 and 2019, it was responsible, on average, for about 22% of the country's annual grain production (CONAB, 2020) being between the states that more contributed to the agribusiness exports (MAPA, 2021). Between 2001 and 2019, Mato Grosso increased its contribution to total agribusiness exports from 5.83 to 17.40%, and as of 2019, it became the state with the highest contribution to Brazilian agribusiness exports. Currently, Mato Grosso is the main exporter of fibers and textile products, cereals and soy and one of the main exporters of meat. The destination of exports of these products is mainly China, Thailand, Spain, Vietnam, India, Egypt and Iran (MAPA, 2021). Mato Grosso also stands out in terms of environmental degradation. In that same period, 2001 to 2019, in the state were deforested 69,065 km² of vegetation with the occurrence of 792,733 foci, corresponding to 30.62% and 17.62% of the national rate, respectively (INPE, 2020a; INPE, 2020b).

Given the considerable participation of Mato Grosso in the deforestation Brazilian ranking, mainly for conversion to agricultural areas, that will often generate food for world consumption, is important understanding how the weather conditions and land use and cover influence the occurrence of fire foci in the state. Analyses like this can generate useful information because the state has a high diversity of ecosystems. Within and between ecosystems, fire–climate relationships have high variability, caused by differences in species composition, vegetation structure, and climate within a region (Fonseca et al., 2019; Gartner et al., 2012; McLauchlan et al., 2020). For this, the quantification and classification of land use and cover, fire foci and climatic conditions using satellite images as a reference for geospatial analysis are important tool for the planning and protection of areas of natural vegetation. The use of technologies related to the geographic information system for the analysis of fire foci in different regions is a resource widely used to obtain, manipulate, analyze, and present a good amount of spatial data. These data are necessary both for the determination of vulnerable fire zones and planning of fire intervention operations (Kavlak et al., 2021). For example, optical and thermal infrared band data of satellite imagery generate information on multi-temporal patterns and trends for determining different mitigation measures, such as determining appropriate locations for allocation of supporting infrastructure for fire cases (Cetin, 2019; Kavlak et al., 2021).

The importance of the state in the Brazilian and world scenario is undeniable. Combining this with a scenario of increased incidence of extreme drought events (Da Silva et al., 2019; Silva et al., 2021), such as those that occurred in the period from 2001 to 2015, it is important to have temporal and spatial information about fire foci in this state. This information may direct prevention activities, monitoring, and mitigation. In this context, the spatiotemporal monitoring of fire occurrences is essential to clarify issues associated with the reduction of harmful gas emissions to the population and the atmosphere, generate information to support biomes conservation strategies and improve prevention and combat fire policies. Therefore, the objective of this research was: 1. analyze the fire foci occurrences in the state of Mato Grosso between years 2001 to 2015, 2. verify the behavior of fire occurrences between the dry and wet seasons, and 3. relate the occurrence of fire with the weather variables, vegetation parameters and land use and cover.

2 Materials and methods

2.1 Study area

The study area covers the entire state of Mato Grosso (MT), located in the center-west region of Brazil (Fig. 1). The state of MT has an area of 903,872.00 km² and a population of 3,567,234 habitants (IBGE, 2018; IBGE, 2021). The biomes found in MT are the Amazon (53.5%), Cerrado (39.7%), and Pantanal (6.8%) (Borges et al., 2014). In the state are found 11 different soil orders. The orders of the highest expression are: Latossolos (Ferral-solos) (38%), Argissolos (Acrisols and Lixisols) (24%) and Neossolos (Fluvisols, Leptosols, Arenosols, and Regosols) (19%) (IBGE, 2018).

According to the Köppen-Geiger classification for Brazil (Alvares et al., 2013), the study area has two climatic domains, tropical monsoon (Am) and tropical dry winter (Aw) (Fig. 1), with two well-defined seasons, wet (October–April) and dry (May–September) (Souza et al., 2013). The highest total annual rainfall occurs in the mesoregions North and Mid-North, and in regions with altitudes close to 800 m (Souza et al., 2013).

2.2 Database

2.2.1 Land use and cover

The state of Mato Grosso has ten different classes of land use and cover (Table 1). These data were obtained from the Brazilian Institute of Geography and Statistics—IBGE, and

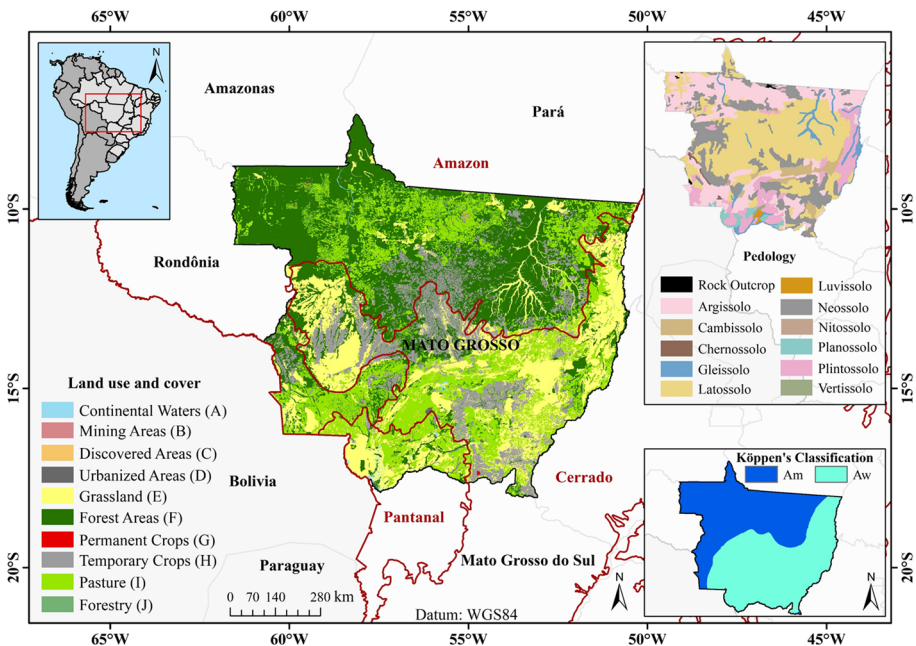


Fig. 1 Location of the study area, classes of land use and cover, pedology, biomes, and Köppen climatic domains

Table 1 Land use and cover, corresponding abbreviation and territorial extension of classes in the state of Mato Grosso

Land Cover/Land Use	Abbreviation	Area (Km ²)	%
Continental Waters	A	5609	0.621
Mining Areas	B	531	0.059
Discovered Areas	C	27	0.003
Urbanized Areas	D	1614	0.179
Grassland	E	198,021	21.908
Forest Areas	F	345,504	38.225
Permanent Crops	G	144	0.016
Temporary Crops	H	121,206	13.410
Pasture	I	229,765	25.420
Forestry	J	1451	0.161
Total area		903,872	100

they were disponibilized in a scale mapping of 1: 250,000 (IBGE, 2018). The ArcGIS 10.5 software was used to read the data and quantify the areas in each class. The Mining area, Urbanized area, Grassland, Forest area, Permanent crops, Temporary crops, Pasture, and Forestry classes were used in analysis. The Discovered class was not used because it has a small area, and the continental water class was not used because it does not present a relationship with the fire foci.

2.2.2 Fire foci data

Monthly fire foci observations for the years 2001–2015 were obtained, in shapefile, on the website of the platform FIRMS (Fire Information for Resource Management System, 2019) of NASA (National Aeronautics and Space Administration). We used fire data from the Moderate Resolution Imaging Spectroradiometer sensor—MODIS (TERRA and AQUA platforms). The Fire Information for Resource Management System (FIRMS) distributes Near Real-Time (NRT) active fire data within 3 h of satellite observation. These data have resolution of 1 km and are created by the most updated version (006) of the active fire algorithm MCD14 (Giglio, 2015). The ArcGIS 10.5 software was used to access and process the database and counting of monthly number of fire foci. These data were also separated for dry season (May–September) and wet season (October–April) and for the classes of land use and cover (Table 1).

2.2.3 Weather variables

Used data from four weather variables, in NetCDF format, validated by Xavier et al. (2016), are accumulated monthly rainfall (mm), average wind speed (m.s^{-1}) at 10 m, average air temperature ($^{\circ}\text{C}$) (simple average between maximum and minimum temperature), and relative air humidity (%). These data cover all Brazilian States in the period 1961–2017, and therefore, it was necessary to extract only from the State of Mato Grosso to the period of 2001–2015. Through R software (R Core Team, 2020), the variables of interest were extracted for the state of Mato Grosso and the years studied here. The `ncdf4` (Pierce, 2013) and `raster` (Hijmans et al., 2019) packages were used to handle these data in the R software (R Core Team, 2020). We also evaluated the water (mm) on the soil surface. Soil water data are produced by NCEP-DOE Reanalysis-2 and available from NOAA/

OAR/ESRL PSD (Kanamitsu et al., 2002). The R software (R Core Team, 2020) and these packages (ncdf4 and raster) were also used in soil water processing. So, we got the average monthly value of each variable.

2.2.4 Remote sensing products

To know the behavior of vegetation over the seasons and years, data from the Enhanced Vegetation Index (EVI) of the product MOD13Q1, V006 (Didan, 2015) were used. This product has a temporal resolution of 16 days and a spatial resolution of 250 m. The tiles h11v9, h11v10, h12v9, h12v10, h13v9, and h13v10 were used to cover the entire state of Mato Grosso, totaling 72 files per year. The MODIS HDF files were downloaded from NASA servers by the MODISTsp package (Busetto et al., 2019) of the R software (R Core Team, 2020). This package also was used to reproject for GeoTIFF format and Datum WGS-84.

For the analysis of the land surface temperature (LST), the daytime average monthly data were obtained from the product MOD11B3 V006 (Wan et al., 2015) in a total of 72 files per year also using the tiles h11v9, h11v10, h12v9, h12v10, h13v9, and h13v10. The original data were in Kelvin and have been converted to degrees Celsius using a calculator tool of the ArcGis 10.5 software.

For both products, MOD13Q1 (EVI) and MOD11B3 (LST), only good quality pixels obtained by "MODIS Quality Control" (QC) were used. In this case, a pixel was only considered good quality when QC met the following requirements (according to product user's guide): Category "CLOUDSTATE" is equal to 0 (significant clouds not present) or 3 (cloud coverage not defined, clear sky is assumed); Category "SCF_QC" equal to 0 (method used with best possible results) or 1 (method used with saturation).

2.3 Statistical analysis

The format, trend, and empirical distribution of the all weather variables, fire foci, and EVI were evaluated annually throughout the study period (2001 to 2015) by boxplot statistics produced by the ggplot2 package (Wickham, 2016) in the R software (R Core Team, 2020).

The fire foci distribution was analyzed according to land use and land cover classes and for this was generated a barplot with fire foci annual density (i.e., fire foci per km²) over time (2001 to 2015). Also was generated a barplot with abundance of fire foci in the land use and cover classes in the dry and wet seasons over years. To better understand the influence of weather variables and EVI in fire foci occurrence in each year, a correlation was obtained through Spearman's correlation coefficient, considering α : 5%. These analyses were realized with R software (R Core Team, 2020).

Aiming to identify the fire foci distribution and concentration in the state, the fire foci densities were calculated using the nonparametric estimator Kernel. Kernel density estimator plots the point intensity of a given phenomenon, corresponding to the radius of its influence (Barbosa et al., 2019). The method was used to spatialize the variable, classifying into the categories Very High (red), High (orange), Medium (yellow), Low (light green), and Very Low (dark green) densities. The rasters interpolated by the Kernel Density have a 1-km resolution. To associate fire foci data, the variables rainfall, relative humidity, and soil water were also spatialized within the state between the years 2001 and 2015 in the rainy and dry seasons. Maps with the average of the dry season and one of the rainy season were generated of each year, allowing more precise analysis of intensity and range in

the seasons. These analyses were realized with Spatial Analyst tools of the ArcGis 10.5 software.

To detect fire foci behavior in the time series according to land use and cover classes was used the nonparametric Mann–Kendall test (Kendall, 1975; Mann, 1945). This analysis consists in verifying if there is a significant tendency of the data over time and if it has positive characteristics or negative, considering α : 5%, the p-value and the Z index of the test. To estimate the magnitude of trends was used the Sen's slope statistic (Sen, 1968; Silva Junior et al., 2018). The Trend package (Pohlert, 2020) was used to realize this analysis in R software (R Core Team, 2020).

3 Results

3.1 Characterization of variables

The average air temperature, considering the annual average, was around 26 °C for the years 2001 to 2014 and 27.05 °C in 2015, higher than the other years studied. The highest monthly average temperatures in this time series occurred in 2002 (28.59 °C), 2005 (28.53 °C), 2010 (28.57 °C) and 2015 (29.21 °C), Fig. 02, occurring in the first two years in October (start of the wet season) and the others in September (end of the dry season).

The wind variable showed a gradual reduction and growth behavior every four years, with the maximum values in the years 2003 (1.86 m.s⁻¹), 2007 (1.68 m.s⁻¹), 2008 (1.80 m.s⁻¹) and 2013 (2.02 m.s⁻¹), all in the final months of the dry season. Rainfall presented high variability between data, ranging from values close to zero in dry season months to 382 mm in rainfall months. In the year-to-date basis, we can highlight the years 2002 (1581.76 mm), 2007 (1596.08 mm), 2010 (1562.56 mm), and 2015 (1503.29 mm) with the lowest values, Fig. 02.

Regarding relative humidity, Fig. 02, the lowest average monthly values occurred in 2008 (48.62%), 2010 (48.82%), 2012 (48.34%), 2013 (48.68%) and 2015 (49.80%). In all analyzed years, the lowest monthly relative humidity always occurred in the dry season (month of August), and the highest values during the wet season. In 2015, the lowest average relative humidity of the wet season was found, 77.98%, against 79.23 to 82.45% in the other years.

By analyzing the land surface temperature, a pattern similar to the average air temperature is observed, with the highest temperatures in October and September. In 2015 also had the highest average (31.74 °C) of wet season continental surface temperature compared to other years.

Regarding soil water, Fig. 2, the years with the lowest monthly values were 2007 (187.13 mm), 2010 (177.35 mm) and 2015 (181.33 mm). These values occurred in the last month of the dry season, September. The wet season of 2015 was the one with the lowest amount of soil water, 2,526.33 mm, compared to the other years that had from 2,984.14 (2014) to 3,468.89 mm (2003). Regarding the vegetation data, a behavior similar to that of precipitation, relative humidity of the air, and soil water and contrary to the land surface temperature is observed every year. In the dry season, over the years, the average EVI values ranged from 0.37 to 0.40 and in the wet season from 0.46 to 0.49.

The fire foci showed greater monthly variation in 2002, 2003 and 2004. It is observed that from 2004 to 2013 the fire foci trend positively followed the surface temperature and

negatively the precipitation. However, in 2014 and 2015, even with rising temperatures and reduced rainfall, there was not a significant upward trend in the number of fire foci (Fig. 2).

3.2 Fire foci

The highest fire foci densities (fire foci.km⁻²) occurred in the years 2002–2005, 2007 and 2010 (Fig. 3), representing 66.5% (931,150 foci) of the total fire foci occurred between 2001 and 2015. In these years, 80 to 83% of the fire foci occurred in the dry season (Fig. 4). Already 2015 was the year in which there was less difference in occurrence between the two seasons, with 40.53% of fire foci in the wet season and 59.47% in the dry season (Fig. 4).

The land use classes with the highest density of fire foci sources in all years analyzed were Mining Area (B), Urban Area (D), Temporary Crops (H) and Pasture (I) (Fig. 3). The

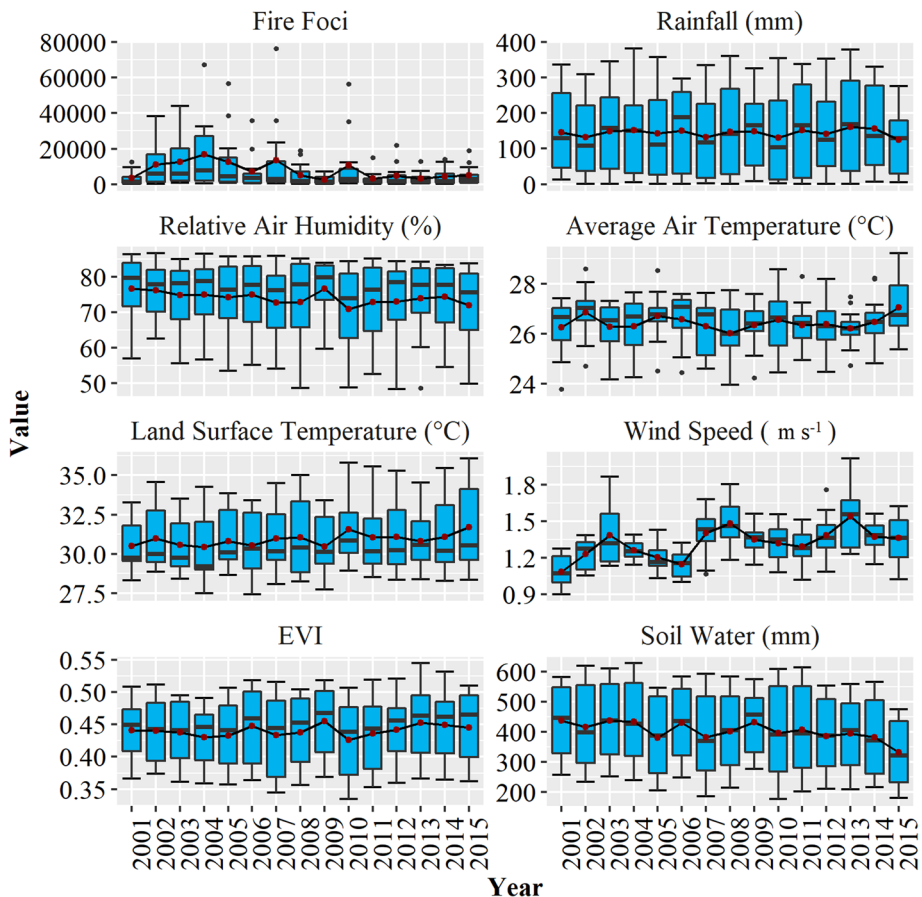


Fig. 2 Boxplot of Fire Foci, Rainfall, Relative Air Humidity, Average Air Temperature, Land Surface Temperature, Wind Speed, Enhanced Vegetation Index, and Soil Water for the years 2001 to 2015

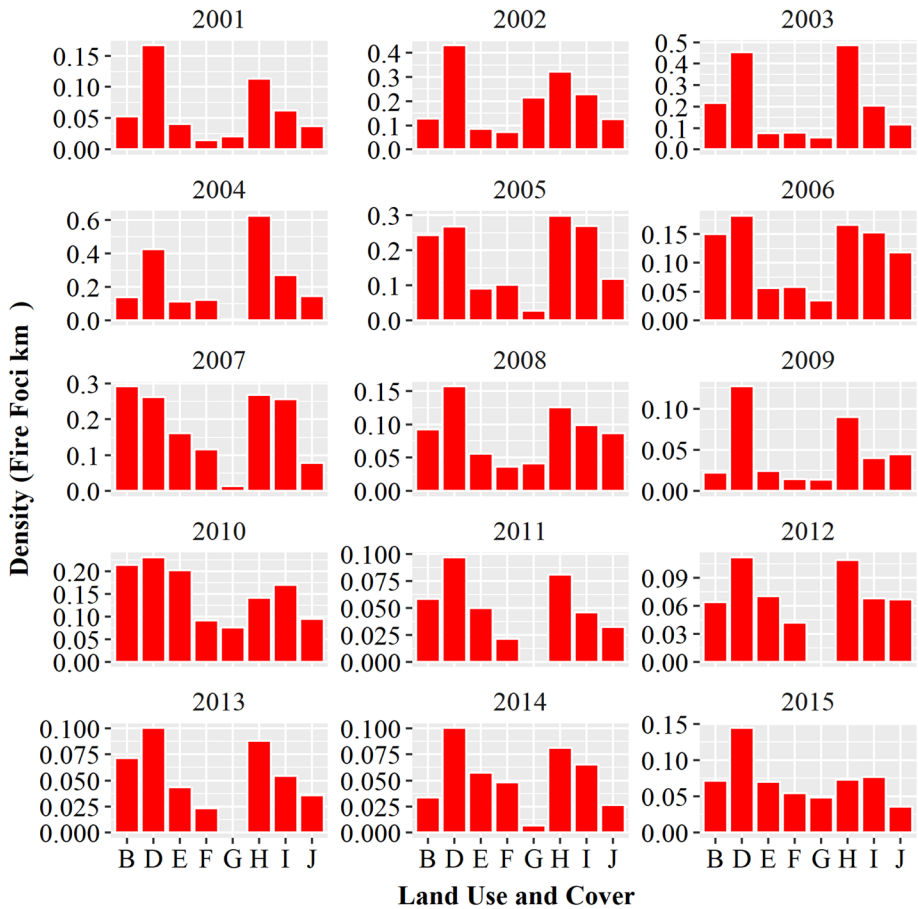


Fig. 3 Fire foci density per class of land use, where **B** Mining Areas, **D** Urban Areas, **E** Grassland, **F** Forest Area, **H** Temporary Crops, **I** Pastures, and **J** Forestry

urban and mining areas, despite the high fire foci density values observed, when added together represent only 0.24% of the state territory (Table 1).

Among the vegetation cover classes, the areas that concentrated the greatest number of fire foci in all years were pasture, temporary crops, grassland and forest. These classes occupy extensive areas in the state’s territory, 25.4%, 13.4%, 21.9%, and 38.2%, respectively. In all classes and years, fire foci were concentrated in the dry season.

3.3 Correlation between fire foci and weather variables

In all years, there was a negative correlation between fire foci and rainfall (ranging from 0.53 in 2015 to 0.9 in 2012), relative humidity (ranging from 0.84 in 2015 to 0.98 in 2004), and soil water (ranging from 0.81 in 2014 to 0.99 in 2002 and 2008) (Table 2). In relation to EVI, there was also a negative correlation with fire foci every year. The EVI is influenced by rainfall, relative air humidity and soil water. Negative correlation values indicate that the lower

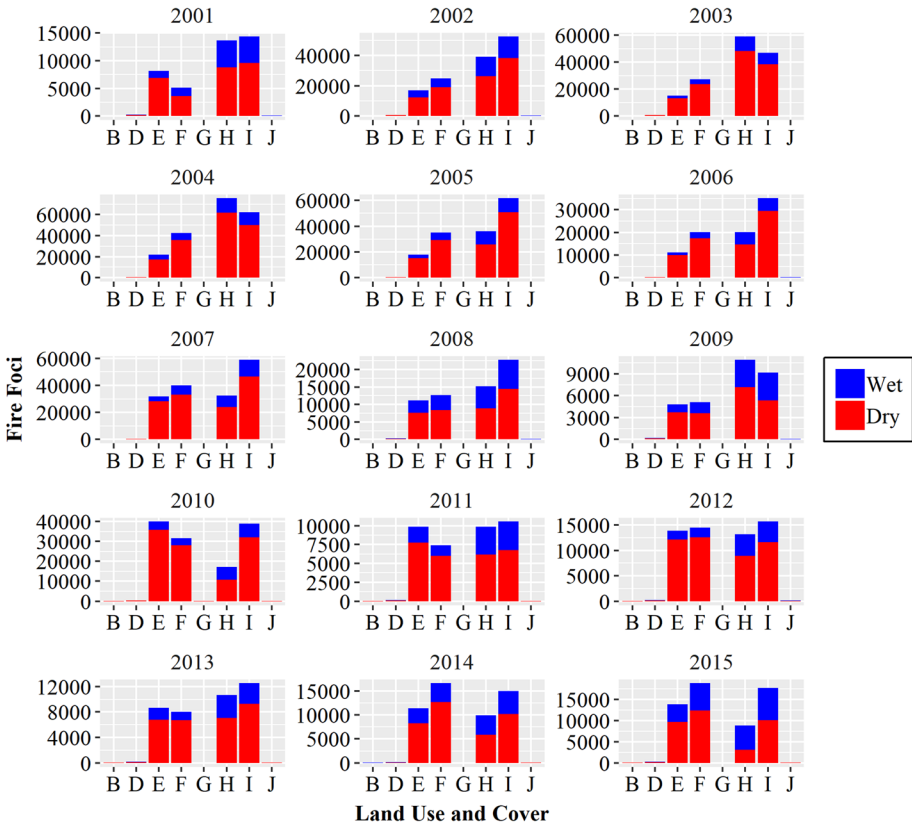


Fig. 4 Fire foci in the dry season (red) and wet season (blue) by land use class, where (B) Mining Areas, D Urbanized Areas, E Grassland, F Forest Area, H Temporary Crops, I Pastures and J Forestry

Table 2 Spearman’s correlation coefficient of monthly average data from 2001 to 2015 between Fire Foci and Land Wind Speed (WS), Surface Temperature (LST), Average Air Temperature (AAT), Rainfall (RF), Enhanced Vegetation Index (EVI), Relative Air Humidity (RH) and Soil Water (SW)

Years	WS	LST	AAT	RF	EVI	RH	SW
2001	0.77	0.59	0.06*	-0.78	-0.85	-0.95	-0.90
2002	0.50	0.55	0.25*	-0.67	-0.88	-0.97	-0.99
2003	0.92	0.45	-0.14*	-0.80	-0.92	-0.96	-0.92
2004	0.31*	0.35*	-0.10*	-0.83	-0.92	-0.98	-0.90
2005	0.77	0.48	-0.06*	-0.78	-0.92	-0.94	-0.92
2006	0.64	0.55	0.31*	-0.80	-0.85	-0.85	-0.85
2007	0.56	0.46	0.03*	-0.84	-0.99	-0.97	-0.91
2008	0.96	0.67	0.42	-0.66	-0.80	-0.92	-0.99
2009	0.72	0.50	0.18*	-0.70	-0.71	-0.86	-0.87
2010	0.62	0.52	-0.08*	-0.81	-0.92	-0.94	-0.90
2011	0.57	0.67	0.49	-0.67	-0.80	-0.85	-0.92
2012	0.50	0.46	0.12*	-0.90	-0.86	-0.96	-0.88
2013	0.64	0.49	0.01*	-0.78	-0.87	-0.94	-0.86
2014	0.65	0.43	0.27*	-0.87	-0.92	-0.94	-0.81
2015	0.78	0.87	0.72	-0.53	-0.65	-0.84	-0.94

Values marked with “” were not significant considering α : 5%

the presence of rainfall, relative humidity, soil water, and greening of vegetation the greater the likelihood of fire foci. The wind and land surface temperature variables showed a positive correlation with fire foci (ranging from 0.5 in 2002 and 2012 to 0.96 in 2008, and 0.43 in 2014 to 0.87 in 2015, respectively) (Table 2). The average air temperature showed a significant correlation with fire foci only in 2008 (0.42), 2011 (0.49), and 2015 (0.72) (Table 2). Positive correlation values indicate that the higher the land surface temperature, average air temperature, and presence of wind, the greater the likelihood of fire foci.

3.4 Kernel density

Most the study area was mainly subjected to the Very Low and Low Kernel density classes (Figs. 5 and 6). However, the two highest density classes of fire foci were observed in significant quantities in the territory of the state over the years.

During the wet season (Fig. 5), except for 2011 and 2013, every year presented a high incidence of High and Very High densities. The highest densities were located mainly in the Central and Northeast regions of the state. In 2004 and 2005, an increase in the size of Very High Density fire foci can be observed. These years are the ones with the highest fire foci for this season, due to the high concentration in October, month in which the wet season begins. The year 2015, characterized by high intensity El Niño, presented a high concentration of fire foci in the Central, Northeast, and Southwest regions, in addition to the presence of medium density throughout almost the state. In the years mentioned, the variables rainfall, relative humidity, and soil water registered low values throughout the East and also in the southwest of the state (Fig. 5).

During the dry season, fire foci in each year also focus mainly on the central region of the state (Fig. 6). However, in 2007, 2010, and 2015, it also was possible to observe very high density spots in the Northeast and Northwest of the state. The relationship with meteorological variables in this season is seen more clearly, where rainfall was lower in almost the entire state accompanied by low relative humidity and soil water (Fig. 6). The years 2011 and 2013 showed the lowest record of fire foci in the two seasons.

3.5 Trend analysis

The Mann–Kendall test showed only three classes of land use and land cover, Urbanized Area (D), Temporary Crops (H), and Forestry (J) with a significant trend of reduction of fire foci in the annual assessment (Table 3). For the wet season, it was also possible to observe the significant tendency of reduction of fire foci in Urbanized Area (D), and Temporary Crops (H), besides the tendency of reduction in Pastures (I) (Table 3). Finally, the dry season also had a significant trend of reduction of fire foci in the 15 years evaluated in Urbanized Area (D), Temporary Crops (H), and Forestry (J). In all classes with a significant trend can be observed a small value in the magnitude of reduction of fire foci (Sen's slope).

4 Discussion

The analyses showed a close relationship between the occurrence of fire foci and climatic variables, mainly relative air humidity, soil water and rain. In the dry season, when the winds are more intense and the relative air humidity and water in the soil are significantly

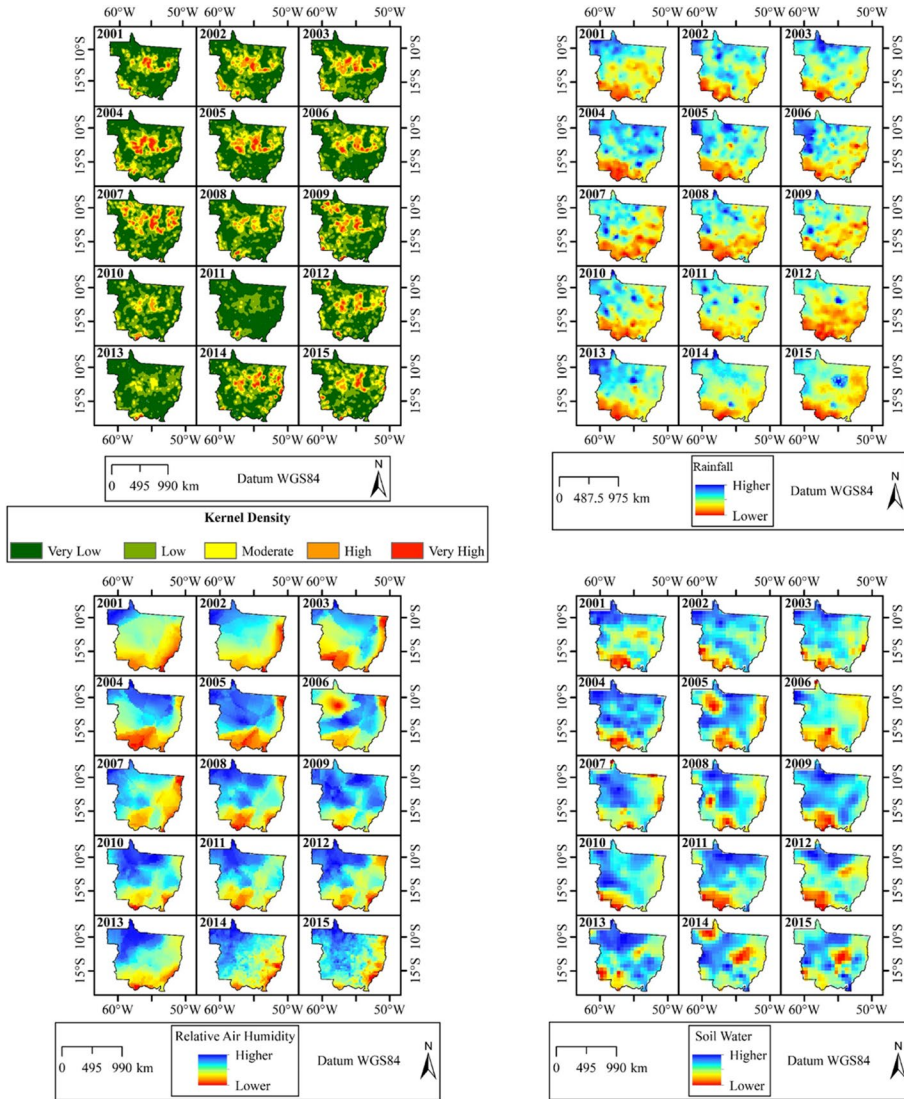


Fig. 5 Kernel density of fire foci and distribution of the highest and lowest rainfall, relative humidity and soil water of the wet season in the state of Mato Grosso between 2001 and 2015

lower, there was a greater number of fire foci in all the years analyzed. In the Amazon region, most burns and forest fires are detected in periods of drought, when there is also low relative air humidity and high temperatures. In dry seasons, the landscape greening is reduced, influenced by the scarcity of rainfall together with relative air humidity and water in the soil, and this consequently reduces the moisture content of combustible materials and causes greater flammability of the vegetation (Justino et al., 2002; Ribeiro et al., 2021). In these periods, the wind also influences the propagation and effects of fires (Machado et al., 2014; Soares, 1990).

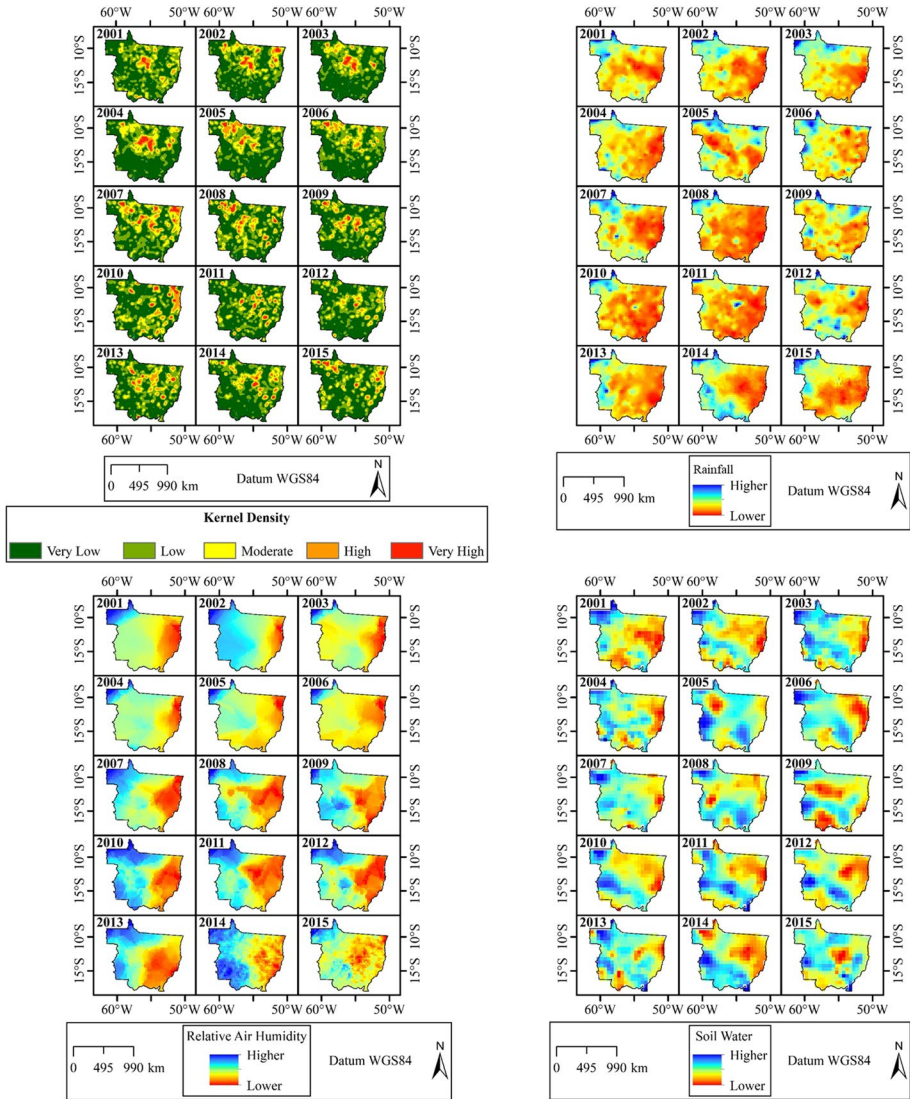


Fig. 6 Kernel density of fire foci and distribution of the highest and lowest rainfall, relative humidity and soil water of the dry season in the state of Mato Grosso between 2001 and 2015

Although studies have not reported a significant trend in the number of fires in the Amazon region between 2002 and 2016 (Marengo & Souza Junior, 2018), we found a trend toward a reduction in the occurrence of fire foci between years 2001 and 2015 in some of the land use classes (Urbanized Area, Temporary Crops, Forestry, Pastures). However, even with the trend towards reduction fire foci, still there was high density of fires in pastures and temporary crops. The trend reduction may be related to adoption of the no-till system of temporary crops by big farmers over time, which replaces the conventional agriculture of cutting and burning the remains. In 2006, the state of Mato Grosso had about

Table 3 Mann–Kendall trend statistics and Sen’s slope for fire foci according to land use and cover class from 2001 to 2015 in the state of Mato Grosso according to the annual total, the total in the wet season and the total in the dry season

		B	D	E	F	G	H	I	J
Annual	Z _{mk}	-1.139	-3.121	-0.396	-0.693	-1.345	-3.365	-1.781	-2.824
	Sen	-3.75	-30.00	-238.00	-932.00	-0.30	-2332.54	-3139.33	-11.00
	p	0.2545	0.0018	0.6922	0.4884	0.1785	0.0008	0.0748	0.0047
Wet Season	Z _{mk}	1.001	-2.579	-0.099	-0.693	-1.140	-2.474	-2.177	-1.536
	Sen	0.22	-5.50	-5.50	-78.00	0.00	-613.00	-515.15	-2.00
	p	0.3167	0.0099	0.9212	0.4884	0.2543	0.0133	0.0294	0.1245
Dry Season	Z _{mk}	-1.338	-2.771	-0.594	-0.989	-1.208	-3.266	-1.781	-3.068
	Sen	-3.42	-29.00	-222.75	-643.80	-0.14	-1754	-2353	-9.00
	p	0.1810	0.0056	0.5526	0.3223	0.2272	0.0011	0.0748	0.0022

Bold values are significant with α : 5%, where: (B) Mining Areas; (D) Urbanized Areas; (E) Grassland; (F) Forest Area; (H) Temporary Crops; (I) Pastures and (J) Forestry

32,400 km² under the conservationist system (IBGE, 2006), while in the 2017/18 crop year the area using this technique in the state exceeded 100,000 km², the largest extension among the Brazilian states (IBGE, 2017).

Complementary Law No. 233, of December 21, 2005, also contributed to the general reduction of fire foci as of 2006. This law prohibited the use of fire for cleaning and management of areas in the period between July 15 and September 15 (dry season). But, even with implementation of the legislation, the larger concentration of fire foci still occurred in August and September, as these are the months with the most favorable environmental conditions for ignition and fire propagation (dry combustible material, accentuated deficit in the relative air humidity, precipitation, and more intense winds). Among the main causes of fires in the state are the action of incendiary, burned to clean areas and lightning (Machado Neto, 2016).

Despite the general trend of reduction of fire foci in some use classes between years 2001 and 2015, the year 2007 showed about 88% more records than the previous year. The year 2010 also registered a significant increase (323%) in the number of fire foci compared to 2009. The extremes in 2007 and 2010 can be explained by the weather conditions observed in these years (Machado Neto, 2016). The years 2006 and 2009 were wetter years compared to the years immediately following, presenting meteorological conditions less favorable to the propagation of fires. Therefore, it can be inferred that in 2006 and 2009 the unfavorable environmental conditions to combustion favored the accumulation of plant biomass. Thus, the significant increase in the number of fire foci in 2007 and 2010 was due to the favorable conditions for combustible material accumulated in the previous years (Ramos et al., 2011; Machado Neto, 2016; Marengo & Souza Junior, 2018).

In 2015, despite being the driest year in recent years in the Amazon region (Garcia et al., 2018; Panisset et al., 2018; Silva Junior et al., 2018), we did not find a high occurrence of fire foci in comparison with previous years. However, was the year less difference in the number of fire foci between dry and wet seasons. In that year, there was a more accentuated proportional decline in precipitation, which implied a progressive extension of the dry season (Marengo & Souza Junior, 2018), as also occurred in 2005 (Barbosa et al., 2019). This caused normally rainy months presented favorable conditions for the occurrence of

fire foci. Given the scenario of increased incidence of extreme events (Da Silva et al., 2019; Silva et al., 2021), this highlights that it is important to understand the causes and seek tools to predict the late start of the wet season or extension of the dry season. Sena et al. (2018), claim that the variability of the wet season onset/demise in South America is likely caused by a combination of physical mechanisms of natural and anthropogenic origin, such as land-use change, global warming, and impacts on the hydrological cycle.

The results found in this study demonstrate the role of climatic conditions in fire control, and they are important for understanding the relationships between fire and land use and cover in this region, for example the occurrence of fires in forest areas. This class naturally retains more humidity, and in the state, it coincides with the region with the greatest amount of precipitation; however, when exposed to dry weather conditions, this ecosystem becomes vulnerable to fire. In the case of the 2005 drought in Amazonia, fires affected large areas of primary forests (Cox et al., 2008; Marengo et al., 2008). Generally, forest fires occur due to the use of fire to clear recently deforested areas and fire coming from adjacent agricultural areas (Barbosa et al., 2019; Rosan et al., 2017). Also, almost 40% of the state is part of the Cerrado biome, characterized by the occurrence of natural fire. This condition is important for species that have fire-related reproductive mechanisms, such as flowering induction and fruit opening after the fire (Munhoz & Felfili, 2007; Stokes et al., 2004). In grassland areas, inserted in greater proportion in Cerrado, the concentrations of fire foci also occurred due to this characteristic of the biome. Savannas and grasslands are highly flammable ecosystems as they have an abundance of fine plant material close to the ground (Cataño, 2021).

Despite state to present an extensive area of Cerrado, the northern and central regions localized in the Amazon biome, in general, were the most affected by fire foci, both in the dry and rainy seasons. These regions cover part of the so-called deforestation arc (a region of intense deforestation), related to the continuous increase in the agricultural frontier and which often uses fire in the process to open new areas (Klink & Machado, 2005; Araujo, 2007). This reinforces that the fire foci occur due to a combination of anthropic action with climatic conditions. Human beings have a direct influence on fire regimes when they change the structure, composition, and spatial distribution of the combustible material, when they cause changes in land use and cover, and when by contribute to greenhouse gases, that drive climate change (Fonseca et al., 2019). Deforestation, still common in the state, is another variable that contributes to the occurrence of fire foci. After deforestation, the areas are burned to facilitate cleaning and conversion to pasture or agricultural areas.

5 Conclusions

Our analysis confirmed our assumptions that fire foci in the state of Mato Grosso are closely related to climate variability and vegetation parameters. We also confirmed that regardless of the period, fire occurrences are concentrated in agricultural cultivation, pasture and native vegetation areas. This reinforces that human action acts as a propelling source in the occurrence of fire for management practices when climatic variables are favorable.

Despite the possible reduction in the study period in some land uses class, fire occurrences are still extremely significant in this state. This demonstrates that fire prevention, inspection and fighting policies should be intensified mainly in the dry season and years with extreme drought forecast, when more months with favorable conditions for fire

occurrences can occur. Thus, public policies related to combating deforestation and the indiscriminate use of fire in Brazil are fundamental, given the importance of these biomes for biodiversity conservation. The concern and assistance of other countries are also indispensable and must be valued by state and national governance, as this is an important region in the world scenario of food production and climate regulation.

The information obtained in this study, using the fire foci spatialization and variables that influence fire, helps in the identification of areas most vulnerable to fires and in the knowledge of where efforts should be concentrated. They also can guide the planning of intervention operations and infrastructure implementation in places susceptible to fire. These results and methodology can support conservation and environmental protection actions since many areas of the biomes and its surroundings are still in the exploration phase of natural resources.

References


- Alencar, A. A., Brando, P. M., Asner, G. P., & Putz, F. E. (2015). Landscape fragmentation, severe drought, and the new Amazon forest fire regime. *Climate Change 2013—The Physical Science Basis*, 25(6), 1–30. <https://doi.org/10.1890/14-1528.1>
- Alencar, A., Rodrigues, L., & Castro, I. (2020). Amazônia em chamas: O que queima e onde. *Nota Técnica, IPAM*, 5, 2020.
- Alvares, C. A., Stape, J. L., Sentelhas, P. C., Sparovek, G., & de Moraes Gonçalves, J. L. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, 22(6), 711–728. <https://doi.org/10.1127/0941-2948/2013/0507>
- Alves, D. B., & Pérez-Cabello, F. (2017). Multiple remote sensing data sources to assess spatio-temporal patterns of fire incidence over Campos Amazônicos Savanna Vegetation Enclave (Brazilian Amazon). *Science of the Total Environment*, 601, 142–148. <https://doi.org/10.1016/j.scitotenv.2017.05.194>
- Aragão, L. E. O., Shimabukuro, Y. E., Lima, A., Anderson, L. O., Barbier, N., & Saatchi, S. (2009). Utilização de produtos derivados de sensores orbitais para o estudo de queimadas na Amazônia. *Anais XIV Simpósio Brasileiro de Sensoriamento Remoto*, 919–925.
- Aragão, L. E. O. C., Anderson, L. O., Fonseca, M. G., Rosan, T. M., Vedovato, L. B., Wagner, F. H., & Saatchi, S. (2018). 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nature Communications*, 9(1), 536. <https://doi.org/10.1038/s41467-017-02771-y>
- Araujo, L. M. A. de, Silva, T. M. V. da, & Nascimento, E. R. do. (2007). Análise dos focos de calor em áreas florestais ao longo do Arco do Desflorestamento. *Anais do XIII Simpósio Brasileiro de Sensoriamento Remoto*, 4421–4423.
- Arvor, D., Dubreuil, V., Ronchail, J., Simões, M., & Funatsu, B. M. (2013). Spatial patterns of rainfall regimes related to levels of double cropping agriculture systems in Mato Grosso (Brazil). *International Journal of Climatology*, 34(8), 2622–2633. <https://doi.org/10.1002/joc.3863>
- Barbosa, M. L. F., Delgado, R. C., Teodoro, P. E., Pereira, M. G., Correia, T. P., de Mendonça, B. A. F., & de Rodrigues, R. Á. (2019). Occurrence of fire foci under different land uses in the State of Amazonas during the 2005 drought. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-018-0157-4>
- Barlow, J., Lennox, G. D., Ferreira, J., Berenguer, E., Lees, A. C., Nally, R. M., et al. (2016). Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. *Nature*, 535(7610), 144–147. <https://doi.org/10.1038/nature18326>
- Barni, P. E., Rego, A. C. M., Silva, F. C. F., Lopes, R. A. S., Xaud, H. A. M., Xaud, M. R., et al. (2021). Logging Amazon forest increased the severity and spread of fires during the 2015–2016 El Niño. *Forest Ecology and Management*. <https://doi.org/10.1016/j.foreco.2021.119652>
- Borges, H. B. N., Silveira, E. A., & Vendramin, L. N. (2014). *Flora arbórea de Mato Grosso: Tipologia vegetal e suas espécies*. Entrelinhas.
- Burton, C., Betts, R. A., Jones, C. D., Feldpausch, T. R., Cardoso, M., & Anderson, L. O. (2020). El Niño Driven Changes in Global Fire 2015/16. *Frontiers in Earth Science*, 8(199), 2020. <https://doi.org/10.3389/feart.2020.00199>

- Busetto, L., Ranghetti, L., & Wasser, L. (2019). MODISstp: A Tool for Automating Download and Pre-processing of MODIS Land Products Data. <https://cran.r-project.org/web/packages/MODISstp/index.html>
- Cataño, M. G. Q. (2021). Variabilidade espaço-temporal dos focos de queimadas sobre a região central da América do Sul. Dissertação, Instituto Nacional de Pesquisas da Amazônia, 1–115.
- Cetin, M. (2019). The effect of urban planning on urban formations determining bioclimatic comfort area's effect using satellite images on air quality: A case study of Bursa city. *Air Quality, Atmosphere and Health*, 12, 1237–1249. <https://doi.org/10.1007/s11869-019-00742-4>
- Choat, B., Jacobsen, A. L., Cochard, H., Sperry, J. S., Wright, I. J., Gleason, S. M., et al. (2012). Global convergence in the vulnerability of forests to drought. *Nature*, 491(7426), 752–755. <https://doi.org/10.1038/nature11688>
- Companhia Nacional de Abastecimento—CONAB. (2020). Séries Históricas das Safras—Grãos por Unidade da Federação. https://www.conab.gov.br/info-agro/safras/serie-historica-das-safras?limit_start=0. Accessed 3 June 2020.
- Cox, P. M., Jones, C. D., Betts, R. A., Harris, P. P., Huntingford, C., Nobre, C. A., et al. (2008). Increasing risk of Amazonian drought due to decreasing aerosol pollution. *Nature*, 453(7192), 212–215. <https://doi.org/10.1038/nature06960>
- Da Silva, S. S., de Oliveira, I. S., Anderson, L. O., Fearnside, P. M., de Melo, A. W. F., da Costa, J. G., et al. (2019). Incêndios florestais e queimadas na Amazônia sul ocidental. *Mapiense*, 3, 27–35.
- De Souza, A. P., Lima, L., Zamadei, T., Martim, C. C., De Almeida, F. T., & Paulino, J. (2013). Classificação climática e balanço hídrico climatológico no estado de Mato Grosso. *Nativa*, 1(1), 34–43. <https://doi.org/10.14583/2318-7670.v01n01a07>
- Didan, K. (2015). MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006. NASA EOSDIS LP DAAC. <https://doi.org/10.5067/MODIS/MOD13Q1.006>
- Fire Information for Resource Management System—FIRMS. MODIS Collection 6 Hotspot/Active Fire Detections MCD14ML distributed from NASA FIRMS. Available on-line [<https://earthdata.nasa.gov/firms>]. 10.5067/FIRMS/MODIS/MCD14ML
- Fonseca, M. G., Alves, L. M., Aguiar, A. P. D., Arai, E., Anderson, L. O., Rosa, T. M., et al. (2019). Effects of climate and land-use change scenarios on fire probability during the 21st century in the Brazilian Amazon. *Global Change Ecology*, 00, 1–16. <https://doi.org/10.1111/gcb.14709>
- García, B. N., Libonati, R., & Nunes, A. M. B. (2018). Extreme drought events over the Amazon Basin: The perspective from the reconstruction of South American Hydroclimate. *Water*. <https://doi.org/10.3390/w10111594>
- Gartner, M. H., Veblen, T. T., Sherriff, R. L., & Schoennagel, T. L. (2012). Proximity to grasslands influences fire frequency and sensitivity to climate variability in ponderosa pine forests of the Colorado Front Range. *International Journal of Wildland Fire*, 21, 562–571. <https://doi.org/10.1071/WF10103>
- Giglio, L. (2015). MODIS Collection 6 Active Fire Product User's Guide Revision A.
- Hijmans, R. J., Etten, J., Sumner, M., Cheng, J., Baston, D., Bevan, A., et al. (2019). Raster: Geographic Data Analysis and Modeling. <https://cran.r-project.org/web/packages/raster/index.html>
- Instituto Brasileiro de Geografia e Estatística—IBGE. (2006). Censo Agropecuário 2006: Brasil, Grandes Regiões e Unidades da Federação. IBGE. ISSN 0101-4234
- Instituto Brasileiro de Geografia e Estatística—IBGE. (2017). Censo Agropecuário 2017: Resultados Preliminares. IBGE. 01036157
- Instituto Brasileiro de Geografia e Estatística—IBGE. (2018). Banco de Informações Ambientais. <https://www.ibge.gov.br/geociencias/informacoes-ambientais/geologia/23382-banco-de-informacoes-ambientais.html?=&t=sobre>. Accessed 3 June 2020.
- Instituto Brasileiro de Geografia e Estatística—IBGE. (2021). Cidades e Estados. Disponível em: <https://www.ibge.gov.br/cidades-e-estados/mt.html>. Acesso em 13 May 2022.
- Instituto Nacional de Pesquisas Espaciais—INPE. (2020a). Terra Brasilis—PRODES (Desmatamento). http://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/legal_amazon/rates. Accessed 3 June 2020a
- Instituto Nacional de Pesquisas Espaciais—INPE. (2020b). Queimadas. https://queimadas.dgi.inpe.br/queimadas/portal-static/estatisticas_paises/. Accessed 3 June 2020.
- Justino, F., Souza, S., & Setzer, A. (2002). Relação entre focos de calor e condições meteorológicas no Brasil. *Anais do XII Congresso Brasileiro de Meteorologia*, 2086–2093. http://www.researchgate.net/publication/43654032_Relao_entre_focos_de_calor_e_condies_meteorologicas_no_Brasil/file/3deec51758692fd9f.pdf

- Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J.J., Fiorino, M., et al. (2002). NCEP-DOE AMIP-II Reanalysis (R-2), Bulletin of the American Meteorological Society, 1631–1643. <http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/kana/reanl2-1.htm>
- Kavlak, M. O., Cabuk, S. N., & Cetin, M. (2021). Development of forest fire risk map using geographical information systems and remote sensing capabilities: Ören case. *Environmental Science and Pollution Research*, 28, 33265–33291. <https://doi.org/10.1007/s11356-021-13080-9>
- Kendall, M. G. (1975). *Rank Correlation Methods*. Charles Griffin.
- Klink, C., & Machado, R. (2005). A conservação do Cerrado brasileiro. *Megadiversidade*, 1.
- Latorre, N. S., Aragão, L. E. O. e C., Anderson, L. O., Andere, L., Duarte, V., Arai, E., & Lima, A. (2017). Impactos de queimadas sobre diferentes tipos de cobertura da terra no leste da Amazônia Legal Brasileira. *Revista Brasileira de Cartografia*, 69(1), 179–192. <http://www.lisie.unb.br/rbc/index.php/rbc/article/view/1488/1088>
- Le Page, Y., Morton, D., Hartin, C., Bond-Lamberty, B., Pereira, J. M. C., Hurtt, G., et al. (2017). Synergy between land use and climate change increases future fire risk in Amazon forests. *Earth System Dynamics*, 8(4), 1237–1246. <https://doi.org/10.5194/esd-8-1237-2017>
- Lewis, S. L., Brando, P. M., Phillips, O. L., Van Der Heijden, G. M. F., & Nepstad, D. (2011). The 2010 Amazon drought. *Science*, 331(6017), 554. <https://doi.org/10.1126/science.1200807>
- Lima, M., da Silva Junior, C. A., Rausch, L., Gibbs, H. K., & Johann, J. A. (2019). Demystifying sustainable soy in Brazil. *Land Use Policy*, 82, 349–352. <https://doi.org/10.1016/j.landusepol.2018.12.016>
- Machado, N. G., da Silva, F. C. P., & Biudes, M. S. (2014). Efeito das condições meteorológicas sobre o risco de incêndio e o número de queimadas urbanas e focos de calor em Cuiabá-MT Brasil. *Ciência e Natura*, 36(3), 459–469. <https://doi.org/10.5902/2179460x11892>
- Machado Neto, A. de P. (2016). *Diagnóstico dos incêndios florestais no Parque Nacional da Chapada dos Guimarães no período de 2005 a 2014*. UFPR. Retrieved from <https://acervodigital.ufpr.br/handle/1884/47544>
- Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica*, 13(3), 245–259. <https://doi.org/10.2307/1907187>
- Marengo, J. A., & Souza Junior, C. (2018). Mudanças Climáticas: Impactos e cenários para a Amazônia, 33. <https://sinapse.gife.org.br/download/mudancas-climaticas-impactos-e-cenarios-para-a-amazonia>
- Ministério da Agricultura Pecuária e Abastecimento—MAPA. (2020). Estatísticas de Comércio Exterior do Agronegócio Brasileiro, Exportação-Importação, Região/UF/Produto. <http://indicadores.agricultura.gov.br/agrostat/index.htm>. Accessed 3 May 2021
- Marengo, J. A., Betts, R., Nobre, C. A., Chou, S. C., Tomasella, J., Sampaio, G., et al. (2011a). *Riscos das mudanças climáticas no Brasil: Análise conjunta Brasil - Reino Unido sobre os Impactos das mudanças climáticas e do desmatamento na Amazônia*. INPE.
- Marengo, J. A., Nobre, C. A., Tomasella, J., Cardoso, M. F., & Oyama, M. D. (2008). Hydro-climatic and ecological behaviour of the drought of Amazonia in 2005. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1498), 1773–1778. <https://doi.org/10.1098/rstb.2007.0015>
- Marengo, J. A., Tomasella, J., Alves, L. M., Soares, W. R., & Rodriguez, D. A. (2011b). The drought of 2010 in the context of historical droughts in the Amazon region. *Geophysical Research Letters*, 38(12), 1–5. <https://doi.org/10.1029/2011GL047436>
- Mclauchlan, K. K., Higuera, E. P., Miessel, J., Rogers, B. M., Schweitzer, J., Shuman, J. K., et al. (2020). Fire as a fundamental ecological process: Research advances and frontiers. *Journal of Ecology*, 108, 2047–2069. <https://doi.org/10.1111/1365-2745.13403>
- Munhoz, C., & Felfili, J. (2007). Reproductive phenology of an herbaceous-subshrub layer of a Savannah (Campo Sujo) in the Cerrado Biosphere Reserve I Brazil. *Brazilian Journal of Biology*, 67(2), 299–307. <https://doi.org/10.1590/s1519-69842007000200015>
- Panisset, J. S., Libonati, R., Gouveia, C. M. P., Machado-Silva, F., França, D. A., França, J. R. A., & Peres, L. F. (2018). Contrasting patterns of the extreme drought episodes of 2005, 2010 and 2015 in the Amazon Basin. *International Journal of Climatology*, 38(2), 1096–1104. <https://doi.org/10.1002/joc.5224>
- Pierce, D. (2013). Ncdf home page: A netcdf package for R'. <http://cirrus.ucsd.edu/~pierce/ncdf/>
- Pohlert, T. (2020). Package ‘trend’: Non-Parametric Trend Tests and Change-Point Detection.
- R Core Team (2020). R: A language and environment for statistical computing.
- Ramos, A. B. R., Nascimento, E. R. P. do, & Oliveira, M. J. de. (2011). Temporada de incêndios florestais no Brasil em 2010: análise de série histórica de 2005 a 2010 e as influências das chuvas e do desmatamento na quantidade dos focos de calor. Curitiba: *Anais do Simpósio Brasileiro de*

- Sensoriamento Remoto*—SBSR. <http://marte.sid.inpe.br/col/dpi.inpe.br/marte/2011/06.30.13.15/doc/p1414.pdf>
- Ramos, H. M. (2017). O regime de precipitação da Amazônia e sua relação com fenômenos de variabilidade climática. Universidade Federal de Santa Catarina.
- Ribeiro, T. M., Mendonça, B. A. F., Oliveira-Junior, J. F., & Fernandes-Filho, E. I. (2021). *Environment, Development and Sustainability*, 23, 1485–1498. <https://doi.org/10.1007/s10668-020-00632-1>
- Rosan, T. M., Anderson, L. O., & Vedovato, L. (2017). Assessing the origin of hot pixels in extreme climate years in the Brazilian Amazon. *Revista Brasileira de Cartografia*, 69(4), 731–741. <http://www.rbc.lsie.unb.br/index.php/rbc/article/view/1420/1129>
- Rowland, F. E., Bricker, K. J., Vanni, M. J., & González, M. J. (2015). Light and nutrients regulate energy transfer through benthic and pelagic food chains. *Oikos*, 124(12), 1648–1663. <https://doi.org/10.1111/oik.02106>
- Santos, S. Q. R., Sansígolo, C. A., Braga, C. C., Neves, T. T., & Santos, A. P. P. (2017). Identificação e caracterização de secas recentes na região Amazônica: Avaliação no contexto climático atual. *Revista Brasileira De Geografia Física*, 10(6), 1746–1759.
- Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63, 1379–1389.
- Silva Junior, C. A., & Lima, M. (2018). Soy Moratorium in Mato Grosso: Deforestation undermines the agreement. *Land Use Policy*, 71, 540–542. <https://doi.org/10.1016/j.landusepol.2017.11.011>
- Silva Junior, C. H. L., Almeida, C. T., Santos, J. R. N., Anderson, L. O., Aragão, L. E. O. C., & Silva, F. B. (2018). Spatiotemporal rainfall trends in the Brazilian legal Amazon between the years 1998 and 2015. *Water*, 10(9), 1–16. <https://doi.org/10.3390/w10091220>
- Silva, M. A., Lima, M., Silva Junior, C. A., Costa, G. M., & Peres, C. A. (2018a). Achieving low-carbon cattle ranching in the Amazon: “Pasture sudden death” as a window of opportunity. *Land Degradation and Development*, 29(10), 3535–3543. <https://doi.org/10.1002/ldr.3087>
- Silva, C. V. J., Aragão, L. E. O. C., Barlow, J., Espirito-Santo, F., Young, P. J., Anderson, L. O., et al. (2018b). Drought-induced Amazonian wildfires instigate a decadal-scale disruption of forest carbon dynamics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 373(2018b0043). <https://doi.org/10.1098/rstb.2018b.0043>
- Silva, S. S., Oliveira, I., Morello, T. F., Anderson, L. O., Karlokoski, A., Brando, P. M., et al. (2021). Burning in southwestern Brazilian Amazonia, 2016–2019. *Journal of Environmental Management*. <https://doi.org/10.1016/j.jenvman.2021.112189>
- Sena, E. T., Silva Dias, M. A. F., Carvalho, L. M. V., & Silva Dias, P. L. (2018). Reduced wet-season length detected by satellite retrievals of cloudiness over Brazilian Amazonia: A new methodology. *Journal of Climate*, 31, 9941–9964. <https://doi.org/10.1175/JCLI-D-17-0702.1>
- Soares, R. V. (1990). *Fire in the tropical biota* (1st ed.). Ecological.
- de Sousa, A. M. L., da Rocha, E. J. P., Vitorino, M. I., de Souza, P. J. O. P., & Botelho, M. N. (2015). Variabilidade Espaço-Temporal da Precipitação na Amazônia Durante Eventos Enos. *Revista Brasileira De Geografia Física*, 8(1), 13–24.
- Stokes, K. E., Allchin, A. E., Bullock, J. M., & Watkinson, A. R. (2004). Population responses of *Ulex* shrubs to fire in a lowland heath community. *Journal of Vegetation Science*, 15(4), 505–514. <https://doi.org/10.1111/j.1654-1103.2004.tb02289.x>
- Wan, Z., Hook, S., & Hulley, G. (2015). MOD11B3 MODIS/Terra Land Surface Temperature/Emissivity Monthly L3 Global 6km SIN Grid V006. NASA EOSDIS LP DAAC. <https://doi.org/10.5067/MODIS/MOD11B3.006>
- Wickham, H. (2016). ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics. <https://cran.r-project.org/web/packages/ggplot2/index.html>
- Xavier, A. C., King, C. W., & Scanlon, B. R. (2016). Daily gridded meteorological variables in Brazil (1980–2013). *International Journal of Climatology*, 36(6), 2644–2659. <https://doi.org/10.1002/joc.4518>
- Zeng, N., Yoon, J. H., Marengo, J. A., Subramaniam, A., Nobre, C. A., Mariotti, A., & Neelin, J. D. (2008). Causes and impacts of the 2005 Amazon drought. *Environmental Research Letters*. <https://doi.org/10.1088/1748-9326/3/1/014002>

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