Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2017-90, 2017
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2017

Natural Hazards and Earth System Sciences
Discussions

Analysis of fire dynamics in the Brazilian savannas

Guilherme Augusto Verola Mataveli[1], Maria Elisa Siqueira Silva[1], Gabriel Pereira[1,2], Francielle da Silva Cardozo[2], Fernando Shinji Kawakubo[1], Gabriel Bertani[3], Julio Cezar Costa[2], Raquel de Cássia Ramos[2], and Viviane Valéria da Silva[2]

[1]Department of Geography, University of São Paulo, São Paulo, 05508-000, Brazil
[2]Department of Geosciences, Federal University of São João del-Rei, São João del-Rei, 36307-352, Brazil
[3]Remote Sensing Division, National Institute for Space Research, São José dos Campos,12227-010, Brazil

Correspondence to: Guilherme Augusto Verola Mataveli (mataveli@usp.br)

Abstract. Wildfires play a key role in the ecology of savannas. The Brazilian savannas (Cerrado biome), where the extension of burned areas and amount of fires can be more numerous than in the Amazon, is frequently burned due to natural fires or land-use and land-cover (LULC) changes. Thus, we aimed to understand the occurrence and the dynamics of fires in the Cerrado using active fire, burned area, precipitation, vegetation condition, estimated using the Vegetation Condition Index (VCI), and LULC data derived from orbital sensors. Results show that the Cerrado was, respectively, the second and first Brazilian biome for the occurrence of hotspots and burned area, which are concentrated during the dry season (May to September), especially in September, when the annual deficit in precipitation and extreme vegetation conditions reached maximum indices. Higher densities of hotspots concentrated in the Northern of the biome, while 75 % of the occurrences were found in the natural remnants of the Cerrado. Totals of hotspots and burned area were higher in years of lower precipitation, such as 2007 and 2010. Spatial correlations showed that hotspots and burned area are better correlated with precipitation than vegetation condition, especially in the Central North and Northeast of the Cerrado.

1 Introduction

Fire is a common process in most of the vegetated areas of the world (Hantson et al., 2013), initiated by human activities or natural causes, such as lightning (Peterson et al., 2010). It consumes large areas of vegetation across the Earth's surface and modifies its characteristics (Vadrevu et al., 2014), also playing an important role in climate due to the emissions related to biomass burning (Kaiser et al., 2012). Moreover, extensive fire activity disturbs the ecosystems, decreasing plants and animal species and causing soil depletion (Fearnside, 2000), and causes social and economic costs (Veraverbeke et al., 2014).

Globally, tropical savannas are the most frequently burned ecosystems (Bowman et al., 2009; Van der Werf et al., 2008). In these areas, humans are responsible for most of the fires (Archibald et al., 2012), especially used for opening areas for agriculture and livestock farming, and for pest control (Shimabukuro et al., 2013). In the Cerrado biome (Brazilian savannas), the second largest biome in South America and mostly constituted of short grassland vegetation, natural fires are common due to lightning (Ramos-Neto and Pivello, 2000). Moreover, since the 1970s this biome is suffering severe losses in the natural vegetation due to agricultural expansion (Fearnside, 2002), being fire an important tool in this land-use and land-cover change (LULCC) process. However, according to Beuchlé et al. (2015), despite the increasing anthropic pressure in the Cerrado, LULCC in the biome has been overlooked until recently when compared to the Amazon biome. The absence of an effective fire policy also contributes to the LULCC process in the natural remnants of Cerrado, which is the most biodiverse savanna in the world (Durigan and Ratter, 2016). Therefore, the description of the fire regime is necessary to understand the LULCC process and to understand the spatial distribution and the dynamics of the biomes affected by fires, especially in biomes with climatic seasonality, such as the Cerrado (Daldegan et al., 2014). Moreover, the role of climatic variables in controlling the occurrence of fires is widely known (Bartsch et al., 2009; Peterson et al., 2010; Akther and Hassan, 2011) and have been analysed in the tropical savannas, where land-use is also important for the occurrence of fires (Van der Werf et al., 2008; Ichoku et al., 2016). However, there is a lack of specific studies for the Cerrado, especially studies analysing the correlation between fires and climatic variables.

Considering the dimension of the phenomenon analysed, orbital remote sensing data is the most effective source of information to understand the fire dynamics (Andeala et al., 2016). Currently, the use of orbital remote sensing allows to observe large areas of the surface daily and repeatedly, increasing the efficiency of fire detection and enabling the understanding of the characteristics of fires (Ichoku et al., 2008; Ichoku et al., 2012; Hantson et al., 2013; Shvetsov and Ponomarev, 2015; Pereira et al., 2016). Among the orbital sensors available for studying fires, Moderate Resolution Imaging Spectroradiometer (MODIS) active fire and burned area products were the first data sets derived from the new generation of moderate resolution orbital sensors (Giglio et al., 2016) and have been widely used to understand the role and characteristics of fires and biomass burning (Ichoku et al., 2005; Kaiser et al., 2012; Hantson et al., 2013; Shi et al., 2015; Shvetsov and Ponomarev, 2015; Huang et al., 2016). Regarding the tropical savannas, we can mention the use of MODIS active fire and burned area products to analyse fires in the savannas of Brazil (Nascimento et al., 2010; Moreira de Araújo et al., 2012; Moreira de Araújo and Ferreira, 2015), Africa (Archibald et al., 2010; Kusangaya and Sithole 2015), Australia (Andersen et al., 2005; Yates et al., 2008; Maier et al., 2013), and in the entire tropical savannas (Van der Werf et al., 2008).

Given the need for more consistent information about the Cerrado and the advantages of using orbital remote sensing data for studying fires, we aimed to understand the occurrence and the dynamics of fires in the Cerrado biome (Brazil) during the period between 2002 and 2015. For this purpose, active fire and burned area products derived from MODIS sensors were used, as well as precipitation data derived from the Tropical Rainfall Measurement Mission (TRMM) satellite, the Vegetation Condition Index (VCI) estimated from the MOD13A3 product, and the land-use and land-cover (LULC) maps provided by MMA (2002) and INPE (2015).

2 Materials and Methods

2.1 Study Area

The Cerrado biome (Fig. 1), spatially distributed over an area of more than 2 million km^2, is the second largest Brazilian biome, only smaller than the Amazon biome, and covers approximately 22 % of the Brazilian territory in 11 different states (IBGE, 2010). The biome presents a wide climatic variability, once it covers a large area extended for many latitudinal belts (Kayano and Andreoli, 2009). Due to the high biological diversity, especially endemic species that represent approximately 44 % of the flora (Klink and Machado, 2005), the Cerrado is a world biodiversity hotspot (Myers et al., 2000). Among the factors that explain the biodiversity in the biome, we can highlight strong climatic seasonality, water availability and anthropic disturbances, such as deforestation and fires (Coutinho, 1990). The Cerrado is composed of different vegetal formations, presenting: I) Grasslands, mainly constituted by herbaceous species and certain shrubs without the presence of tree species; II) Savannas, presenting sparse tree and shrubs over a grassy extract; and III) Forest formations, where tree species with continuous or discontinuous canopy dominate (Dias, 1992).

However, the LULCC process caused by the agricultural expansion since the 1970s (Fearnside, 2000) reduced the natural vegetation of the biome to approximately 55 % (INPE, 2015), as shown in Table 1. Before the 1970s, the Cerrado was considered unsuitable for agriculture due to the poor soils in the biome, although, the advances in agricultural techniques, favorable conditions for mechanization, government incentives and the low price of land contributed to transform the Cerrado into a growing agricultural region (Bickel and Dros, 2003).

2.2 MODIS fire products

MODIS sensor is onboard the polar orbit Terra and Aqua satellites, providing data in 36 spectral channels between 0.4 μm and 14.4 μm. Products derived from MODIS have nominal spatial resolution ranging from 250 to 10,000 meters, depending on the product, and temporal resolution of 1 to 2 days (Justice et al., 2002). These sensors provide data about the dynamics of the biosphere aiming to understand the impact of the processes caused by human activities or by nature over the surface, the oceans and the lower atmosphere (Justice et al., 2002). The MODIS time of acquisition is different according to the platform: while Terra platform crosses the Equator in its downward orbit at 10:30 and 22:30 in local time, the Aqua platform in its upward orbit crosses the Equator at 13:30 and 01:30 in local time, enabling, thereby, four daily imaging surveys from the same surface (Giglio et al., 2003).

MODIS active fire products (MOD14 and MYD14 products, derived from the MODIS sensor onboard Terra and Aqua satellites, respectively) detect burning pixels with nominal spatial resolution of 1 km using a contextual algorithm that applies thresholds to the middle–infrared and thermal infrared brightness temperature (T4μm and T11μm, respectively) (Giglio et al., 2003). Still according to Giglio et al. (2003), MODIS has two 4 μm channels (21 and 22), and, usually, channel 22 is used to detect active fires, however, when it saturates or has missing data, it is replaced with channel 21; T11μm is derived from channel 31. In addition, false detections are rejected by examining the brightness temperature relative to adjacent pixels. The sensitivity of MODIS active fire products was tested for a savanna region in Australia: fires with an active flaming area of 100–300 m^2 can be detected, being that the detection algorithm is slightly more sensitive at night and strongly dependent on the viewing angle (Maier et al., 2013). Still according to the authors, these results are transferable to other tropical savanna areas, such as the Cerrado.

The MODIS globally gridded 0.5 km burned area product (MCD45A1) contains burning and quality information on a per-pixel basis monthly. MCD45A1 algorithm analyses the daily surface reflectance dynamics from both MODIS sensors for detecting the approximate date of burning and mapping the spatial extent of recent fires (MODIS Fire Products ATBD, 2006). Moreira de Araújo and Ferreira (2015) evaluated the performance assessment of MCD45A1 in the Cerrado biome and found good results, proving the efficiency of MCD45A1 product for analysing the occurrence and the dynamics of fires in the Cerrado.

2.3 TRMM precipitation data

TRMM satellite results from a joint program between the United States of America and Japan space agencies and aims to provide precipitation data in the tropical and subtropical areas of the globe (Kummerow et al., 2000). TRMM satellite is operational since 1997 and is equipped with three different sensors: I) Precipitation Radar (PR), built to provide a 3-D view of rainfall distribution over the tropics and subtropics; II) Microwave Imager (TMI), which aims to analyse the content of the integrated precipitation column, cloud liquid water and ice, and rain intensity and type; and III) Visible and Infrared Scanner (VIRS), a sensor designed for observing clouds type, coverage and top temperature (Kummerow et al.,1998). For analysing the precipitation regime in the Cerrado biome between 2002 and 2015, TRMM monthly precipitation product (3B43), provided with spatial resolution of approximately 30 km in millimeters per month (mm month^{-1}), was used. TRMM satellite monthly estimates have been validated for Brazil by Pereira et al. (2013), who compared TRMM data with monthly precipitation estimated by 183 meteorological stations during the 1998-2010 period. The comparison showed strong correlation between TRMM data and the meteorological stations in Brazil, however, TRMM tends to overestimate monthly precipitation in 15 %.

2.4 MOD13A3 product and Vegetation Condition Index (VCI)

The use of vegetation indices is an important approach for monitoring both vegetation and LULC classes. Considering the goals of MODIS sensors, global vegetation indices derived from MODIS provide consistent spatial and temporal comparisons of vegetation conditions (Justice et al., 2002). The global MODIS 1 km Normalized Difference Vegetation Index (NDVI-MOD13A3 product) is monthly provided and considers all data from the 16 days 1 km products that overlap the month employing a weighted temporal average if data is cloud free, or a maximum value in case of clouds (MODIS Vegetation Index ATBD, 1999). In this study, MOD13A3 product was used to estimate the VCI in the Cerrado biome during the period between 2002 and 2015.

Satellite-based drought indices, such as the NDVI based VCI (Kogan, 1995), are important sources of information for detecting the occurrence, the duration, the intensity and the impacts of drought (Quiring and Ganesh, 2010; Jiao et al., 2016). Initially proposed to evaluate the global weather impact over vegetation and later proved useful for evaluating wildfire danger, VCI is a relative measurement of the NDVI value at the observation date with respect to extreme conditions of NDVI over a reference period (Chéret and Denux, 2007), as shown in Eq. (1):

$$VCI = \frac{NDVI - NDVI_{Min}}{NDVI_{Max} - NDVI_{Min}} * 100 \quad (1)$$

where NDVI, $NDVI_{Min}$ and $NDVI_{Max}$ correspond to the NDVI, NDVI minimum and NDVI maximum values, respectively. According to Chéret and Denux, (2007), one of the most influent variables for assessing fire danger is the vegetation condition, being remote sensing capable of providing relevant information about this variable and being VCI able to represent this variable. Thenkabail et al. (2004), who analysed different vegetation indices for monitoring drought and vegetation conditions in Southwest Asia, also proved VCI as a sensitive indicator for monitoring vegetation conditions, presenting better results than other indices, such as the Temperature Condition Index (TCI). The great advantages of using VCI are that it can be easily estimated, it does not require station observation data and it can provide near real-time estimates over the globe at a relatively high spatial resolution (Quiring and Papakryiakou, 2003).

2.5 Land-use and land-cover data

Two different maps were used to analyse the occurrence of fires in the LULCs of the Cerrado. The first LULC mapping was performed using images of the Cerrado acquired in 2002 by the Enhanced Thematic Mapper Plus (ETM+) sensor onboard the Landsat-7 satellite and results from the project "Conservation and Sustainable Use of Brazilian Biological Diversity" (PROBIO), financed by the Brazilian Ministry of the Environment (MMA) (MMA, 2002). PROBIO mapping was performed in the 1:250,000 scale, being that all images used were processed, visually classified and validated by a team of experienced professionals in remote sensing and Geographical Information Systems (GIS). Validation process of the PROBIO mapping showed kappa and overall accuracy indices of 92 % and 97 %, respectively (MMA, 2002). Furthermore, considering the intense LULCC process in the Cerrado, the MMA promoted in 2013 the union of Brazilian public institutions with wide experience in remote sensing, GIS, and large-scale mapping, such as the Brazilian Institute of Environment (IBAMA), the National Institute for Space Research (INPE), and the Brazilian Agricultural Research Agency (EMBRAPA), in order to realize the first version of the project "Land-Use and Land-Cover Mapping of the Cerrado Biome" (TerraClass Cerrado) (INPE, 2015). The mapping was performed in the 1:250,000 scale using images of the Cerrado acquired in 2013 by the Operational Land Imaging (OLI) sensor onboard the Landsat-8 satellite. All images were processed, visually classified and validated by a team of experienced researchers, achieving an overall accuracy index of 80.2 % (INPE, 2015).

2.6 Data Processing

In order to analyse the dynamics and the occurrence of fires in the Cerrado biome, MODIS active fire products, provided in Hierarchical Data Format (HDF) format, were initially converted to American Standard Code for Information Interchange

(ASCII) format files containing the same information of the original data. Initially, all hotspots detected by the MODIS active fire products in the Brazilian territory between 2002 and 2015 were grouped according to the delimitation of the Brazilian biomes proposed by IBGE (2010), aiming to analyse the contribution of the hotspots occurred in the Cerrado nationally. Sequentially, the time series of monthly total hotspots in the Cerrado biome was generated considering the date of the occurrence of the hotspots available in the MODIS active fire products. Still, total hotspots for each year analysed and monthly average of hotspots were calculated. The spatial distribution of the hotspots in the Cerrado was analysed by summing all the hotspots occurring in the Cerrado during the 2002-2015 period in a regular grid of 4 km.

Regarding burned area analysis, initially all the 16 tiles of the MCD45A1 product, which cover the Brazilian territory, were acquired, also aiming to evaluate the contribution of burned area in the Cerrado nationally, as proposed for the hotspots. MCD45A1 product was acquired for the period 2002-2015 in HDF, converted to GEOTIFF format, reprojected to Lat/Long WGS84 datum projection and mosaicked using the MODIS Reprojection Tool and grouped according the delimitation of the Brazilian biomes. Then, only most confidently detected pixels regardless of temporal direction (flag = 1) were considered, as previously proposed by Moreira de Araújo et al. (2012) and Moreira de Araújo and Ferreira (2015) for studying burned area in the Brazilian biomes and in the Cerrado, respectively. For the analysis of the burned area considering only the Cerrado biome, tiles h12v10, h12v11, h13v09, h13v10, and h13v11, which cover the delimitation of the Cerrado biome, were considered and processed as described above. Finally, the time series of monthly total burned area in the Cerrado biome was generated for the 2002-2015 period, as well as annual estimates of burned area for each year analysed and monthly average burned area.

Aiming to analyse the major land-uses related to the occurrence of fires in the biome, hotspots detected by the MODIS active fire products were joined to the LULC maps proposed by MMA (2002) and INPE (2015) according to the spatial location of the hotspots. Firstly, both maps were reclassified to four LULC classes: Natural Remnants, Agriculture, Pasture and Others. Considering the changes in the biome and the data available, annual hotspots in the Cerrado for the period between 2002-2007 were joined to the mapping provided by MMA (2002), while hotspots between 2008-2015 were joined to the LULC map provided by INPE (2015). The annual percentage of the occurrence of hotspots in the land-uses of the Cerrado between 2002 and 2015 and for the entire 2002-2015 period were then calculated.

For TRMM data processing, 3B43 product images were obtained in Network Common Data Form (NetCDF), reprojected to Lat/Long WGS84 datum projection, converted to GEOTIFF format and clipped to the study area according to the delimitation of the Cerrado proposed by IBGE (2010). Monthly and annual average precipitation for the Cerrado biome during the period between 2002 and 2015 were then estimated.

VCI was estimated using the global 1 km monthly NDVI MODIS product. Initially, all the steps described for MCD45A1 in the Cerrado were performed for the MOD13A3 product. Sequentially, maximum and minimum NDVI for each pixel of the study area were estimated based on MODIS NDVI time series from 2002 to 2015, which is necessary to define the maximum and minimum NDVI masks used to estimate VCI. Finally, monthly and annual VCI for the Cerrado biome were estimated using Eq. (1); for annual VCI, the term NDVI in Eq. (1) corresponded to the annual average NDVI of each pixel located in the study area.

Statistical analysis consisted on spatially calculating the Pearson's Correlation Coefficient (R) between the monthly values of the variables analysed considering a regular grid of 4 km for the spatial correlation between monthly total hotspots and monthly average VCI and between monthly total burned area and monthly average VCI, while the spatial correlation between monthly total hotspots and monthly average precipitation and between monthly total burned area and monthly average precipitation were calculated considering a regular grid of the same spatial resolution of the TRMM 3B43 product. The significance of the spatial correlations for the period of 168 months analysed was tested using the t-Student test with significance level of 5 %.

3 Results and Discussion

Considering the entire Brazilian territory, MODIS fire products detected 5,235,881 hotspots and estimated 1,964,544 km^2 burned during the 2002-2015 period. Within this total, 1,904,182 hotspots (approximately 36 %) were detected and 1,358,775 km^2 (approximately 69 %) were burned in the area corresponding to the Cerrado, making the biome, respectively, the second and the first Brazilian biome for the occurrence of hotspots and burned area during the period analysed, as shown in Fig. 2.

Despite having approximately half of the area of the Amazon biome, the Cerrado presented only 10 % less hotspots than the Amazon during the period between 2002 and 2015. However, considering the density of hotspots by area in the Brazilian biomes, hotspots density in the Cerrado (0.94 hotspots km^{-2}) is approximately 60 % higher than in the Amazon (0.58 hotspots km^{-2}). Regarding burned area, even considering the difference in the area of the biomes, the Cerrado concentrated 69% of the Brazilian burned area between 2002 and 2015, while the Amazon was responsible for 220,182 km^2 of the burned area during 2002-2015, approximately 11 % of the total. These results agree with those found by Moreira de Araújo et al. (2012), who analysed the spatial patterns of hotspots and burned area in Brazil during the 2002-2010 period and found the highest concentration of hotspots in the Amazon biome, while the Cerrado was responsible for 73 % of the Brazilian burned area. It should be considered that the performance assessment of the MCD45A1 product in dense vegetation areas, such as the Amazon, is not good, where omission errors are frequent, as shown by Cardozo et al. (2012). On the other hand, Moreira de Araújo and Ferreira (2015) validated the MCD45A1 for the Cerrado using burned area maps derived from Landsat images and found strong correlation values (R=0.96, R^2=0.92), proving the efficiency of the product for characterizing burned area in the biome.

Considering only the Cerrado, Fig. 3 shows monthly total hotspots detected by MODIS active fire products and monthly total burned area estimated by the MCD45A1 product during the 2002-2015 period. Analysing Fig. 3, there is a clear interannual variability in the occurrence of fires along the considered period, despite the annual seasonality. Hotspots and burned area are concentrated during the dry season (May to September for most of the Cerrado), however, they still have high average in October, beginning of the rainy season for most of the Cerrado, as will be shown below. Highest monthly total hotspots were found in September for all years analysed, except for 2008, when monthly total hotspots in October was 6 % higher than in

September. Highest monthly total hotspots ranged significantly, from 15,537 (September/2009) to 98,238 (September/2007) hotspots. On the other hand, lowest monthly total hotspots were found in January for 2010, 2012 and 2013, in February for 2002, 2004, 2006, 2007, 2014 and 2015, in March for 2003, 2005, 2008 and 2011, and in April for 2009. Lowest monthly total hotspots ranged from 461 (February/2002) to 1,182 (January/2010) hotspots. Regarding burned area, highest monthly total burned area were found in August for 5 years (2002, 2003, 2006, 2009 and 2014), in September for 9 years (2004, 2005, 2007, 2008, 2010, 2011, 2012, 2013 and 2015), and ranged from 7,449 km^2 (August/2009) to 105,338 km^2 (September/2010). Lowest monthly total burned area were concentrated in January (2004, 2008), March (2011, 2015) and December (2002, 2003, 2005, 2006, 2007, 2009, 2010, 2012, 2013, 2014), ranging from 2 km^2 (December/2010) to 23 km^2 (March/2015).

According to Fig. 4(a), monthly average hotspots ranged from 1,022 (February) to 47,670 (September) and monthly average burned area ranged from 14 km^2 (December) to 38,913 km^2 (September), while monthly average precipitation ranged from 10 mm (August) to 257 mm (January). The increase in the occurrence of fires initiates in May, agreeing with the beginning of the dry season, grows steadily and reaches the maximum in September, end of the dry season for most of the Cerrado biome. In October, beginning of the rainy season for most of the Cerrado, when precipitation (105 mm) is almost four times higher than the average precipitation during the dry season (27 mm), monthly average hotspots and burned area start decreasing, but still have high average (24,489 hotspots and 10,403 km^2, respectively). Spontaneous combustion, the possibility of fires ignited criminally and, mostly, the natural occurrence of fires related to lightning are the causes of fires in the beginning of the rainy season. For example, Ramos-Neto and Pivello (2000) found that 91 % of the fire events registered at the Emas National Park, located in the Cerrado, between June/1995 and May/1999 were caused by lightning during the wet season or in the seasonally transitional months. Furthermore, due to the influence of distinct meteorological phenomena, such as the Intertropical Convergence Zone in the northern of the biome (North of 6° S), the dry season can be displaced ahead in the year (Kayano and Andreoli, 2009). In the Central-southern areas of the Cerrado, the dry season is characterized by the incursion and settlement of dry air masses over the region, while the rainy season is characterized by local heat convection and the action of the South Atlantic Convergence Zone (Kayano and Andreoli, 2009). Throughout the rainy season, precipitation elevates and the average of hotspots and burned area decrease; average of hotspots (5,414) and burned area (1,683 km^2) in the rainy season is, respectively, 3.62 and 10.14 times lower than the average of hotspots and burned are in the dry season (19,627 hotspots and 17,072 km^2, respectively).

Annual total hotspots in the biome ranged from 53,798 (2009) to 248,911 (2007) (Fig. 4(b)) and annual total burned area ranged from 19,023 km^2 (2009) to 249,982 km^2 (2010), while annual precipitation ranged from 1,209 mm (2007) to 1,706 mm (2009). It is possible to note that the occurrence of hotspots and burned area was lower in years of higher precipitation. The year 2009 presented the highest precipitation and the lowest total annual hotspots and burned area, while 2007 presented highest occurrence of hotspots and lowest precipitation. Highest total annual burned area was found in 2010, approximately 15,000 km^2 higher than the annual total burned area in 2007. According to Coelho et al. (2016), the 2002-2015 period is inserted in a greater period of reduction of precipitation in Central and Southeast Brazil, and has been referenced as a drying period in large scale studies.

Results found for the distribution of hotspots, burned area and precipitation in the Cerrado showed the same pattern found by Moreira de Araújo and Ferreira (2015). It is also worth mentioning that monthly total hotspots and burned area values are strongly correlated in the Cerrado biome (Fig. 5). According to Moreira de Araújo and Ferreira (2015), the significant correlation between hotspots and burned area show that combining both thermal and optical data may result in more accurate burned area estimates and reduce omission and commission errors in Cerrado locations where landscape is predominantly composed of highly fragmented areas related to agriculture land-use.

Furthermore, monthly total hotspots and burned area in September/2007 and September/2010 (98,238 and 97,573 hotspots, and 96,152 and 105,338 km^2 respectively) represent two remarkable episodes, once the total number of hotspots in these single months is higher than the total hotspots detected by MODIS active fire products in the entire years of 2006, 2008, 2009, 2011 and 2013 and the burned area was higher than the burned area in the entire years of 2003, 2004, 2005, 2006, 2008, 2009, 2011, 2013, 2014, and 2015. In these months, the physical conditions for the occurrence of fires were extremely favorable: since the beginning of the dry season in 2007 and 2010 monthly average precipitation was lower than the monthly average precipitation for the Cerrado between 2002 and 2015. Average precipitation in the dry season of 2007 and 2010 was, respectively, 55 % and 68 % of the average precipitation in the Cerrado for the 2002-2015 period (26.7 mm). The drought during the dry season contributed to make the vegetation vulnerable to fires, as shown in the VCI images for September/2007 and September/2010 (Fig. 6 (a) and (b), respectively).

Low values of VCI (red colors) indicate poor/stressed vegetation, usually due to unfavorable weather conditions, and high values of VCI (green colors) indicate healthy vegetation conditions (Stankova and Nedkov, 2015). According to Coleve (2011), we can consider VCI values between 0 % and 20 % as extremely dry, between 20 % and 40 % as dry, between 40 % and 60 % as normal, between 60 % and 80 % as good, and between 80 % and 100 % as excellent. Analysing Fig. 6 (a) and (b), we can see that most of the areas of the Cerrado in September/2007 and September/2010 presented low values of VCI, lower than 5 %, especially in the Southwestern region of the biome. Average VCI values in the Cerrado for September/2007 and September/2010 was, respectively 25 % and 33 % lower than the monthly average VCI for September (24 %), as shown in Fig. 7, which shows annual and monthly average VCI values for the Cerrado between 2002 and 2015.

Monthly average VCI follows the same pattern of precipitation in the Cerrado: VCI starts decreasing in the beginning of the dry season (May), reaches the lowest value in September and increases again with the beginning of the rainy season (October). Average VCI in the dry season was 45 %, while in the rainy season the average index was 64 %. Annual VCI averages for the Cerrado ranged from 54% (2002 and 2012) to 62 % (2009), considered normal or good (Fig. 7 (a)), as proposed by Coleve (2011). Analysing biomass burning, LULCC and the hydrological cycle in the Northern sub-Saharan Africa, a savanna region suffering an intense LULCC process, Ichoku et al. (2016) also found that the seasonal peak of fires is anti-correlated with annual water-cycle indicators such as precipitation and vegetation greenness, except in humid West Africa, where this situation occurs only during the dry season and burning virtually stops when monthly average precipitation reaches 120 mm.

Regarding the spatial distribution of fires in the biome, Fig. 8 shows the total of hotspots detected by MODIS active fire products in the Cerrado during the 2002-2015 period considering a regular grid 4 km. The LULCC process in the Cerrado began in the 1970s in the Southern region of the biome, and advanced over the years to the Northern region (Fearnside, 2000). Therefore, in the Southern of the biome land-use is well settled, and the presence of natural remnants of the Cerrado is not frequent, causing lower concentration of hotspots. According to INPE (2015), in 2013 São Paulo (SP), Paraná (PR) and Mato Grosso do Sul (MS) states, located in the Southern of the biome, presented only 17 %, 37 %, and 31 % of natural cover in the areas of Cerrado, respectively.

Over the years, the agricultural frontier advanced from the Center and North of the Mato Grosso state (MT in Fig. 8) to the Central North and Northeast of the biome. Grecchi et al. (2014) analysed, between 1985 and 2005, the decrease of natural remnants in the Cerrado areas of the Mato Grosso State, traditional in the cultivation of soybeans, and concluded that approximately 42 % of the natural remnants of Cerrado in the state were lost in the period of 20 years analysed. Furthermore, the Northern is the current agricultural expansion area in the Cerrado, especially in the eastern region of Maranhão, Piauí and Tocantins, western of Bahia (MA, PI, TO and BA in Fig. 8, respectively), and in the region known as MATOPIBA (boundary of Maranhão, Tocantins, Piauí and Bahia states). According to Spera et al. (2016), the MATOPIBA can be considered an agricultural frontier since the early 2000s, and, opposed to other areas of the Cerrado, does not have a previous land-use related to cattle ranching, therefore, agriculture is advancing over the natural remnants with the use of fire for converting the land-use rather than advancing over previously cleared pasture areas. Moreover, according to INPE (2015), Bahia, Tocantins, Maranhão and Piauí states still have, respectively, 67 %, 72 %, 72 %, and 83 % of natural cover in the areas of Cerrado, making them potential areas for agricultural expansion.

Regarding LULC in the Cerrado biome, approximately 75 % of the hotspots detected by the MODIS active fire products occurred in natural remnants during the 2002-2015 period, as shown in Fig. 9. Followed by natural remnants, 14 % of the hotspots occurred in pasture areas, 9 % in agriculture areas, and 2% in areas of other land-uses. Comparing the LULC map provided by MMA (2002) with the mapping for 2002 provided by INPE (2015), natural remnants in the Cerrado decline from 60.5 % to 54.6 % between 2002 and 2013, therefore, in a period of 11 years natural remnants were reduced in 120,150 km^2. The role of fire in the LULCC process and fires ignited naturally explain the major occurrence of fires in the natural remnants. Moreover, still comparing the LULC maps provided by MMA (2002) and INPE (2015), agricultural areas increased 1.2 % (24,434 km^2) and pasture areas increased in 3 % (61,093 km^2) in the 2002-2013 period. In agricultural and pasture areas, as previously discussed, fire is traditionally used for pest control, crop rotation, and pasture management. Nascimento et al. (2010) found similar results for the occurrence of hotspots in the LULC of the Cerrado for the period between May/2008 and May/2009. We found 74.7 %, 14.3 % and 8.7 % hotspots in the natural remnants, pasture areas and agriculture areas (Fig. 9), while Nascimento et al. (2010) found 75.6 %, 13.2 % and 11 % for the respectively LULC. Ichoku et al. (2016) found more than 75 % of the satellite fire detections in the Northern Sub-Saharan Region occurring in savanna and woody-savanna areas during the 2001-2014 period, which is also suffering the LULCC process from natural areas to croplands. Fortunately, the Cerrado is the most adapted Brazilian biome to fires, where the functioning of the ecosystem is dependent of natural fires (Coutinho, 2006). Even considering this adaptation, the intense use of fires for opening areas for agriculture and livestock has led to serious problems related to flora and fauna, loss of soil nutrients, soil compaction and erosion (Certini, 2005).

Spatial correlations between monthly total hotspots and monthly average precipitation (Fig. 10(a)), between monthly total burned area and monthly average precipitation (Fig. 10(b)), between monthly total hotspots and monthly average VCI (Fig. 10(c)) and between monthly total burned area and monthly average VCI (Fig. 10(a)) are shown in Fig. 10, while Fig. 11 presents the respective t-Student tests. Fig. 10 and 11 show that hotspots and burned area are better correlated with precipitation than VCI in the Cerrado. Correlations between monthly total hotspots and monthly average precipitation, between monthly total burned area and monthly average precipitation, between monthly total hotspots and monthly average VCI and between monthly total burned area and monthly average VCI were, respectively, significant in 83 %, 75 %, 52 % and 49 % of the Cerrado. Spatially, better correlations were found in the areas that concentrated most of the hotspots (Fig. 8), located in the Central North and Northeast of the biome. It is also worth mentioning the good correlations between hotspots and precipitation and between burned area and precipitation in the Southern of the biome when compared to those found for VCI values. In this region fires are related with sugarcane pre-harvest burning; Brazil is the world leader in cropping sugarcane and most of the Brazilian sugarcane cultivation areas are located in the Cerrado areas of São Paulo state (SP in Fig. 8), responsible for approximately 50 % of the national production (Rudorff et al., 2010). According to Aguiar et al. (2011), more than 100,000 km^2 of sugarcane cultivation areas used pre-harvest burning between 2006 and 2011 in São Paulo state, being that pre-harvest burning was higher in years of lower precipitation, such as 2010.

Moreover, other climate controllers may influence over the occurrence of fires in the Cerrado. For example, Bartsch et al. (2009) analysed the influence of soil moisture on forest fires in Siberia using orbital remote sensing data and concluded that soil moisture needs to be considered when assessing the risk of forest fire, once it impacts over the beginning of ignition and limits the size of burned area; Akther and Hassan (2011) combined both surface temperature, the normalized multiband drought index and the temperature vegetation wetness index for predicting fire danger conditions over Boreal Forest in Canada and found more than 90 % of fires felling in the very high or moderate fire danger classes.

Furthermore, Van der Werf et al. (2008) analysed the climatic control on the variability of fire in the tropical and subtropical areas of the globe and also found weak relations between precipitation and fires, showing the importance of other factors in controlling the occurrence of fires in the savannas: besides climate, land-use and grazing also influence the amount of fuel available for burning, therefore, the relationship between fires and precipitation or VCI may not be uniform. Additionally, the authors also point out that in the savannas the seasonal ignition of anthropic fires depends on the land management: prescribed fire are set in the end of the dry season aiming to increase the removal of unwanted plant species and favor resprouting or in the beginning of the dry season to reduce soil depletion and the probability of uncontrolled wildfires., which may contribute to the results found in this study and by them. Accordingly, Price et al. (2012) investigated the use of prescribed fires in savanna landscapes of western Arnhem Land (Australia) and concluded that imposing prescribed fires in the beginning of the dry season can substantially reduce burned area and fire severity.

Analysing the results found in Fig. 9, the four years with lowest occurrence of hotspots in the natural remnants (2009, 2013, 2008 and 2011) were years of high annual precipitation. This result indicates that the occurrence of fires in pasture and agriculture areas of the Cerrado may depend more on the land management than the climatic conditions. However, according to Van der Werf et al. (2008), climate may impose limitations for the occurrence of fires in these areas, once drier periods improve the removal of vegetation during the clearing process; fires in the savannas predominantly occur over short grassland vegetation, which development is directly related to the previous wet season. Accordingly, Randerson et al. (2005) positively correlated the severity of the fire season in the Cerrado with the terrestrial water storage in the early wet season, which, according to Chen et al. (2013), suggests that the increase of fuel loads in the Cerrado may expand occurrence of fires in the upcoming dry season.

4 Conclusions

Active fire and burned area data, precipitation data, and the Vegetation Condition Index derived from orbital remote sensing (MODIS, TRMM and VCI, respectively) were used to understand the occurrence and the dynamics of fires in the Cerrado biome. The methods applied are easily implemented and can be used for analysing the occurrence and dynamics fires in different areas of the globe.

We found that during the 2002-2015 period the Cerrado, adapted and dependent of fires, was, respectively, the second and first Brazilian biome for the occurrence of hotspots and burned area. The occurrence of fires is changing, especially considering the LULCC process in the biome since the 1970s caused by the agricultural expansion, leading to severe losses and modifying the biome. Fires in the biome are concentrated from May to September, according to the dry season, and reach the maximum in the end of the dry season (September), when the annual deficit in precipitation and extreme vegetation conditions reached maximum indices. Besides the seasonal modulation by precipitation, fire occurrence seems to respond to its interannual variability. Drier (wetter) years are associated with more (less) fires in the studied area. It would be interesting to further identify which areas in the Cerrado biome are more dependent on the interannual precipitation variability. Both interannual and seasonal precipitation variability are potential variables which can help the elaboration of a risk index associated with fire occurrence.

Considering the spatial distribution of fires, higher densities were found in the Northern region, the current agricultural expansion area of the biome. In the Northern, we have the main concentration of natural remnants of Cerrado, opposed to the Southern region, where occupation is older, land-uses are settled and natural remnants of Cerrado are not frequent. We also found that 75 % of the fires occurred in the natural remnants of Cerrado, showing the importance of fire in the LULCC process and the susceptibility of the vegetation to natural fires.

Finally, precipitation is better correlated with fires than VCI in the Cerrado, however, only precipitation and vegetation conditions are not enough to explain the occurrence of fires in the Cerrado; therefore, other climatic variables, such as soil moisture and temperature, should be analysed in future studies. Still, future studies should specially focus on the land management to explain the occurrence of fires in the biome, which seems to be a very important variable for the occurrence of fires in the Cerrado.

Acknowledgements

We thank the National Counsel of Technological and Scientific Development (CNPq, grant number 162898/2015-0), the Minas Gerais State Research Foundation (FAPEMIG, grant number APQ-01698-14), and the Coordination for the Improvement of Higher Education Personnel (CAPES, grant number 6123/2015-05) for their financial support.

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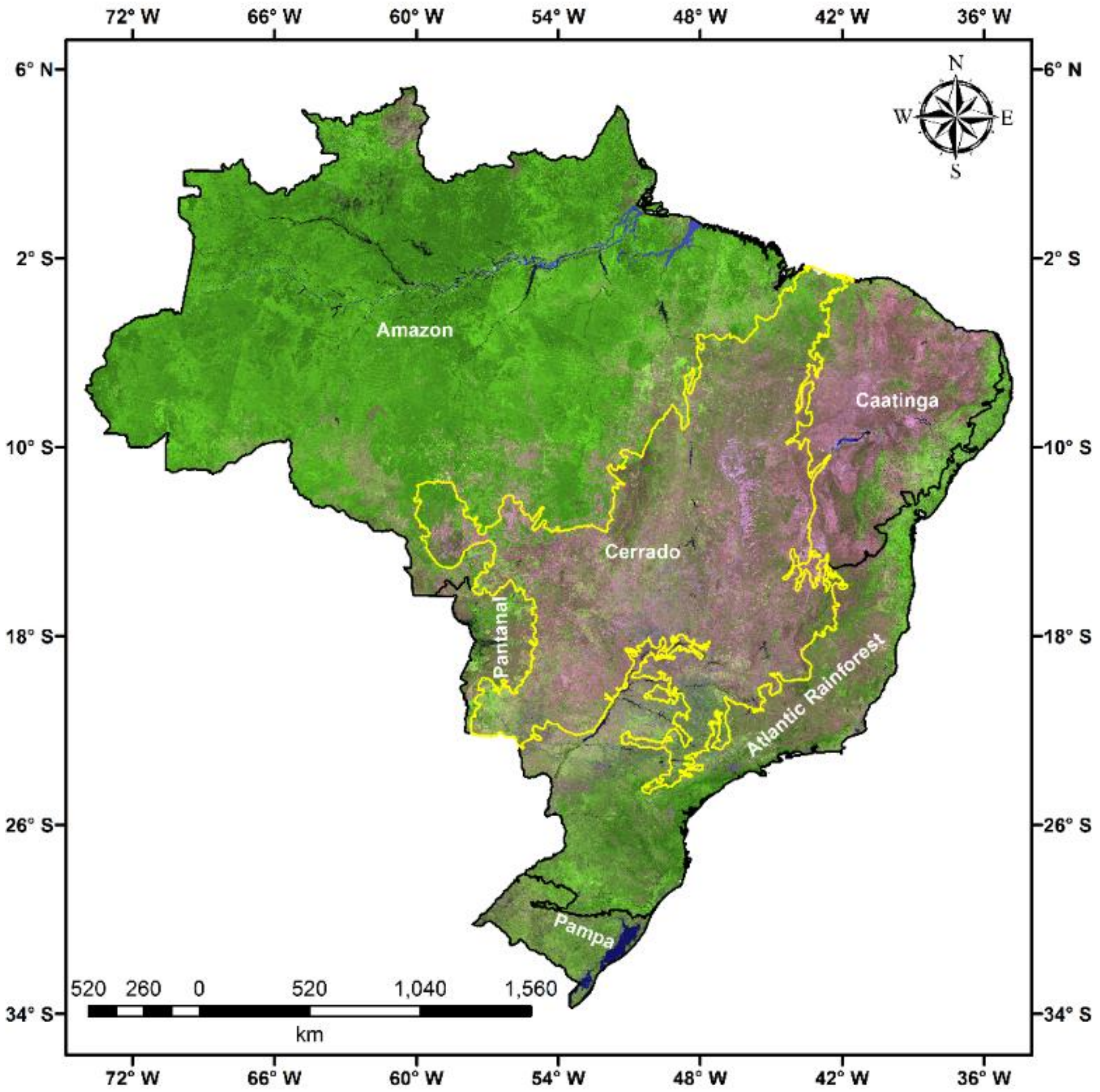

Figure 1: Location of the Brazilian biomes, highlighting the Cerrado biome. MODIS sensor image, R6G2B1 color composite.

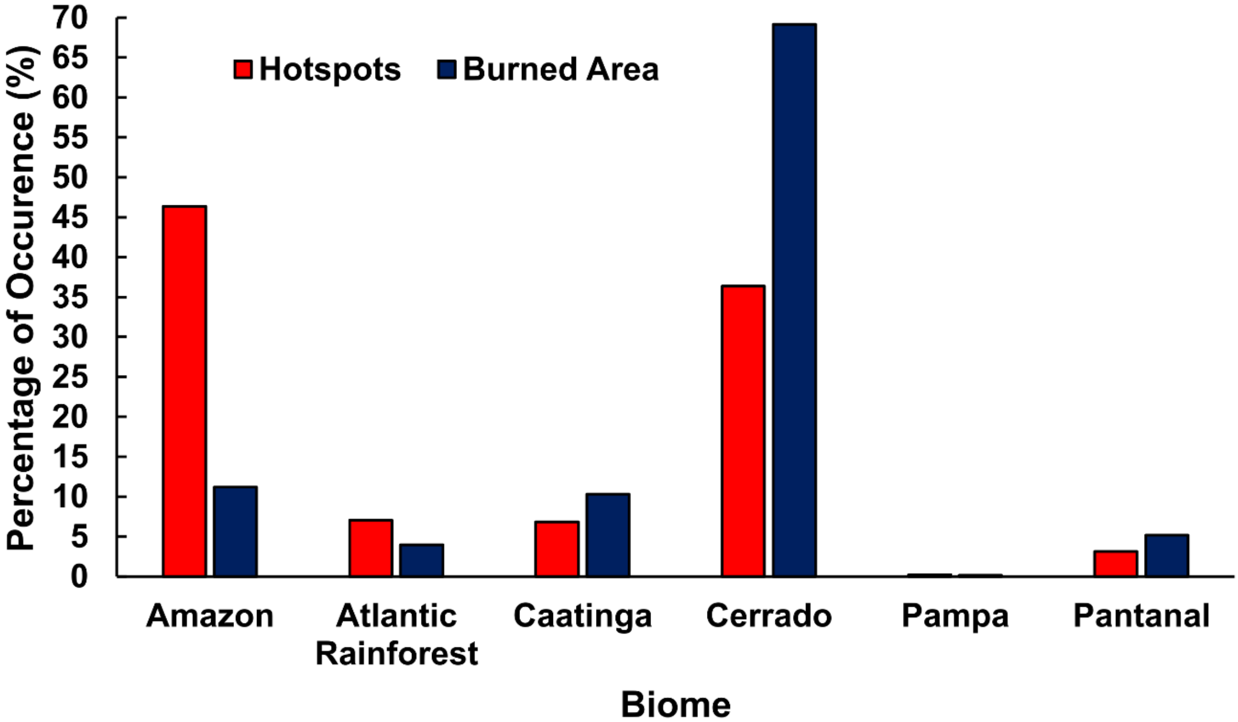

Figure 2: Percentage of hotspots and burned area in the Brazilian biomes during the 2002-2015 period.

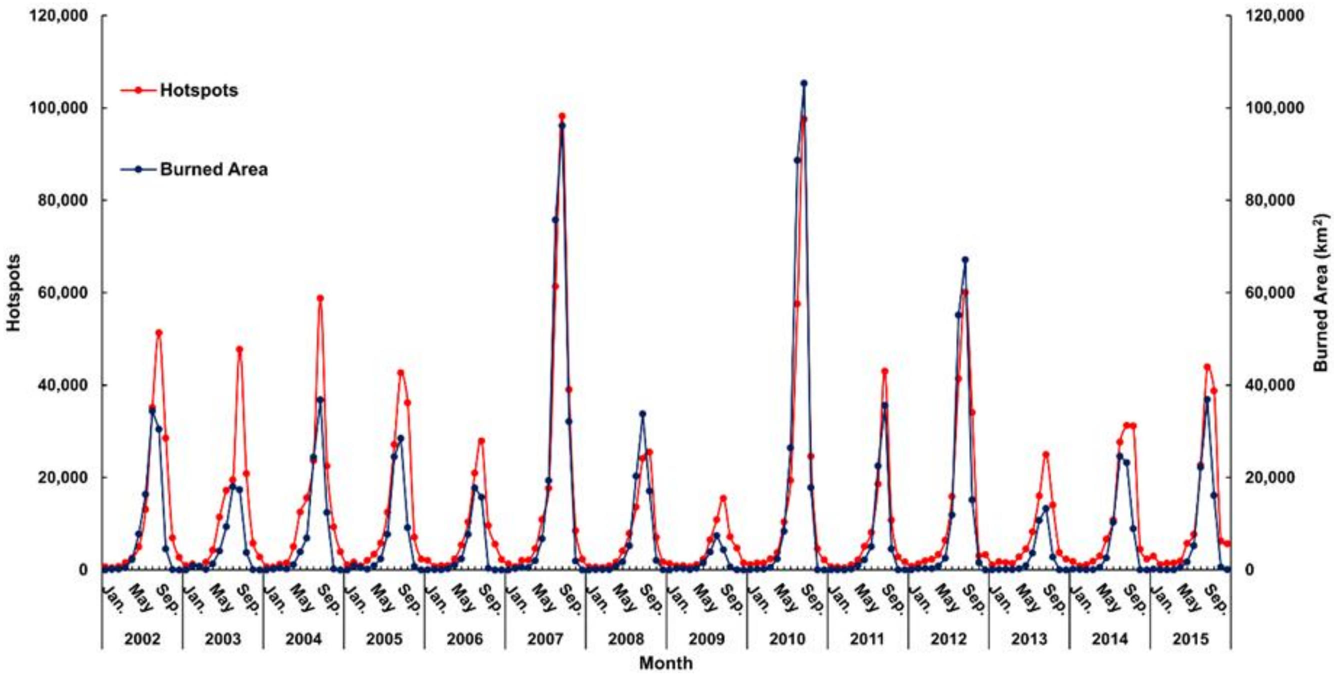

Figure 3: Monthly total hotspots and monthly total burned area in the Cerrado biome between 2002 and 2015.

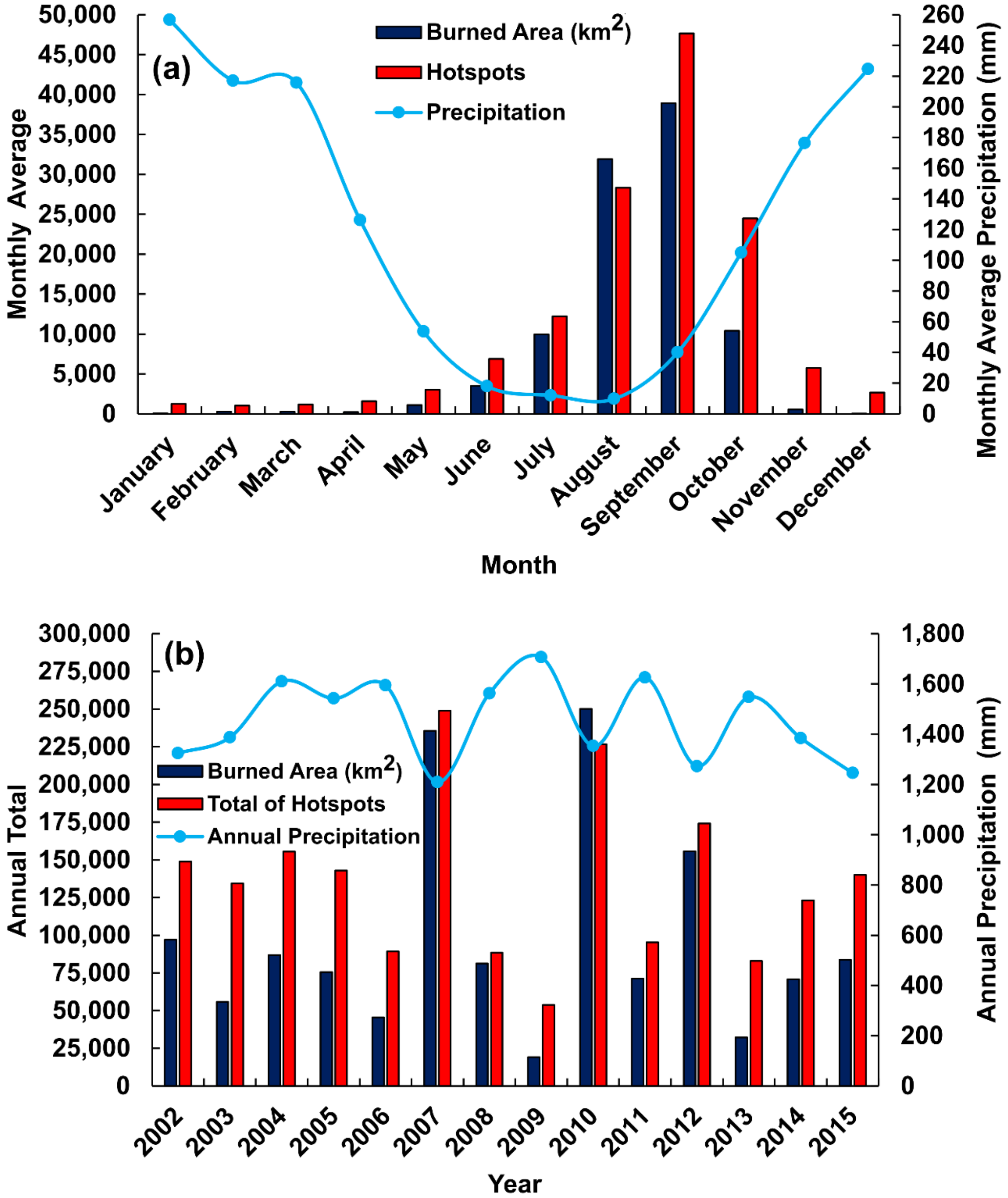

Figure 4: (a) Monthly average hotspots, monthly average burned area and monthly average precipitation, and (b) Annual total hotspots, annual total burned area and annual precipitation for the Cerrado biome between 2002 and 2015.

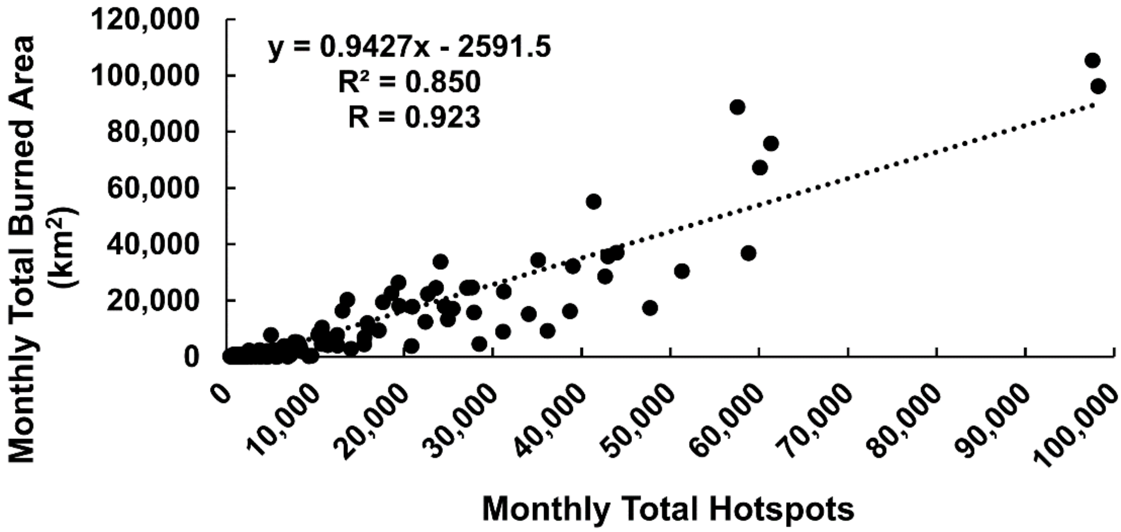

Figure 5: Relationship between monthly total burned area and monthly total hotspots in the Cerrado for the 2002-2015 period.

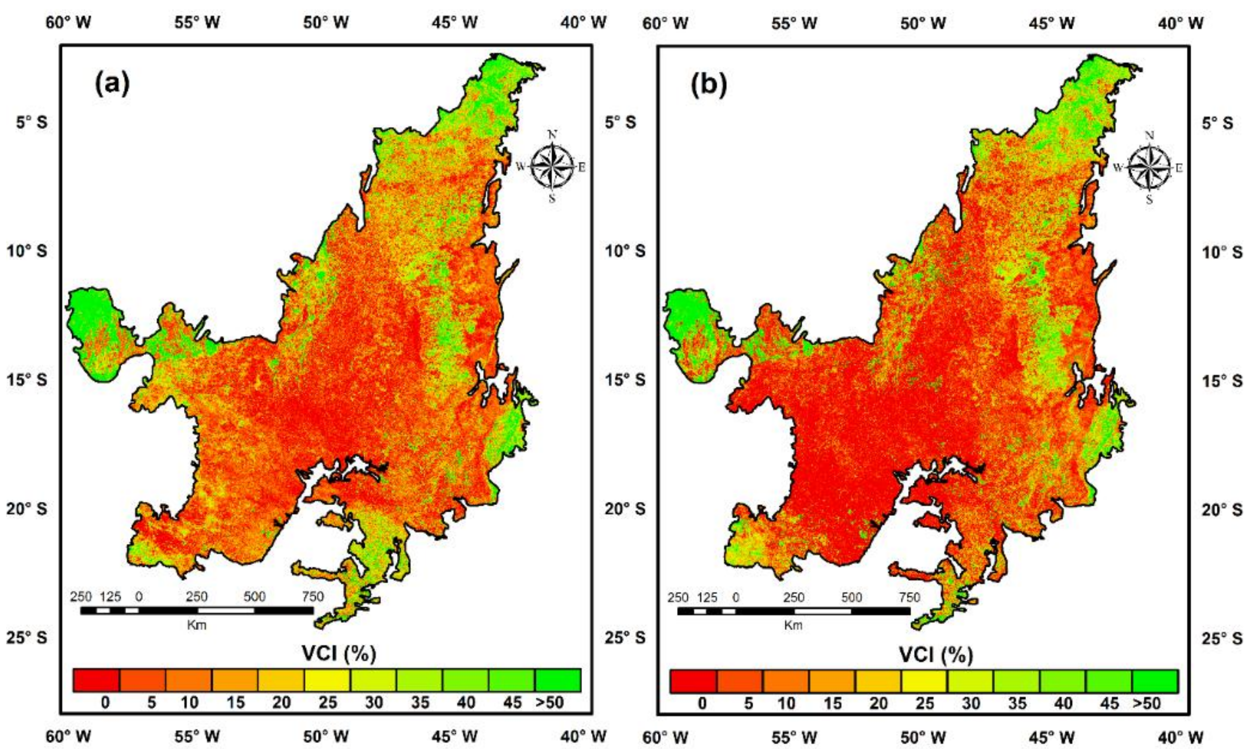

Figure 6: VCI images estimated for (a) September/2007 and (b) September/2010 in the Cerrado biome.

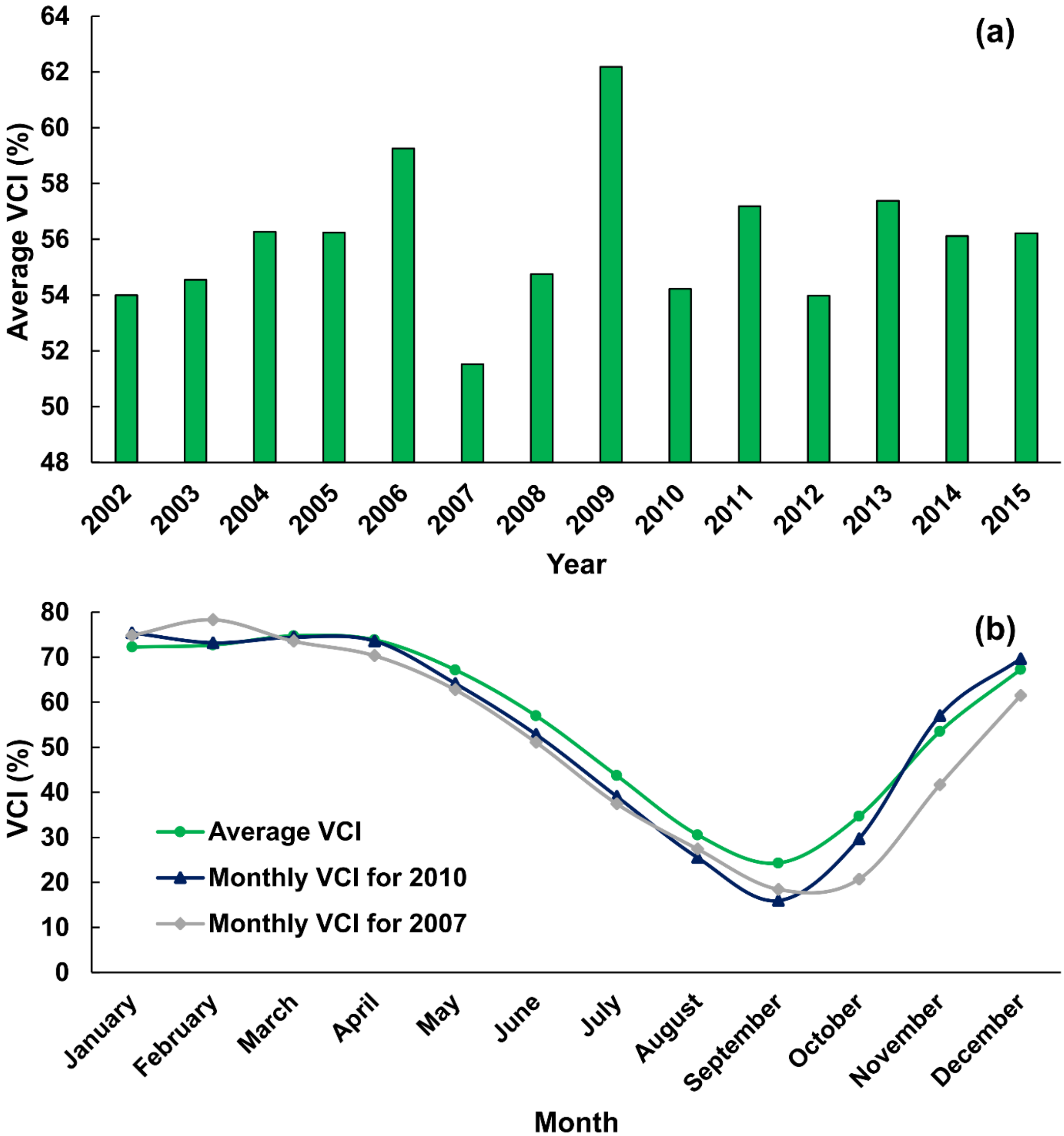

Figure 7: (a) Annual average VCI, and (b) monthly average VCI for the 2002-2015 period and for 2007 and 2010 in the Cerrado.

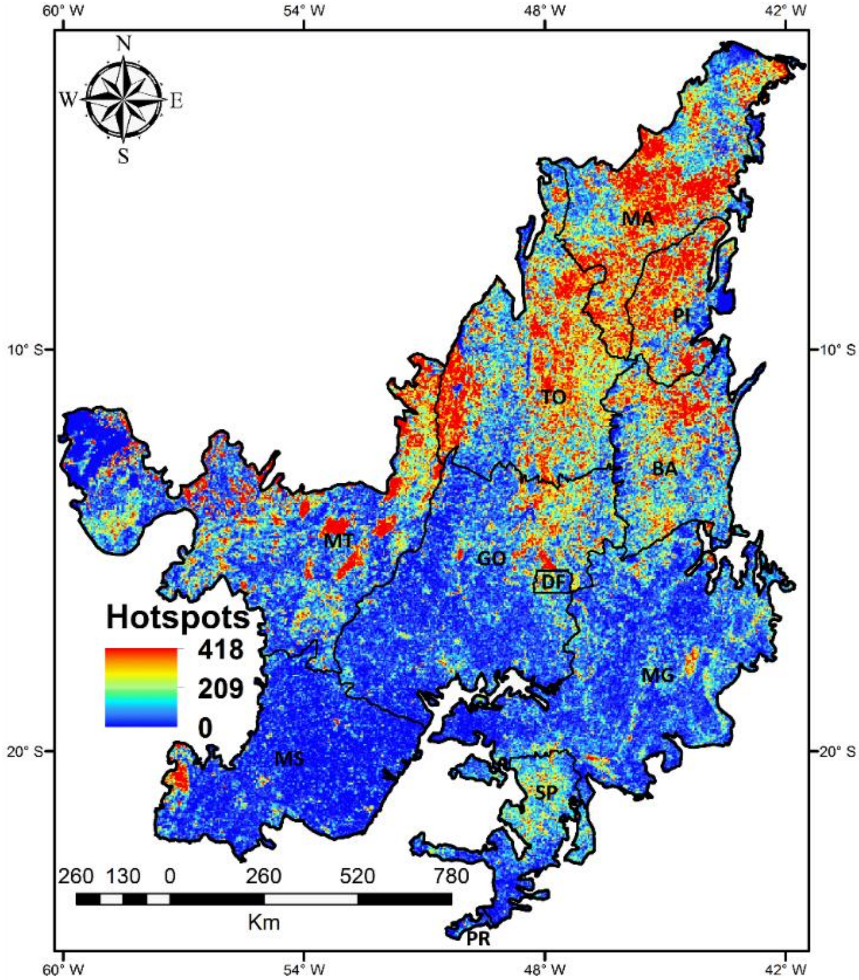

Figure 8: Total of hotspots detected by the MODIS active fire products in the Cerrado biome between 2002 and 2015.

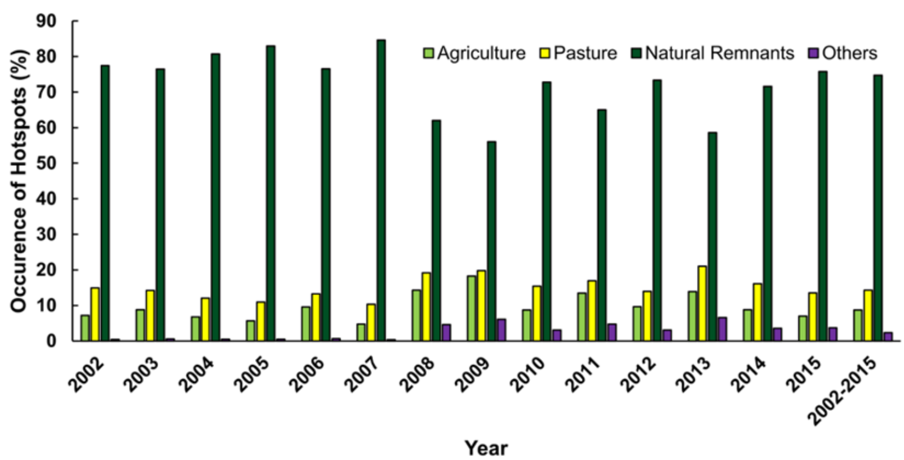

Figure 9: Percentage of the occurrence of hotspots in the LULC of the Cerrado biome between 2002 and 2015.

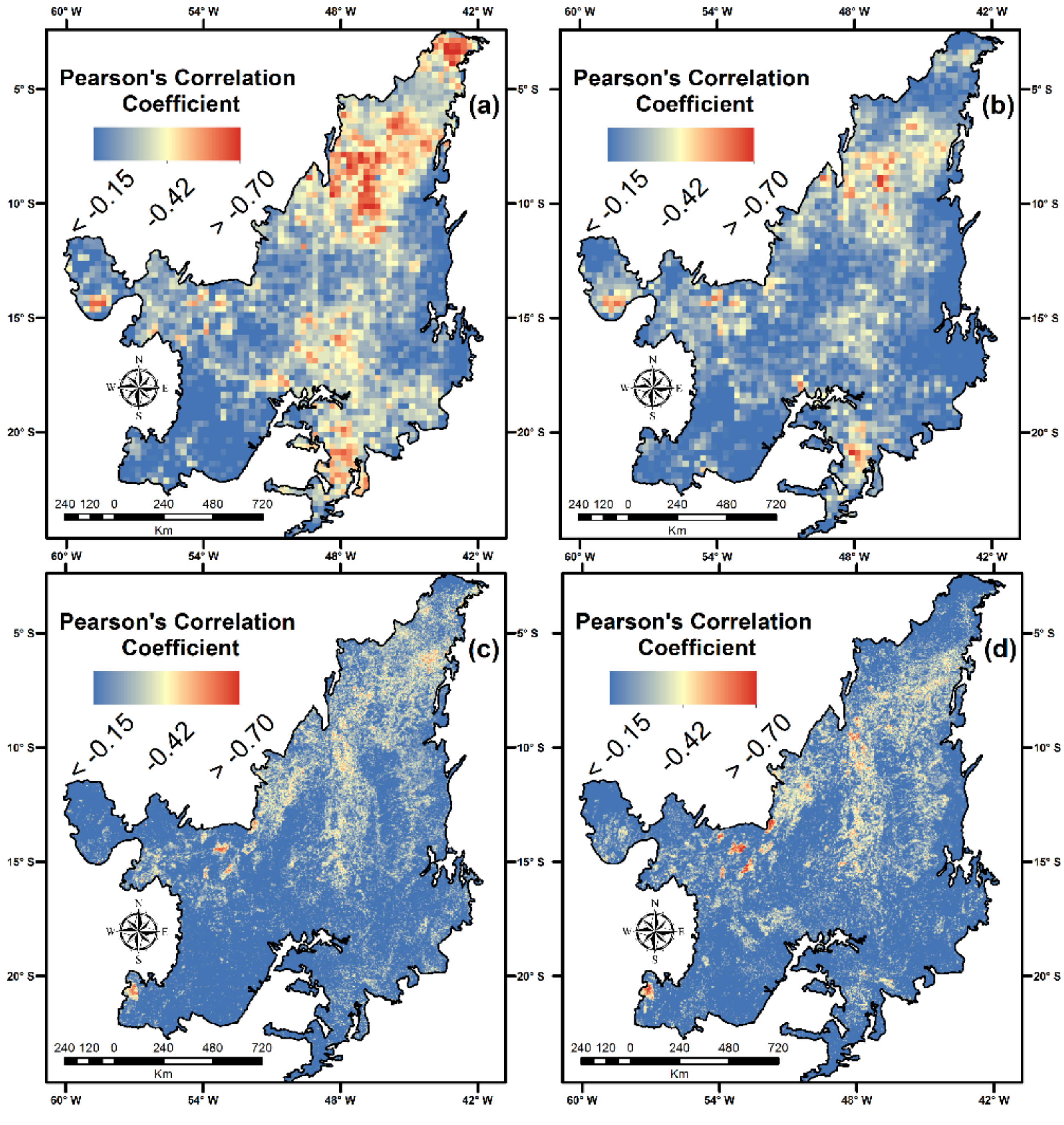

Figure 10: Spatial correlation between (a) monthly total hotspots and monthly average precipitation, (b) monthly total burned area and monthly average precipitation, (c) monthly total hotspots and monthly average VCI and (d) monthly total burned area and monthly average VCI in the Cerrado biome during the 2002-2015 period.

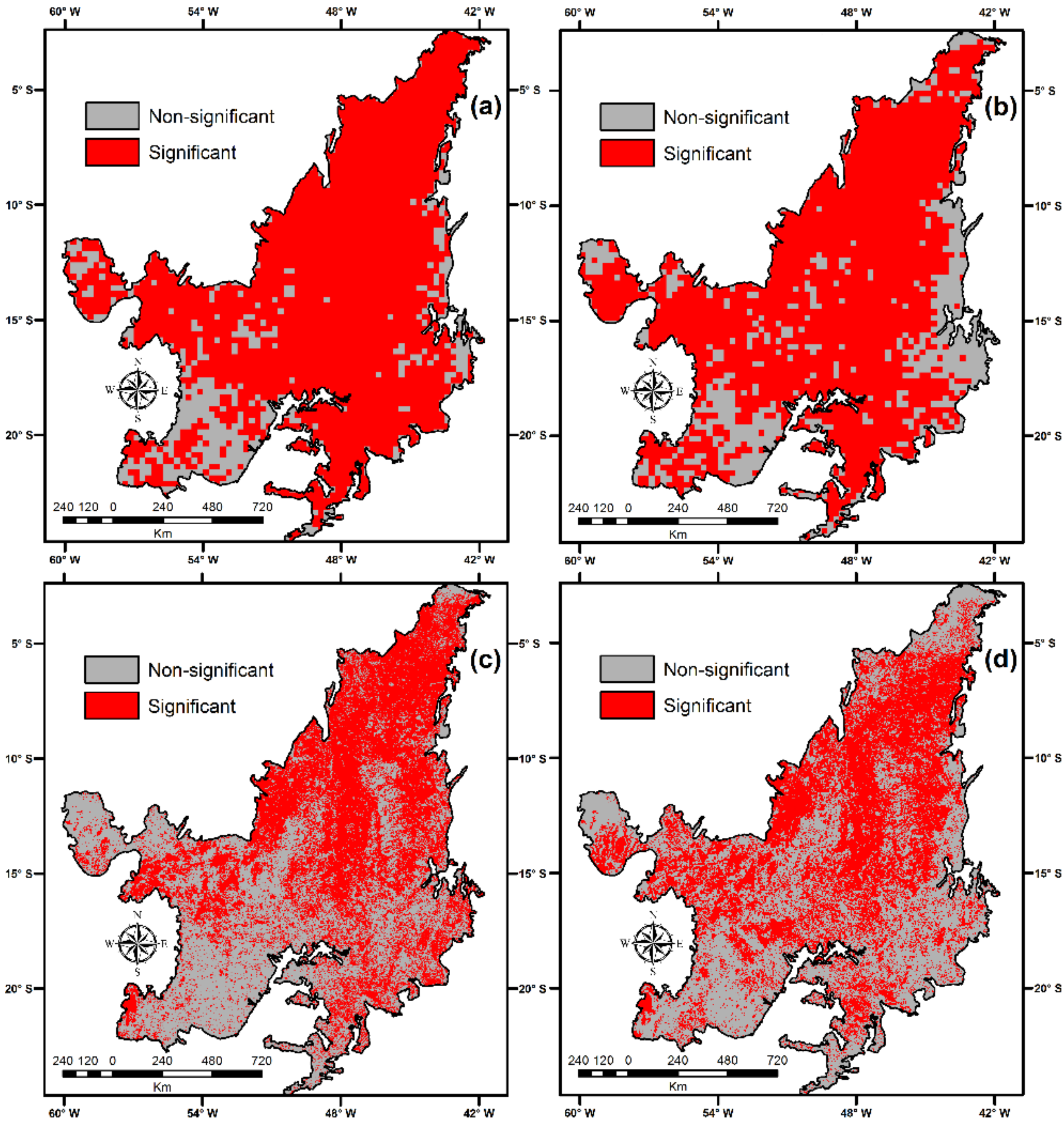

Figure 11: Spatial t-Student test for the spatial correlations between (a) monthly total hotspots and monthly average precipitation, (b) monthly total burned area and monthly average precipitation, (c) monthly total hotspots and monthly average VCI and (d) monthly total burned area and monthly average VCI in the Cerrado biome during the 2002-2015 period.

Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2017-90, 2017
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2017

Table 1. LULC in the Cerrado biome for the year 2013. Source: INPE (2015).

LULC	Area (km^2)	%
Agriculture	238,518	11.69
Bare Soil	3,621	0.18
Mining	247	0.01
Natural Remnants	1,113,699	54.62
Not Observed/Others	25,622	1.25
Urban/Occupation	11,123	0.54
Pasture	600,832	29.46
Silviculture	30,525	1.50
Water	15,056	0.74