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ORIGINAL ARTICLE

Overview of fire foci causes and locations in Brazil based on meteorological satellite data from 1998 to 2011

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Abstract We evaluated the distribution, percentage, and homogeneous regions of fire foci in Brazil over 1998–2011. Included are numbers of fire foci by regions and states as well as their seasonal and monthly variations, with emphasis on human activities and their relationships with producing systems and rainfall inhibitors. We used data from forest fire meteorological satellites, obtained from the Centro de Previsão do Tempo e Estudos Climáticos. Evaluation of regional fire foci distributions gave 37.15 % for the central west and just 1.75 % in the south. Brazilian regions with the highest densities of forest fires per unit area were the northeast, central west, and north. Lowest densities were in the north, southeast, and south. The states of Mato Grosso, Pará, Maranhão, Bahia, Rondônia, and Tocantins had the greatest numbers of fire foci during our study period. The Federal District and the states of Sergipe, Espírito Santo, Rio de Janeiro, Rio Grande do Norte, and Alagoas had the smallest numbers. Spring (62.2 %) and winter (28.7 %) had higher frequencies than summer (6.7 %) and autumn (2.7 %). A clustering technique showed three homogeneous regions of fire foci in Brazil. The regional grouping technique showed the influence of synoptic systems and large-scale patterns of fires in the country. In addition to the use of NOAA-12 satellite images for monitoring Brazilian fire foci, orbital platforms such as MMODIS-01D and T-AQUA can be used. Finally, anthropogenic activities (deforestation, agriculture, livestock, mining, and industrial) and the variability of meteorological systems affected the fire increase during the study period.

Keywords Remote sensing · Forest ecosystems · Forest fires · Statistical methods · Deforestation · Meteorological systems

Introduction

Owing to the increase in agropastoral and criminal activities, the number of fires in Brazil has increased significantly in recent years. This has caused the loss of biodiversity and soil biota as well as increased the greenhouse effect, air pollution (particulate matter and biogenic), and respiratory disease frequency. The detection and monitoring of fires is beyond the scope of the deforestation problem, because they result in environmental, climate, and ecological changes (Graneman and Carneiro 2009; Libonati et al. 2010; Armenteras-Pascuala et al. 2011).

In the last decade, interest in fires has increased considerably because of their environmental consequences, especially in Environmental Protection Areas (EPAs) and Protected Areas (PAs) (Governo Federal 2012), and because of the transport of combustion products through plume smoke. These products are potentially hazardous to human health across wide areas, potentially reaching the general population (Eva and Fritz 2003; Silva de Souza et al. 2012).

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In addition to substantial damage to forest ecosystems, the fires are of fundamental ecological importance because of their influence on air pollution and climate change, which have direct and indirect impacts on habitats and ecosystems (Ferraz and Vettorazzi 1998). Beyond the current loss of forests, forest fires and their impacts are factors in global environmental imbalance and have great social and economic consequences.

Forest fires can be of natural or anthropogenic origin. In addition to human activities, fires have increased significantly because of climate variability related to the El Niño-Southern Oscillation (ENSO) (Gutman et al. 2000; Hessl et al. 2004; Alencar et al. 2006; Swetnam and Anderson 2008). High temperatures and increased occurrence of severe droughts in many regions of the world have contributed to a remarkable increase in the number of fires within a variety of ecosystems (Swetnam and Anderson 2008). However, recent advances in meteorology have enabled fire prediction based on improved real-time datasets and historical data. These improvements have also led to a better understanding of regional and global climate variability (ENSO, Pacific Decadal Oscillation, and Pacific/North American teleconnection), especially regarding their interference in related fire regimes (Hessl et al. 2004; Heyerdahl et al. 2008; Trouet et al. 2009).

Vegetation characteristics affect the quality and reliability of forest fire detection via satellites. Generally, in certain ecosystems such as tropical savannas in northern and central western Brazil, fire durations are a few hours. These may occur between satellite passages, and as a result, the fires will not be detected (Brown et al. 2006). This satellite detection depends on emitted thermal energy and atmospheric conditions between the fire and satellite sensor (Chuviesco and Congalton 1989).

Forest fuels, which are a product of vegetation cover and its dynamics, are important to the ignition and spread of fires. The knowledge of the basic characteristics of fuels aids risk estimation and the prediction of fire behavior (Chuviesco and Congalton 1989). Therefore, characterization of forest fuels and their association with hotspots can increase detection efficiency for forest fires, especially in Brazil (Evangelista et al. 2007).

Brazil's territorial expanse and diversity of vegetation cover, as well as its significant number of forest fires, emphasize the need for the improvement of existing control/detection systems for such fires. Several initiatives have been implemented in recent years to improve the management of public agencies and civilians toward avoiding disasters, such as the creation of the Centro de Pesquisa para Prevenção de Emergências e Desastres. Another initiative of the Brazilian government was the formation of the Sistema Nacional de Prevenção e Combate aos Incêndios Florestais, which assigns the Instituto Brasileiro do Meio Ambiente e dos Recursos Renováveis the power to coordinate the prevention and combat of forest fires and burns.

In Brazil, the detection and monitoring of forest fires using meteorological satellite images is the most efficient and cost-effective technique (Morisette et al. 2005; Libonati et al. 2010). However, there are also well-known fire risk indexes (FRIs) that assist in the prediction and probability of fires. The FRI is a statistical tool that infers the probability of fire occurrence, based on daily or timely meteorological conditions (Evangelista et al. 2007; Bontempo et al. 2011). The FRIs are divided into rates of occurrence (indicating fire likelihood) and indexes of propagation (indicating trend behavior of fires).

Technological advances have enabled the use of satellite remote sensing images, which detect and locate fires in real time. Brazil invests in technologies that enable the monitoring and control of hotspots in real time, which are of great help in fighting fires (Graneman and Carneiro 2009). However, there have been only a few studies in the country that generated an average rating of fires based on timely meteorological satellite data. There have also been few studies that characterize regions and associate them with meteorological systems and modes of climate variability.

Therefore, the objective of the present study was to evaluate the seasonal and spatial distribution of fire foci in Brazil between 1998 and 2011, including the number of foci by states and regions (homogeneous regions). The emphasis is on human activities and their relationships with system production and inhibitors of rainfall, and we ultimately determine which satellites can be used as a reference for identifying fire foci.

Characterization and location of study areas

Brazil is in the central-eastern portion of South America, between 5°16′20″N and 33°44′32″S and 34°45′54″E and 73°59′32″W. Its total area is 8,514,876.599 km^2 (IBGE 2012), which is about 47 % that of South America (SA). All of its northeast, east, southeast, and northern regions adjoin the Atlantic Ocean. Currently, Brazil is geopolitically divided into 26 states and a Federal District; there are five regions: north, northeast, south, southeast, and central west (Fig. 1).

Producer systems and inhibitors of rainfall in Brazil

Brazil has continental dimensions and is therefore affected by many meteorological systems. In the present study, analysis was restricted to the synoptic scale, on which acts the producers and inhibitors of rainfall that can affect change of fire foci. Frontal Systems (FS), the South

Fig. 1 Geopolitical map of Brazil

Atlantic Convergence Zone (SACZ), South Atlantic Subtropical Anticyclone (SASA), Intertropical Convergence Zone (ITCZ), Mesoscale Convective Complexes (MCC), and Bolivian High (BH) systems are the major producers and inhibitors of rain in Brazil (Minuzzi et al. 2007; Reboita et al. 2010).

The SACZ is common in spring and summer and is defined as a northwest–southeast (NW–SE) band of cloudiness that stretches from the southern and eastern Amazon to the southwestern South Atlantic (Carvalho et al. 2004). FS occur in Brazil throughout the year, mostly affecting rainfall in the south and southeast (Liebmann et al. 1999). However, FS produce greater rainfall in spring and summer, owing to increased tropical convection. In these seasons, there can also be an association between FS and SACZ, which provides moisture to the FS, thereby intensifying rainfall (Oliveira-Júnior et al. 2014).

The ITCZ influences rainfall patterns in the northeast and north of Brazil and defines its rainy/dry season upon moving south/north of the equator. In summer, the BH varies its location and intensity in central Brazil and interacts with other synoptic systems over the northeast, causing subsiding motion there and ultimately affecting the penetration of FS in the continent, especially the central west. The BH reaches maximum intensity during December through February and weakens during April and May (Chaves and Cavalcanti 2001). Because of their geographic locations, the north and northeast regions are affected by various producers and inhibitors of rainfall at a regional scale, such as easterly wave disturbances (EWD), instability lines (IL), and sea breeze systems (Chaves and Cavalcanti 2001; Gois et al. 2005; Barros and Oyama 2010; Lyra et al. 2014).

Other types of meteorological systems include the upper tropospheric cyclonic vortex (UTCV), which varies its location. It routinely occurs over the northeast, south, southeast, and central west regions. This cyclonic circulation appears in the upper troposphere and is also called a cold low, because its center is colder than its periphery. The circulation extends gradually to lower levels and may be associated with surface cyclones or even promote cyclogenesis (Kousky and Gan 1981; Minuzzi et al. 2007; Reboita et al. 2010). The UTCV blocks displacement of FS to the northeast coast, contributing to their permanence in the southeast where they produce heavy rainfall. In the south, the UTCV can also generate heavy rains (Rao and Bonatti 1987). Migration of the SASA extends over a large part of Brazil. In winter, it migrates to continental regions, which inhibits rain in the south, southeast, and central west, owing to its subsiding motions. In summer, the SASA is over the Atlantic Ocean, which favors moisture transport to the continent (Reboita et al. 2010; Correa et al. 2014). Finally, atmospheric blocks (AB) prevent the movement of transient atmospheric features (anticyclones and troughs) in the eastern region, and these blocks persist for several days. AB occurs in the southeast region, especially in late winter and early spring (Minuzzi et al. 2007; Mendes et al. 2009; Reboita et al. 2010). According to some studies, there is a reduction in the number of blockages during years typical of El Niño and an increase in frequency during La Niña years (Kayano and Kousky 1989; Marques and Rao 2012).

As previously mentioned, ENSO events have a great impact on production systems and inhibitors of rainfall in Brazil, because they affect the longitudinal position of the ascending branches of the Walker Cell (WC). In the warm phase (El Niño), the main ascending branch remains over the warm waters of the equatorial Pacific. This causes subsidence and high pressure over northern SA, blocking the ITCZ and SACZ to be further north and FS further south than normal, thereby increasing rainfall in the region of ascent (Rao et al. 1993). During the cold phase (La Niña), there is intensification of the ascending branches of the WC in SA, amplifying rainfall in the north and northeast. The ENSO variably influences the south and northeast regions and thereby their rainfall patterns (Campos and da Silva 2010; Reboita et al. 2010; Rao 2012).

Materials and methods

Time series of fire foci

Fire foci data were obtained from the Centro de Previsão do Tempo e Estudos Climáticos (CPTEC; http://pirandira.cptec.inpe.br/queimadas/) (CPTEC 2012). Currently, CPTEC uses 14 meteorological satellites (geostationary and polar orbiting) for their observation network. These satellites pass the country during morning, afternoon, evening, and night (Table 1). The study period was 1998–2011 (13 years). Yearly and seasonal evaluations were made using imagery from orbital periods of commercial satellites, attempting to identify areas of greatest fire foci in Brazil. We divided the total number of fire foci during the study period by land area (km^2) of the states according to IBGE data (Table 2), thereby obtaining foci density per unit area (D).

Consistency analysis and grouping of the series of fire foci

Quality control of fire data series was done based on exploratory analysis (descriptive statistics and box plots) and monthly and yearly frequency distributions of the observed data, for each satellite and selected region. This procedure allowed the identification of outliers, based on average interval variation of the expected data. To define regions and months with homogeneous fire characteristics, we used a cluster analysis (Everitt and Dunn 1991). In seasonal grouping of homogeneous fire characteristics, we used the hierarchical agglomerative method of Ward (1963), taking the square of the Euclidean distance as a dissimilarity measurement (Everitt and Dunn 1991):

$$d_{\mathrm{e}} = \left[\sum_{j=1}^{n} \left(P_{p,j} - P_{k,j}\right)^2\right]^{0,5}, \tag{1}$$

where d_{e} is the Euclidian distance and $P_{p,j}$ and $P_{k,j}$ are quantitative variables j of the individuals p and k, respectively.

To form groups, the Ward method minimizes dissimilarity or total sum of squares within groups, also known as the sum of squared deviations (SQD). At each step, groups are formed such that the resulting solution has the lowest SQD within groups. This considers the unions of all possible pairs of groups, and the two that produce the least increase in SQD are grouped until all groups form a single unique group including all individuals (Everitt and Dunn 1991).

After the cluster analysis of fires across the country, another cluster analysis was performed at a regional scale. In this evaluation, the following seasons were used: summer (December, January, and February—DJF), autumn (March, April, and May—MAM), winter (June, July, and August—JJA), and spring (September, October, and November—SON), and the dry, transition, and wet season regimes.

Results and discussion

Performance of meteorological satellites over 1998–2011

We analyzed the performance of the meteorological satellites used to evaluate the fires in Brazil (Table 1). Figure 2 shows that the polar-orbiting satellites had greater success in detecting fires compared with geostationary satellites. The poorer performance of the latter satellites was because they only cover one-third of the land surface and continued degradation at image edges. Therefore, it is necessary to have at least five geostationary satellites (Kidd 2001).

NOAA-12, AQUA-T, and MMODIS-01D detected the largest number of fire foci across Brazil over 1998–2011, relative to other meteorological satellites. This is because their images are processed operationally for the well-known Advanced Very High Resolution Radiometer (AVHRR) (NOAA12) and Moderate Resolution Imaging Spectroradiometer (MODIS) (MMODIS-01D and AQUA-T), ensuring a high accuracy rate for fire foci in the study period. The AVHRR makes measurements in the visible

Table 1 Characteristics of meteorological satellites and periods

Meteorological satellites	Period	Characteristics satellites
NOAA 15	Morning	Polar orbit—Helios synchronous
NOAA 15	Night	Polar orbit—Helios synchronous
NOAA 12	Morning	Polar orbit—Helios synchronous
NOAA 12	Night	Polar orbit—Helios synchronous
NOAA 18	Morning	Polar orbit—Helios synchronous
NOAA 18	Afternoon	Polar orbit—Helios synchronous
NOAA 14	Night	Polar orbit—Helios synchronous
NOAA 16	Afternoon	Polar orbit—Helios synchronous
NOAA 16	Dawn	Polar orbit—Helios synchronous
NOAA 17	Dawn	Polar orbit—Helios synchronous
GOES 08	Night	Geostationary (35.800 km)
GOES 10	All	Geostationary (35.800 km)
GOES 12	All	Geostationary (35.800 km)
METEOSAT-02	All	Geostationary (35.800 km)
MMODIS-01D	All	Polar orbit—Helios synchronous
AQUA-T	Afternoon	Polar orbit—Helios synchronous
AQUA-M	Morning	Polar orbit—Helios synchronous
TERRA-M	Morning	Polar orbit—Helios synchronous
TERRA-T	Afternoon	Polar orbit—Helios synchronous

Source: CPTEC (http://pirandira.cptec.inpe.br/queimadas/), (2012)

and infrared regions of the spectrum at spatial resolution of 1 km, resulting in thousands of measurements daily. The AVHRR sensor captures and records any temperature warmer than 47 °C and interprets it as fire foci. Despite the low spatial resolution (1.1 km), burned areas with a minimum of 900 m^2 can be detected (França and Setzer 2001).

MODIS captures data in 36 spectral bands in wavelengths of 0.4–14.4 µm and is very sensitive to fire. It can distinguish a fire from coal burning and hence provides better estimates of the amount of aerosols and gases from scattered fires in the atmosphere (Kidd 2001). One of the land products derived from the MODIS sensor is a pixel-resolution fire mask, which is separated into files representing 5 min of image acquisition along a given swath (Justice et al. 2002). Increased saturation temperatures of the 1-km resolution sensors at 3.9 and 11 µm reduce ambiguities leading to false alarms or omission errors typical of AVHRR-based fire products (Giglio et al. 2003). The NOAA-12 satellite has been used as a reference for monitoring fire foci in Brazil (Graneman and Carneiro 2009; CPTEC 2012). However, this study showed that satellites MMODIS-01D and AQUA-T can be used for this purpose and for research in the field of fire.

Regional distribution of fire foci in Brazil

The central west region had the greatest number of fire foci. It had 3,484,834 foci, which accounted for 37.1 % of the total in Brazil between 1998 and 2011. In the last two decades, the economy in this region has significantly amplified, based on extensive cattle cutting and milk within extensive farming for staple foods. More recently, there has been intensive production of corn and soybeans (economic vectors) as well as an increase in mining and industry. Given the base of its economy and large extent, the central west has seen continuing deforestation to meet the demands of its growing economy. Burning is a cheap, fast, and common practice in the region, frequently used in deforestation, soil cleanup, and pasture renewal (França and Setzer 2001). In this process, the soybean was the main vector contributing to the increased burning problem in the region, owing to the need for increased production (Chuvieco et al. 2008; IBGE 2012).

The region with the second largest number of fire foci was the northeast, with 2,544,540 foci, corresponding to 27.1 % of the total number of foci. Agriculture and livestock, mainly cattle and extensive sugarcane production (IBGE 2012), were the principal factors related to fires in the region during the study period. Fire is used routinely in illegal deforestation in the northeast for various agricultural purposes (pasture renewal, clearing areas for cultivation) and sometimes results from festivities (fireworks and balloons), religious rituals, and garbage burning (Eva and Fritz 2003; Chuvieco et al. 2008; IBGE 2012).

The region with the third largest number of fire foci (2,520,360 recorded) was the north, representing 26.9 % of the national total. Deforestation was primarily responsible

Table 2 Brazilian states and territorial areas (km^2) according to IBGE (Instituto Brasileiro de Geografia e Estatística)

States	Territorial areas (km^2)
Maranhão (MA)	331,935
Mato Grosso (MT)	903,329
Rondônia (RO)	237,590
Tocantins (TO)	277,621
Piauí (PI)	251,576
Ceará (CE)	148,920
Pará (PA)	1,247,950
Distrito Federal (DF)	5,787
Bahia (BA)	564,830
Alagoas (AL)	27,779
São Paulo (SP)	248,196
Mato Grosso do Sul (MS)	357,145
Goiás (GO)	340,103
Paraíba (PB)	56,469
Pernambuco (PE)	98,146
Minas Gerais (MG)	586,520
Acre (AC)	164,122
Paraná (PR)	199,316
Rio Grande do Norte (RN)	52,810
Sergipe (SE)	21,918
Roraima (RR)	224,301
Rio de Janeiro (RJ)	43,780
Santa Catarina (SC)	95,703
Amapá (AP)	142,827
Espírito Santo (ES)	46,098
Amazonas (AM)	1,559,161
Rio Grande do Sul (RS)	268,781

Source: IBGE (2012)

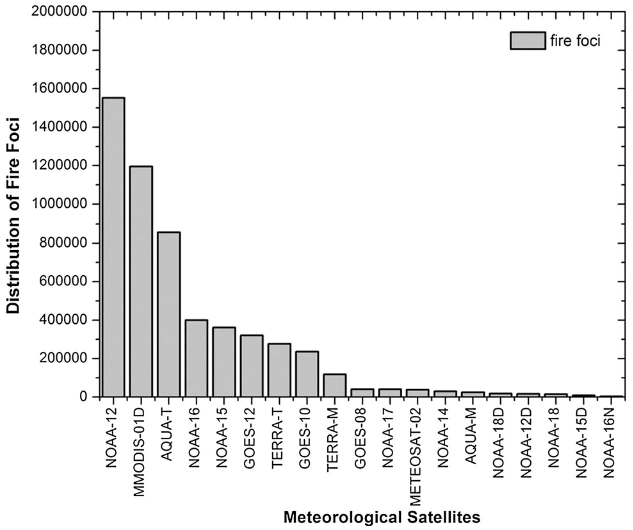

Fig. 2 Distribution of fire foci from meteorological satellites over 1998–2011

for the increase in fire number here during the study period, followed by extraction of minerals and agriculture. All these practices significantly increase deforestation of the Amazon rainforest because of the expansion of soybean cultivation in the Cerrado, thereby extending the agricultural frontier into forest areas (Morisette et al. 2005). Following this extension, livestock and small producers were also important agents of deforestation (Cui and Perera 2008). Another such agent is the extraction of wood, associated with the opening of roads. Nonetheless, among all economic activities in the region, the greatest impact on the forest is from cattle, because this activity requires the destruction of large forest tracts. Livestock raising constitutes about 75 % of deforested area in the Amazon (Margulis 2003; IBGE 2012).

The southeast and south had the lowest number of fire foci, with 6,67,718 (7.1 %) and 164,382 foci (1.8 %), respectively (Fig. 3). Among the economic activities that start fires in the southeast, there is agriculture, followed by mining and industry (Eva and Fritz 2003). Among such activities in the south, ranching should be highlighted, along with agriculture. Cleared areas in the Pampas have greatly increased. However, both the southeast and south have had few fire foci because socioeconomic dynamics have been exhausted in relation to agricultural expansion of small plantations. Moreover, this expansion was followed by effective policies encouraging agricultural mechanization, reduction in deforestation and, finally, stagnation of the working population (Chuvieco et al. 2008; IBGE 2012).

Total fire foci in the Brazilian states during the study period were characterized by strong variability (Fig. 4a). This variability is attributable to expansion of the agricultural frontier (cropland or land of family farms) in the country over the past two decades as encouraged by the Federal Government (IBGE 2012). This development was followed by rudimentary practices of planting and harvesting, deforestation, criminal fires, and ultimately intra-seasonal and inter-annual variability of the production systems and inhibitors of rainfall in the country. States with the largest numbers of fire foci were Mato Grosso (2,128,312), Pará (1,487,057), Maranhão (878,098), Tocantins (563,996), Bahia (621,447), Rondônia (512,091), and Piauí (440,067). Except for Bahia and Piauí, these states are part of the so-called arc of deforestation, currently termed the arc of sustainable deforestation (Governo Federal 2012).

Main activities in the arc of deforestation are grain production, intensive farming, and trade of wood, which are associated with high rates of deforestation and fire foci (Silva de Souza et al. 2012). Besides, the arc of

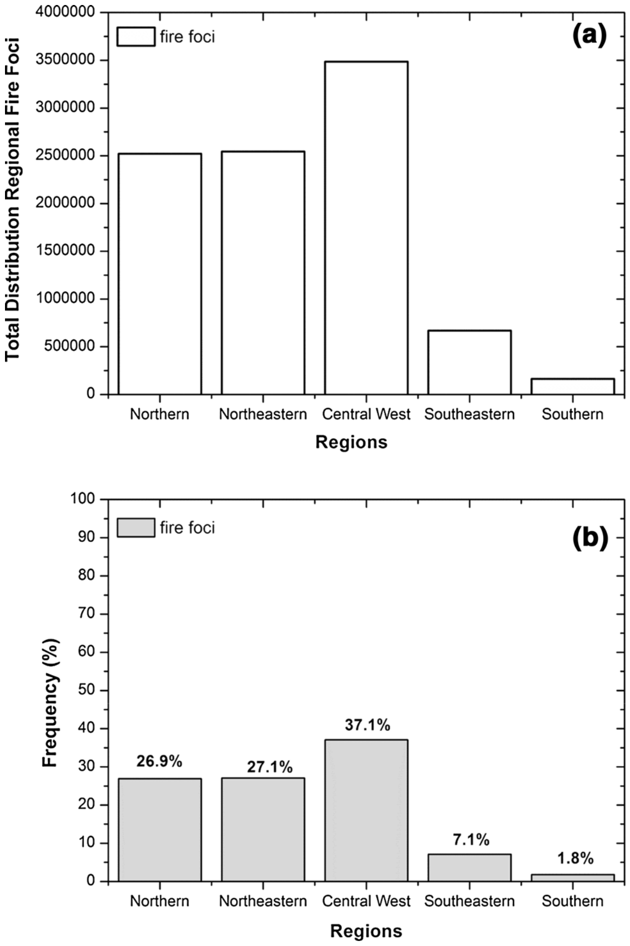

Fig. 3 Distribution (**a**) and frequency (%) (**b**) of the fire foci in north, northeast, central west, southeast, and south regions of Brazil from 1998 to 2011

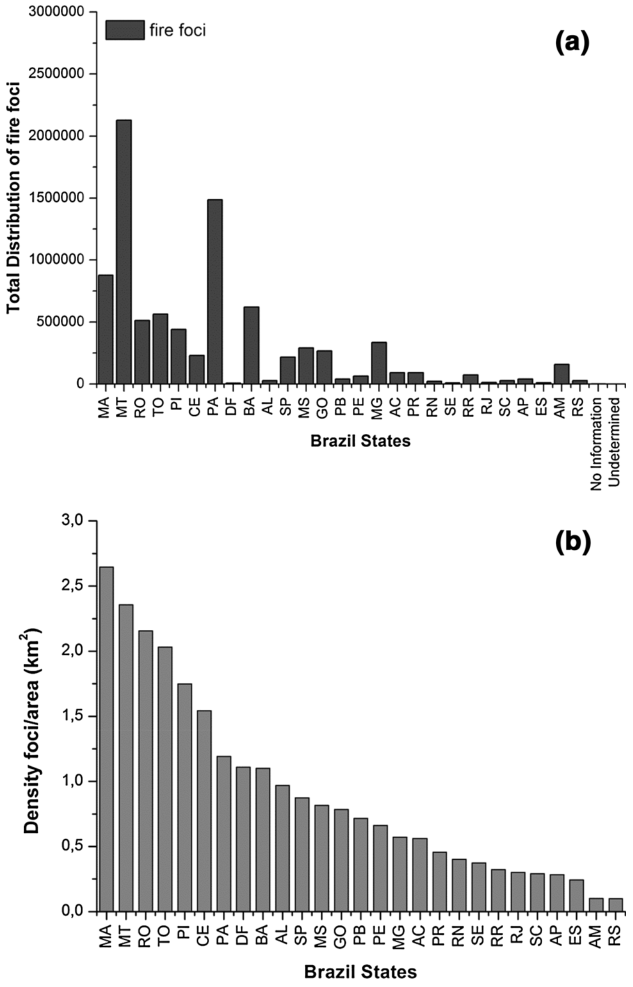

Fig. 4 Distribution of fires (**a**) and density of foci/area (km^2) (**b**) by Brazilian region/state over 1998–2011

deforestation comprises the states in the central west (Mato Grosso), north (Pará, Rondônia and Tocantins), and northeast (Maranhão, Piauí and Bahia) regions, the Federal District (6,416 foci), along with Sergipe (8,179), Espírito Santo (11,244), Rio de Janeiro (13,202), Rio Grande do Norte (21,234), and Alagoas (26,900). We did not identify foci by the meteorological satellite used (Table 1), named indeterminate data (651 foci) and no information (181 foci), which in percentage terms had low values, in the order of 0.008 % (no information) and 0.002 % (undetermined) (Fig. 4a).

States with the highest density of foci per unit area (*D*) were Maranhão, Mato Grosso, Rondônia, Tocantins, Piauí, and Ceará ($1.5 < D < 2.5$), whereas the lowest density states ($D < 0.5$) were Roraima, Rio de Janeiro, Santa Catarina, Espírito Santo, Amapá, Amazonas, and Rio Grande do Sul. Regions with the highest densities were the northeast (Maranhão, Piauí and Ceará), central west (Mato Grosso), and north (Rondônia and Tocantins). Lowest densities were in the north (Amazonas, Roraima, and Amapá), southeast (Rio de Janeiro and Espírito Santo), and south (Santa Catarina and Rio Grande do Sul) (Fig. 4b). The density permitted quantification of the actual impact of fire foci during the study period by considering the land area of each state and region (Table 2).

Homogeneous regions of fire foci in Brazil

Based on the Ward method, three homogeneous groups of fire foci in Brazil were statistically rated (Fig. 5). In many regions, it was difficult to characterize the four seasons because climatic characteristics vary by region. There are regions categorized by rainfall, dry season, and wet season or transition. Other regions follow air temperature evolution and can be defined by the four seasons (Reboita et al. 2010).

Homogeneous group 1 was represented by only one region (northeast). This group has a strong influence on the homogenization of fire foci by meteorological systems and human activities, similar to homogeneous group 3. Large-

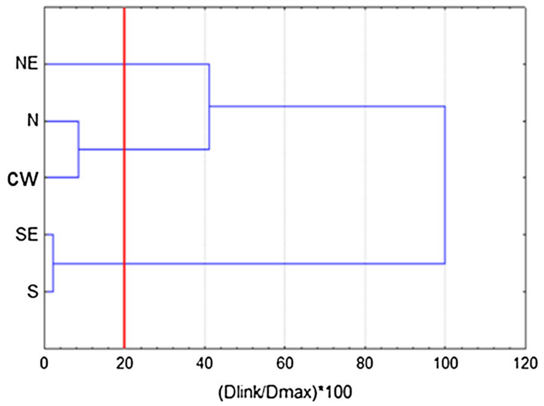

Fig. 5 Homogeneous regions of fire foci in Brazil from 1998 to 2011

scale systems are responsible for about 30–80 % of the observed rainfall. Remaining systems are mesoscale and local, which define rainfall regimes such as the ITCZ, which produces February–May rainfall in the states of Maranhão, Piauí, Ceará, part of Rio Grande do Norte, and west of Paraiba and Pernambuco. Other systems are FS or their remnants penetrating southern Bahia and Maranhão between November and January, the EWD and FS affecting rainfall across the east coast of the northeastern Brazil (NEB) in April and June, and the UTCV with its influence throughout NEB, predominantly between November and March (highest frequency in January) (Hastenrath and Heller 1977; Moura and Shukla 1981; Molion and Bernardo 2002; Santos et al. 2010; Lyra et al. 2014). It is noteworthy that even in the NEB region in the 21st century, most forest fires from human activities were from setting fire to clear land for pastures, open farmland, and sugarcane harvesting. Most of the latter harvest in the region is done manually, burning the straw of the cane to make the job easier.

The composition of homogeneous group 2 (north and central west) was largely determined by similar climatic conditions between regions, long dry seasons, or drought periods with high air temperatures and lower humidity, especially in the west central region. In these regions, there are seasonal fires associated with meteorological conditions, especially in late winter and early spring (central west) and the dry season (north). However, a significant increase in agriculture there in recent decades produced variations of vegetation cover and consequently increased areas of fire and variability of meteorological systems active in both regions; for example, the behavior of BH, SACZ, and FS and ultimately the maintenance of Equatorial Continental (cE) and Continental Tropical (cT) air masses during winter in parts of Brazil (Marengo and Hasternrath 1993; Marengo et al. 2001). During recent years, there has been a clear increase in fire events in the Amazon rainforest and Cerrado region, especially as a result of the increasing human activities. The construction of new roads was also associated with the fire increase. Human activity may be the main factor, but certain types of biomes are more susceptible to fires, because of their climate, topography, and vegetation. For example, certain arboreal species have greater resistance to fire, which is the case of the Cerrado. Therefore, the factors that influence the increase in forest fires in homogeneous group 2 were human activities and the variability of meteorological systems.

Compared with homogeneous group 2, homogeneous group 3 (southeast and south) had greater variability of meteorological systems. This was especially true in the southeast, owing to its topography, geographic location, and meteorological systems that directly or indirectly impact climatological rainfall. These systems include the SACZ, FS, and MCC, the main rain-producing systems, and the SASA, UTCV, and AB (Zeri et al. 2011) that, depending on their locations, cause long periods of drought (Minuzzi et al. 2007). In the southern region, the distribution of annual rainfall is uniform. This is because of the passage of FS, which are responsible for most of the rainfall there. The trajectory of these systems is related to the location and intensity of the subtropical jet in SA, followed by MCC, UTCV, and systems organized by cyclogenesis and frontogenesis (Reboita et al. 2010). The strong variability of meteorological systems in homogeneous group 3 was the main factor for the increase in fire foci relative to human activities.

The same assessment was made with the Ward method on a regional scale. Group 1 corresponds to January, February, March, April, May, June, July, and November in the southeast region, January, February, March, April, May, June, July, and December in the south, and January, February, March, April, May, October, and November in the central west; these correspond to the summer/fall and early winter sequence (Fig. 6a, b). The exception was winter in the central west (Fig. 5e). Group 1 in the north (January, February, March, April, May, August, and December) and northeast (February, March, April, May, June, and July) refer to the beginning of the dry season, transition, and end of the rainy season (Fig. 5c, d). Group 2 was limited to two consecutive months in all regions of Brazil, in the central west (June and July) and south (October and November). The exceptions were the southeast (three consecutive months: August, September, and October) and northeast (non-consecutive months: August and December). Finally, there was the third group, with 2–3 months of homogeneous fire foci in all regions of Brazil (Fig. 6). The only exception was the southeast. The south (August and September), northeast (September, October and November), north (August and September), and central west

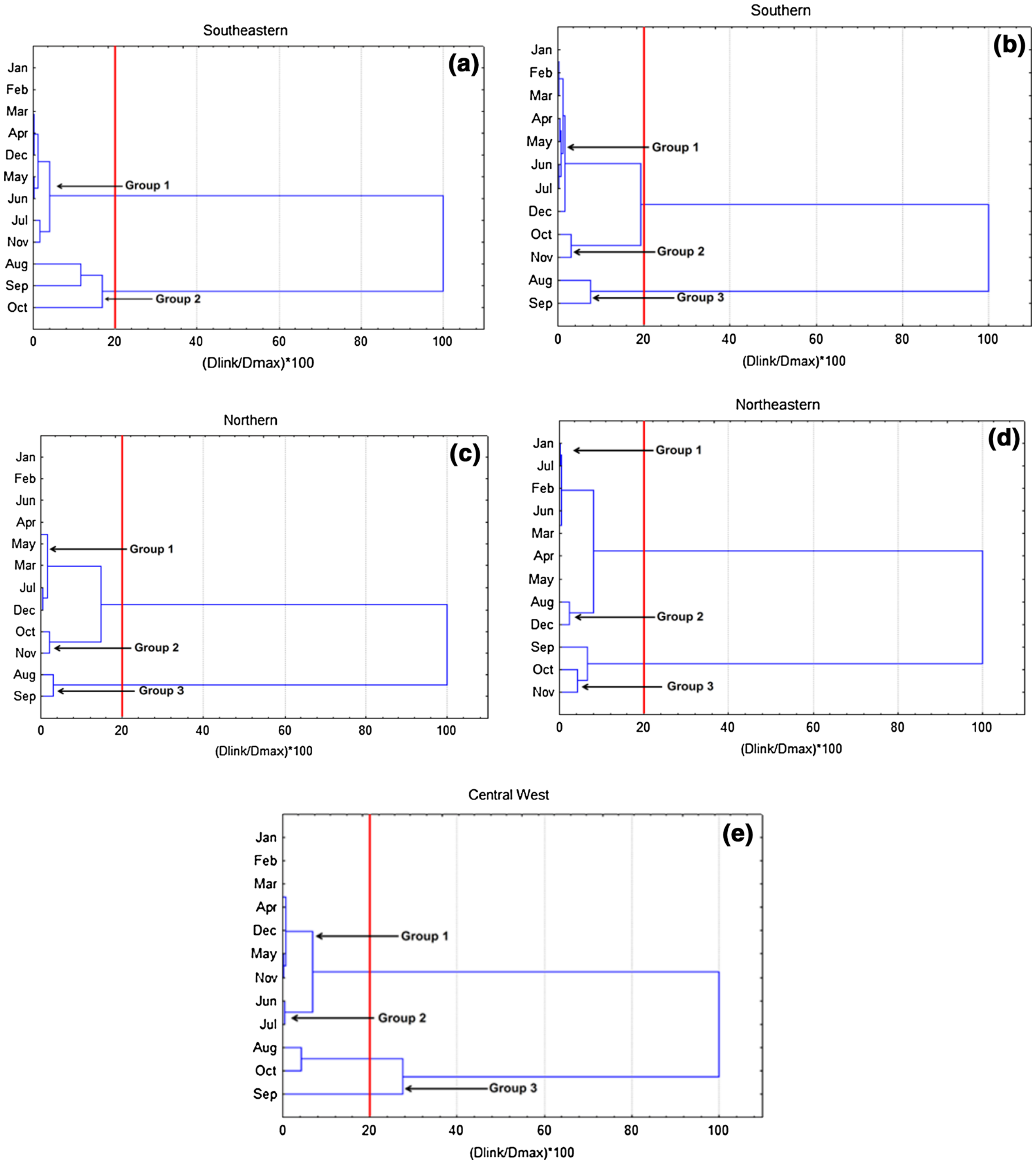

Fig. 6 Homogeneous regions of regional fire foci in Brazil over 1998–2011: **a** southeast, **b** south, **c** north, **d** northeast, **e** central west

(August, September and October) followed the pattern previously mentioned.

Three homogeneous groups of fires were identified in the North region. In the equatorial climate rainy region, virtually, no well-defined dry season and transition helped to maintain the climate regime. This is because of the action of the ITCZ, IL, FS penetration, and annual cycle of convective activity in the region (Marengo and Hasternrath 1993; Reboita et al. 2010). However, in some years, there were intense droughts upon the occurrence of ENSO events that changed the normal climate regime in the region, which occurred in 2005 (weak El Niño) and 2010 (moderate El Niño). The local rainy season is between November and March, and the dry season (without substantial convective activity) is between May and September. April and October are months of transition between regimes (Marengo and Hasternrath 1993; Marengo et al. 2001; Reboita et al. 2010), which are similar to groups identified by the clustering method.

The northeast region was similar to the north in that three homogeneous groups of fires were identified. The dry season with low rainfall is restricted to a few months and features a semiarid climate with the occurrence of severe drought (Rao et al. 1993; Reboita et al. 2010). This increases the susceptibility to fires. In general, the dry, transition, and wet seasons in the northeast are governed by ENSO, SST variation in the Atlantic Ocean, trade winds, the ITCZ, FS, and actions of the UTCV. In addition to the aforementioned mechanisms and systems, we highlight the EWD and migration of the SASA (Molion and Bernardo 2002; Gois et al. 2005; Reboita et al. 2010). There is an increased probability of fires because of the dry weather or prolonged severe droughts (northeast). This is associated mainly with criminal fires (north and northeast), especially those related to deforestation and expansion of agriculture.

Because of its latitude, the south (three homogeneous groups) has greater influence from mid-latitude systems, and FS are the main cause of rainfall during the year. FS trajectories are closely linked to the location and intensity of the SA subtropical jet. On average, inverted troughs are located over the states of Rio Grande do Sul and Santa Catarina and are more common during spring and summer of HS (Rao and Hada 1990; Reboita et al. 2010). These troughs influence the dynamics of fire foci in the south, although this region had fewer fires than other regions.

The southeast (two homogeneous groups) and central west (three homogeneous groups) regions are influenced by both tropical and mid-latitude systems and are most affected by synoptic systems that impact the southern portions of the country. There are some differences of system intensity and seasonality. Winter is dry and summer rainy in both regions (Rao and Hada 1990; Minuzzi et al. 2007; Reboita et al. 2010). The dynamics of fire foci in these regions have important differences and are strongly linked to prevailing weather conditions and human activities.

Despite the varying climate in Brazil, we assessed fire foci seasonality. Spring and winter had the highest fire frequency, with 5,394,420 foci in spring (62.2 %) and 2,487,060 in winter (28.7 %). There was less frequency in autumn with 238,116 (2.7 %) and summer with 553,663 (6.7 %) (Fig. 7a). Box plots showed that the highest frequencies in the country were in August, September, and October (Fig. 7b). These months correspond to late winter and early spring in some regions (south, southeast, and central west).

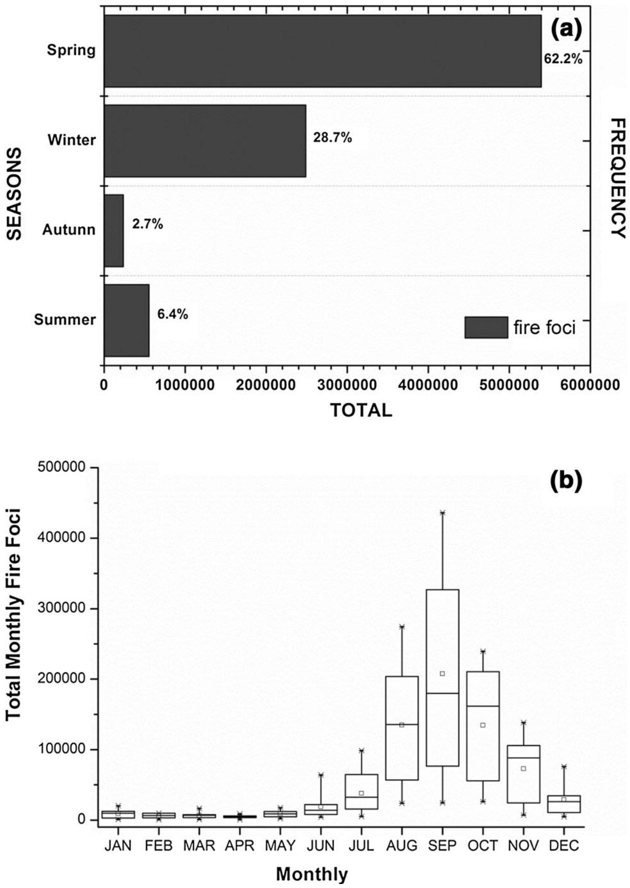

Fig. 7 Seasonal frequency (%) (**a**) and monthly box plot (**b**) of fire foci in Brazil over 1998–2011

The frequency and distribution of fires in Brazil are strongly associated with weather conditions. These conditions and hotspot detection by satellites are important tools in monitoring and provide information on fires at a regional scale. Spatial dynamics are conditioned by biomes, use and occupation of land, agricultural practices, deforestation, and public policies, among others.

Conclusions

The present analysis of annual fire foci in Brazil using meteorological satellites reveals considerable annual variability. This variability is attributable to anthropogenic activities, followed by meteorological system producers and inhibitors of rainfall.

The central west region had the most fires in the country, and the south the least. Areas of highest fire frequencies were the arc of sustainable deforestation (Mato Grosso, Pará, Rondônia, and Tocantins) and Maranhão and Bahia, with the lowest frequencies in Rio Grande do Norte, Rio de Janeiro, Espírito Santo, Sergipe, and the Distrito Federal (Federal Capital).

Regions with the highest densities of fire foci per unit area were the northeast, central west, and north, and the lowest densities were in the north, southeast, and south. States with the highest densities were Maranhão, Mato Grosso, Rondônia, Tocantins, Piauí, and Ceará. Lowest densities were in Roraima, Rio de Janeiro, Santa Catarina, Espírito Santo, Amapá, Amazonas, and Rio Grande do Sul. Comparison of total fire foci with the densities allowed quantification of the actual impacts of fire foci during the study period relative to the land area of each state and region.

There were three groups of homogeneous fire regions (1—northeast; 2—north and central west; and 3—southeast and south) identified by cluster analysis, and the northeast was unique. Grouping of these regions was determined primarily by the behavior and seasonality of meteorological systems and human activities (agriculture and livestock) there.

Spring and winter had the highest fire frequencies in Brazil, and autumn and summer had the lowest. The meteorological satellite data were effective in evaluating the fires, although some data were not defined as fires. In addition to the NOAA-12, the MMODIS-01D and T-AQUA satellites can be used for monitoring fires in Brazil. NOAA-12 data are already used as a reference for monitoring of fire foci in the country.

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