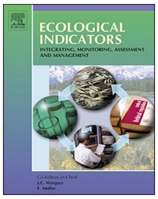
Ecological Indicators 115 (2020) 106340

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Influence of fire foci on forest cover in the Atlantic Forest in Rio de Janeiro, Brazil

W.K. Freitas[a,*], G. Gois[a], E.R. Pereira Jr[b], J.F. Oliveira Junior[c,d], L.M.S. Magalhães[e], F.C. Brasil[a], B.S. Sobral[b]

[a] DSc., Postgraduate Program in Environmental Technology – PGTA, Fluminense Federal University – UFF, Volta Redonda, Rio de Janeiro 27.255-125, Brazil
[b] Analyst of Land and Cartography Institute of Rio de Janeiro State – ITERJ, Rio de Janeiro CEP 20 060-060, Brazil
[c] DSc., Institute of Atmospheric Sciences, ICAT, Alagoas Fluminense Federal University – UFAL, Maceió, Alagoas CEP 57.072-900, Brazil
[d] DSc., Postgraduate Program in Biossystems Engineering – PGEB, Fluminense Federal University – UFF, Niterói, Rio de Janeiro CEP 24.210-240, Brazil
[e] DSc. Postgraduate Program in Sustainable Development Practices – PPGPDS, Rural Federal University of Rio de Janeiro – UFRRJ, Seropédica, Rio de Janeiro 23.851-970, Brazil

ARTICLE INFO

Keywords:
Anthropogenic processes
Vegetation index
Tropical forest
Climate change

ABSTRACT

In current times, variability and global climate change still require clarification of its effects on vegetation. The central issue in this discussion is how the distribution of fire foci can influence the vegetation cover pattern considering the spatial and temporal scales. Meteorological station data, together with Remote Sensing tools and Geographic Information Systems (GIS), produce very consistent results for monitoring the factors associated with the atmosphere – vegetation relationship. The present article aims to evaluate the relationship between occurrence of the fire foci and the Enhanced Vegetation Index (EVI) in the state of Rio de Janeiro (SRJ), during the period from January 2000 to December 2015. EVIs were obtained through analysis of the sensor images Moderate Resolution Imaging Spectroradiometer (MODIS), with spatial (250 m) and temporal (16 days) resolutions, during 15 years, taking into consideration the different forest typologies of the biome in Atlantic forest as well as the SRJ administrative divisions. After the organization of the time series of fire foci, the Kernel density (20 km) was calculated for each month, to design the circular neighborhood around the fire foci. Afterward, the EVIs were obtained through analysis of the images of the sensors mentioned above, considering the same temporal and spatial scales. The present study revealed the occurrence of more than 10,000 fire foci in SRJ. According to the Pettit test, the years 2000, 2013, 2014 and 2015 recorded the highest frequency of occurrences. The North and Metropolitan regions of SRJ had a higher frequency of the fire foci, especially in the Ombrophylous Dense Forest and Pioneer Formations. However, Ombrophylous Forests, Seasonal Forest and Pioneer Formation showed an increase in forest cover from 2000 to 2013. In light of observed relationships between fire foci and EVI, the convergence of approaches to fire foci and EVI can be an effective tool for planning and management of natural resources in the Atlantic Forest.

1. Introduction

Along Earth́s geological trajectory processes of heating and cooling have maintained several climatic cycles (Dickson, 2017). However, activities established by the human species may have modified global climate according to authors defending the emergence of a new geological period (Joly, 2007; Intergovernmental Panel on Climate Change – IPCC, 2014; Corlett, 2015; Zalasiewicz et al., 2017). Tropical forests play several ecosystemic roles such as regulation of temperature and climatic processes (Constanza et al., 1997; IPCC, 2001; Caúla et al., 2015). In Brazil, the Atlantic Forest and its associated ecosystems (Ombrophylous and Seasonal forests, High Altitude Grassland, resting areas, and fragments of mangrove forests) account for 12% of the forest remnants in an extremely fragmented landscape distributed in 17 states, where most are smaller than 50 ha and home to about 70% of the Brazilian population (Santana et al. 2015; Scarano and Ceotto, 2015; Bergamin et al., 2017; Marques et al., 2016). This region is responsible for about 70% of the Gross Domestic Product (GDP) and about 60% of the industrial Brazilian economy (Martinelli et al., 2013). While natural landscapes in this biome have been substantially replaced by land use and occupation, mainly agriculture and urbanization, it remains one the most important biodiversity hotspots in the world (Mittermeier et al.,

---

[*] Corresponding author.
E-mail address: wkfreitas@gmail.com (W.K. Freitas).

https://doi.org/10.1016/j.ecolind.2020.106340
Received 19 November 2018; Received in revised form 7 January 2020; Accepted 21 March 2020

2011; Laschefski et al., 2012; Martinelli et al., 2013; Scarano and Ceotto, 2015; Fundação SOS Mata, 2018, 2019).

Vegetation highly correlates with atmospheric processes that influence water vapor (H_2O) level, radiation balance, surface energy balance (SEB), and biogenic and greenhouse gas (GHG) emissions (IPCC, 2012; Artaxo et al., 2014; Hurteau et al., 2014; Sun et al., 2018; Yuan et al., 2018). Global warming increases the frequency with which extreme climatic events occur, such as physical (floods, droughts, and wildfires), biological (physiological and behavioral patterns of species), ecological (bio-invasions, extirpations, and extinction), and socioeconomic negative impacts, especially for the most vulnerable populations (epidemics, reduction in food supply, and others) (Saxe et al., 2001; IPCC, 2012; De Keersmaecker et al., 2015; Tozato et al., 2015; Wu et al., 2015; Scarano and Ceotto, 2015). Canhos et al. (2008) and Gobbo et al. (2016) emphasize that variability and change in the current global climate still raises unanswered questions. Artaxo et al. (2014) highlight the importance of using innovative geotechnologies, such as orbital sensors in environmental satellites, to assess the impact of climate change, at the regional and global scale.

Currently, weather station data is used alongside products acquired from Remote Sensing (RS) techniques (satellites, SODAR, LIDAR, and radar), which are stored and viewed by Geographic Information Systems (GIS) (Sahana and Sajjad, 2019). The combined use of these RS techniques is proper for biosphere monitoring (White and White, 2016). GIS tools have been successfully used to geographically represent climate and fire foci data and are still considered simple, low cost and efficient techniques (Oliveira et al., 2015; Gobbo et al., 2016; White and White, 2016; Clemente et al., 2017a).

Detection of fire foci can be used to interpret information that is recorded at the earth's surface by remote space sensors, which can be used to evaluate multiple phenomena that occur on the earth's surface such as wildfires (Williams et al., 2001; Anderson et al., 2005; Tomzhinski et al., 2011; Caúla et al., 2016; Soares et al., 2016; Oliveira-Júnior et al., 2017). However, not all fire foci are related to the occurrence of a fire, and some can be identified during charcoal production, industry operation, and other sources of heat (Clemente et al., 2017a).

The Enhanced Vegetation Index (EVI) is a product generated by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, and part of the TERRA and AQUA orbital platforms that were launched by the National Aerospace Agency (NASA) and is obtained through measuring the reflectance in the spectral bands of red and the near-infrared electromagnetic spectrum, mainly because the sensor is more sensitive to the green vegetation signal (Anderson et al., 2005; Formigoni et al., 2011). According to these authors, the EVI can provide effective results to monitor vegetation cover and the effects of seasonality on the vegetal component, and also to detect fire foci. Much is discussed about vegetation behavior related to changes in climate, and vice versa, including projections that reveal shrinking forest cover in South America (Scholze et al., 2006; Cook and Vizy, 2008; Franklin et al., 2016). However, the central issue in this discussion is how in recent years, fire foci can influence the vegetation cover pattern of the Atlantic Forest in a densely populated region with a high degree of urbanization such as the state of Rio de Janeiro, which according to Santana et al. (2015) and Instituto Brasileiro de Geografia e Estatística – IBGE (2018), holds approximately 18% of the original biome and a population of 17 million inhabitants.

Therefore, the main objective of this work is the spatial and temporal evaluation of fire foci and EVI using data acquired from the MODIS sensor to interpret forest cover variation in the state of Rio de Janeiro (SRJ), considering the period of January 2000 to December 2015.

2. Data and methods

2.1. Study area

The SRJ has a total area of 43,782 km^2, a population density of 378 inhabitants km^{-2}, and an urbanization rate of 97.3% (Instituto

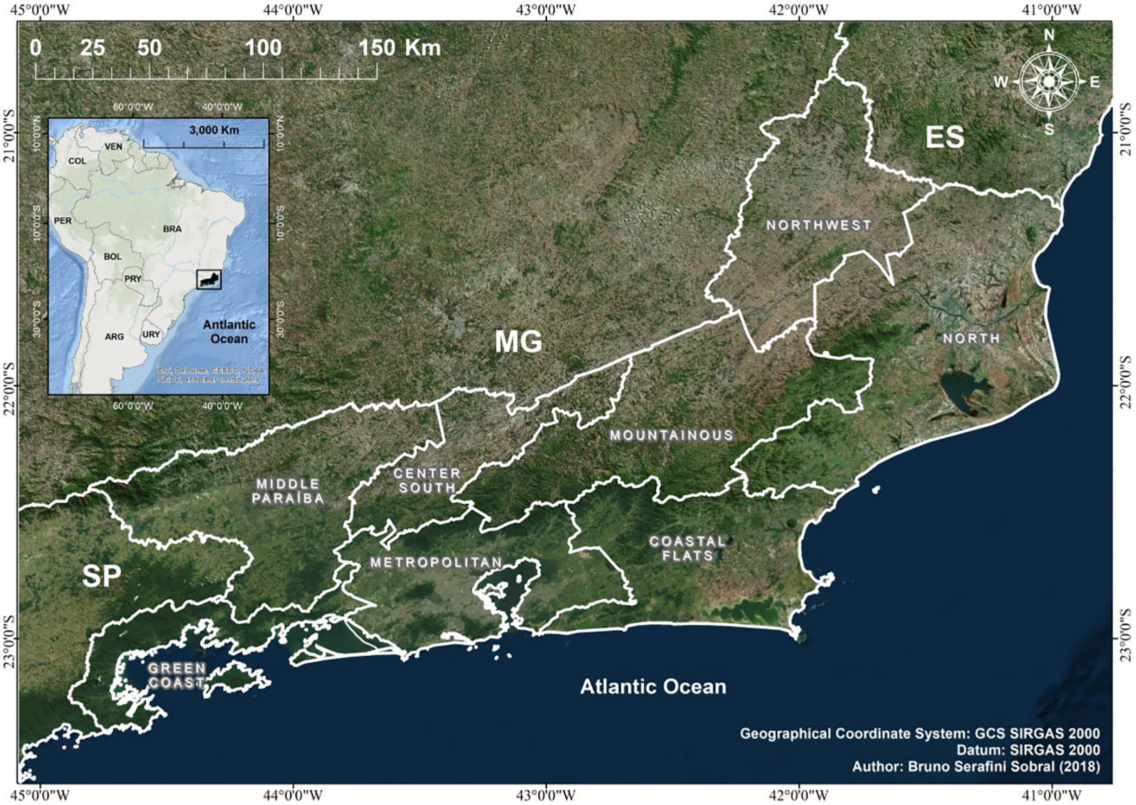


Fig. 1. Administrative regions in the SRJ, Brazil.

Brasileiro de Geografia e Estatística – IBGE, 2018). It is located in the Southeast region of Brazil, between latitudes 20°45′54″ and 23°21′57″S and longitudes 40°57′59″ and 44°53′18″W, and it is divided geopolitically into 92 municipalities and eight Administrative Regions (Green Coast, Middle Paraiba, Center South, Metropolitan, Coastal Flats, Mountainous, North and Northwest) – (Clemente et al., 2017a) (Fig. 1).

The physiography of the state is characterized by a mountainous topography with steep slopes and isolated inselbergs, a diverse coastal morphology with cliffs, bays, coves, and estuaries, and a mosaic of land cover types. The Serra do Mar ridge crosses the state from Northeast (NE) to South-west (SW) and reaches altitudes above 2300 m (Nehren et al., 2013).

The state has diverse climatic characteristic because of its geographical position, which favors dynamic processes in the atmosphere. Meteorological systems range from local to mesoscale and large scale. The Southern Atlantic Convergence Zone (SACZ), Frontal Systems (FS), South Atlantic Subtropical Anticyclone (SASA), and the High-Level Cyclonic Vortex (HLCV) all interfere with the rainfall regime and in air temperature distribution, being SACZ and HLCV the major influences during drought periods in the Southeastern region of Brazil (Brito et al., 2017; Clemente et al., 2017a; Sobral et al., 2019).

The entire state is located in the Atlantic Forest biome, and its remnants now occupy < 20% of the statés area, including the following associated ecosystems: forest (Ombrophylous and Seasonal) (Fig. 2) pioneering formations, and ecotones.

Ombrophylous Forest refers to a forest typology composed predominantly of perennial trees, which are subjected to dry periods of up to 60 days. Seasonal forests occur under a climate with well-defined seasons, with dry periods between 90 and 120 days, leading to the loss of 20–50% of the leaves in the forest complex. While the Pioneer Formations occur in coastal areas, formed on sandy quaternary deposits of marine origin, subject to abiotic adversities (high temperatures, periods of drought, constant wind, high salinity, and nutrient shortage), that make their structure and organic functions different from any other environments (Garbin et al., 2017).

2.2. Data collection

Different orbital sensors are used to detect fire foci, according to the Center for Weather Forecasting and Climate Studies (CPTEC) of the Brazilian National Institute for Space Research (INPE). The platforms of the Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor TERRA/AQUA present orbital polarization, an image angle of approximately 55°, altitude of 700 km, and an image band of 2330 km. For Brazil, the TERRA (MOD) satellite platform overlaps the Ecuador border at 22:30 and 10:30 local time (LT), in the N–S direction and in a descending orbit. The AQUA satellite platform (MYD) overlaps the Ecuador border at 13:30 and 1:30 LT, in the S–N direction and in ascending orbit. These satellites travel and register the surface image of the planet Earth every 1–2 days, acquiring data in 36 spectral bands with a spatial resolution of 1 km, covering the spectrum of 0.4 to 14.4 μm with spatial resolutions of 250 m (2 bands), 500 m (5 bands), and 1 km (29 bands) (Caúla et al., 2016).

Fire foci data were obtained from the Queimadas database (BDQueimadas), which was made available by CPTEC/INPE at http://www.dpi.inpe.br/proarco/bdqueimadas/. Images generated by the MODIS sensor (product MOD13Q1, collection 5.0), with spatial (250 m) and temporal (16 days) resolutions, collected during 15 years (February 2000–December 2015) (Centro de Previsão do Tempo e Estudos Climáticos – CPTEC, 2018) were used.

After organizing the downloaded fire foci time series, the Kernel density method (Chen et al., 2015; Clemente et al., 2017a) was applied using the Spatial Analyst Tools of ArcGIS software version 10.2, which projects a circular neighborhood around each fire focus (20 km) for each month during the studied period (Environmental System Research Institute Inc. – ESRI, 2018).

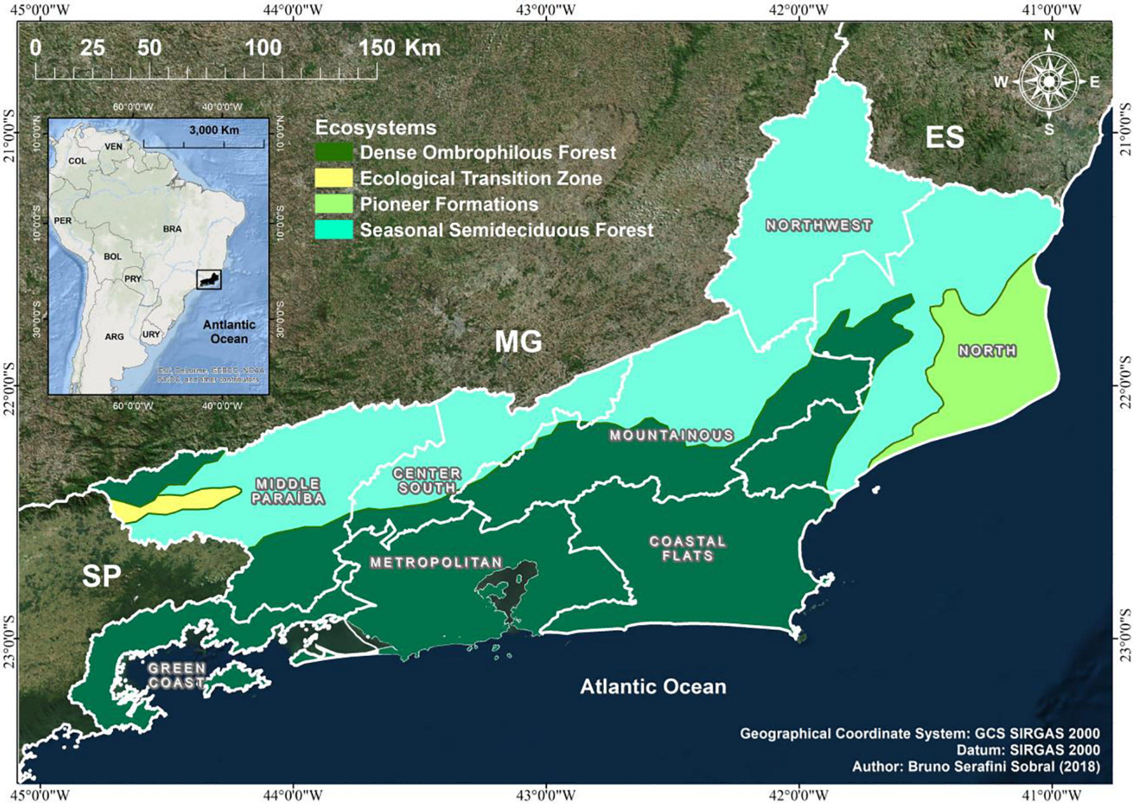


Fig. 2. Phytophysiognomies of the Atlantic Forest within the SRJ, Brazil.

The EVI was obtained by analyzing MODIS sensor images, which are available at https://lpdaac.usgs.gov/. For each EVI image, images with "Pixel Reliability" are also generated and they provide information about the radiometric quality of the images, where each pixel can be classified into five categories: −1 (no data); 0 (reliable, unrestricted data); 1 (marginal data, with restrictions); 2 (snow/ice); and 3 (cloud) (Johann et al., 2012). The EVI/MODIS and "Pixel Reliability" images form a mosaic and are distributed in the range of −2000 to 10,000, by multiplying the integers by 10,000. For this work, a database of MODIS products from the *Empresa Brasileira de Pesquisa Agropecuária* (EMBRAPA) was created (EMBRAPA, 2018).

2.3. Statistical analysis

Pettitt's test (1979) was applied to the SRJ fire foci time series (2000–2015) and sought to identify years of significant abrupt changes. The years in which significant changes occurred in the time series were selected considering the distributions: monthly (a), annual (b) and seasonal (c).

The Kruskal-Wallis test was applied to assess vegetation cover (EVI) (Zar, 1999), and boxplot representations were used for the years when changes in fire foci were often repeated, verifying the existence of a difference between mean EVI value and the number of fire foci ($p < 0.05$). All statistics were generated using the R software environment version 3.4.2 (R Core and Team, 2018).

3. Results

Fire foci data registered within the SRJ included 10,548 fire foci. The results of the Pettit test indicated that the years 2000, 2013, 2014 and 2015 presented spatial differences in the occurrence of fire foci in the ERJ. For the year 2000, no map was generated due to the lack of consistency in the data that resulted from the TERRA satellite initial operations in January of that year, which left a gap for that month. Additionally, no map was generated for the year 2014, because in that year the same amount of fire foci as 2015 was recorded (Table 1).

Figs. 3 and 4 show the geospatial representation of the quantity of fire foci per unit area (km^2), for the years 2013 and 2015. Kernel's density revealed that the highest (high/medium) concentrations of fire foci were mainly observed for the Northern and Metropolitan regions of the SRJ (Figs. 2 and 3). It is also worth noting the core of fire foci formed in the Coastal Flats region in the years of 2013 and 2015. Contrariwise, the Mountainous and Green Coast regions recorded the lowest values (Fig. 4). Fire foci in the SRJ show high variability in focus density, and such variability occurred along the coast in both years. Additionally, this variability in the density of fire foci takes place windward of the Serra do Mar ridge (Fig. 4), especially in the dense Ombrophylous Forest and Pioneer Formations, as presented in Fig. 2.

Table 1
Time series (2000–2015) of number of fire foci according to the Pettitt test results for the SRJ.

Time series (2000–2015)	Pettitt test (p value)	Number of abrupt changes of fire foci in SRJ
2000	0.00508	**16***
2001	0.05020	4
2002	1.24000	3
2003	0.00131	4
2004	0.00017	2
2005	0.20300	4
2006	0.00872	3
2007	0.00000	0
2008	0.00082	4
2009	1.37000	5
2010	0.02970	2
2011	0.10200	4
2012	0.0000003	1
2013	0.34100	**11***
2014	1.76000	**8***
2015	0.09490	**8***

*Years with more repetition.

Based on the Kernel density, 2015 registered expressive number of fire foci in the SRJ, with 13%, 37%, and 50%, observed for the high, medium, and low classes, respectively. In the same period, its effects practically tripled (13%) over the statés territory (Table 2). These fire foci were registered during a very dry season (2013/2014) in the Southeast region of Brazil, followed by the occurrence of a very strong El Niño event in 2015.

The inter-annual analysis of the average EVI for the SRJ showed a significant difference in the quantity of fire foci (2013 and 2015), according to the Kruskal-Wallis test ($p < 0.05$). Also according to the Kruskal-Wallis test ($p < 0.05$), the occurrence of fire foci peaked at years 2013 and 2015, with 2013 presenting the highest values of EVI (Fig. 5b). Seasonally drier months (July and August) ($p < 0.05$) recorded significant decreases in their average EVI values (Fig. 5a), while the rainy season (spring and summer) ($p < 0.05$) presented a significant increase in the average EVI values, with an emphasis on the months of February, March, and December. In the seasonal EVI evaluation (Fig. 5c) for the SRJ, there was variability between the seasons, highlighting a significant decrease in spring (< 4000) and, thus, the EVI was more sensitive to variations in this season.

The ecosystems in the Ombrophylous Forest, Seasonal Forest, and Pioneer Formations (Fig. 2) presented an increase in forest cover from 2000 to 2013 for all administrative regions of the state, and a decrease in the period from 2013 to 2015 (Fig. 6b).

Figs. 7 and 8 present the average annual EVI values for the Atlantic Forest ecosystems (a) and different administrative regions of the SRJ (b) in the year of 2015. During this year the greatest record of fire foci was observed in the Ombrophylous Forest (Fig. 7), with greater emphasis on the Metropolitan and Coastal Flats regions (Fig. 8).

4. Discussion

4.1. Fire foci in the SRJ at a local scale

The results of this study corroborate with Fernandes et al. (2011), Caúla et al. (2016) and Clemente et al. (2017a), which indicate that the Metropolitan and Northern regions of SRJ are areas with greater number of fire foci, possibly due to the combined action of interannual climatic variations, anthropic actions and the evolution of orbital sensors. However, not all fire foci represent a fire event (burning or forest fire), and some of these sources may be associated with activities related to biomass burning (e.g. coal, fossil fuels), industrial activities, among others (Van der Werf et al., 2010; Caúla et al., 2016; Clemente et al., 2017a).

In the North of SRJ, industrial activities represent 64.4% of the region's economy (Medeiros Junior, 2013). The petroleum exploration and sugar cane cultivation (with fields burning before harvest), in areas with a high incidence of solar radiation and significant water deficit, may explain the increase in fire foci (Figs. 2 and 5) in this region (Fernandes et al., 2011).

The Metropolitan region of SRJ has been undergoing an intense urbanization process over the last decades, with an economy based on services and industry (Medeiros Junior, 2013). This scenario may be directly related to the formation and intensification of the "urban heat island" (UHI) phenomenon (Lucena et al., 2012), resulting mainly from the burning of fossil fuels (Ribeiro et al., 2009).

A high occurrence of fire foci in the Coastal Flats was also observed, especially in 2015. This region is composed of marine-level sandy plain ecosystems, dune fields, and beaches, as well as extensive pastures and exposed soil areas, which influence the albedo values of the surface and atmospheric temperature, which probably contributes to the increase in radiation absorption (Machado et al., 2014) (Figs. 3 and 4).

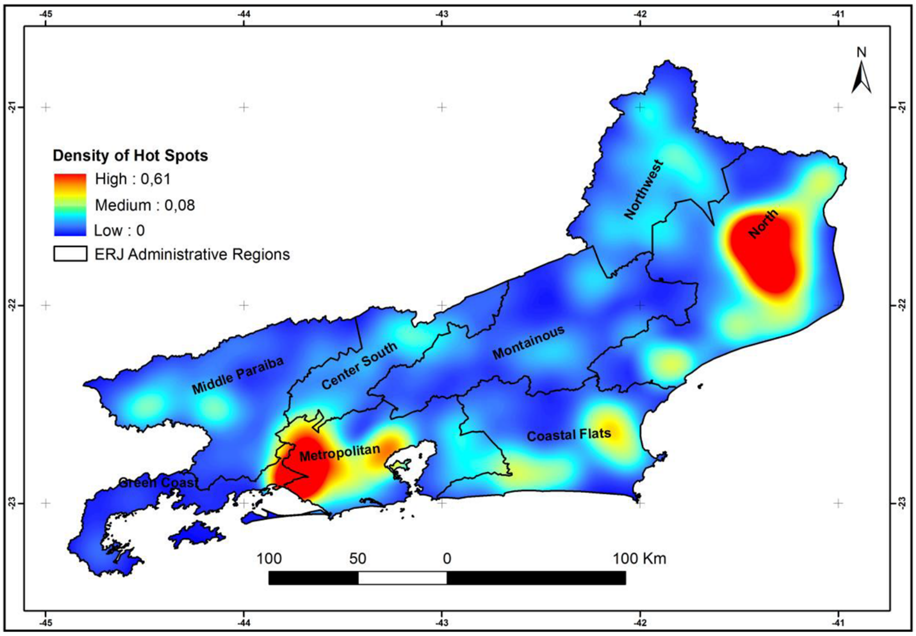


Fig. 3. Fire foci density (km^2) calculated for the year 2013 considering classes High, Medium and Low.

The Middle Paraíba region presented moderate amounts of fire foci, although the region concentrates industrial and agricultural activities, as well as the intensification of road traffic along the Presidente Dutra Federal Highway (BR-116), an important connection axis between the two largest urban centers of the country (São Paulo e Rio de Janeiro) (Caúla et al., 2016; Clemente et al., 2017b) (Figs. 3 and 4).

On the other hand, the Mountainous and Green Coast regions recorded the lowest number of fire foci, since both are one of the three priority areas for biodiversity conservation in the Atlantic Forest, the *Serra do Mar* Corridor, home to more than 70% of extinction endangered species of this biome (Pinto et al., 2006). Likewise, the Northwest region presented low relevance for the production of fire

Table 2
Total Areas (Km^2) and quantities (unities) of fire foci divided by classes (High, Medium and Low) in the SRJ, Brazilian the years of 2013 and 2015, respectively.

Classes	2013		2015		Total
	Area (Km^2)	Quantity (count)	Area (Km^2)	Quantity (count)	
High	1.889	931	5.528	3.562	**11.910**
Medium	9.027	1.461	16.148	2.473	**29.109**
Low	32.841	1.349	22.082	772	**57.044**
Total	**43.757**	**3.741**	**43.758**	**6.807**	**98.063**

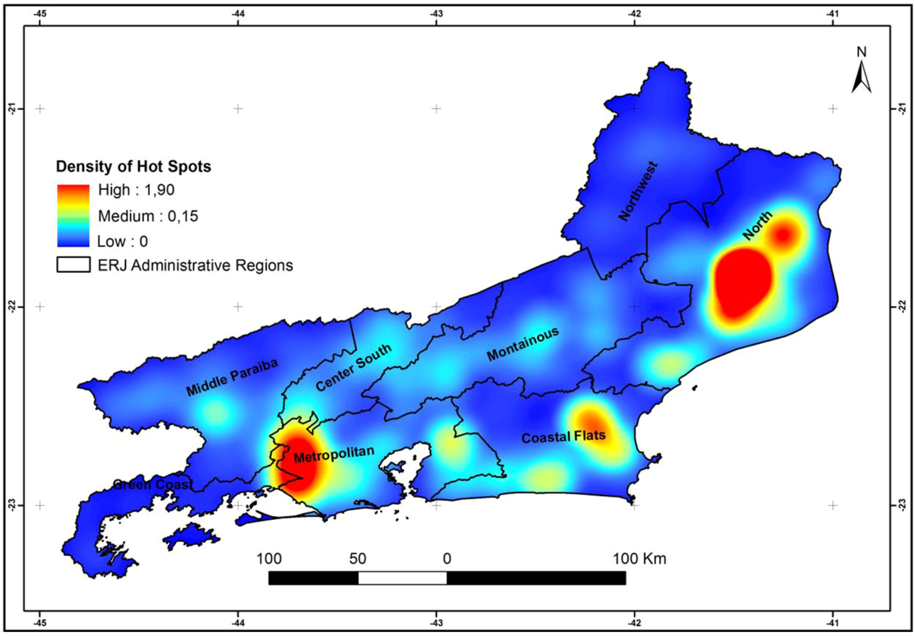


Fig. 4. Fire foci density (km^2) calculated for the year 2015 considering classes High, Medium and Low.

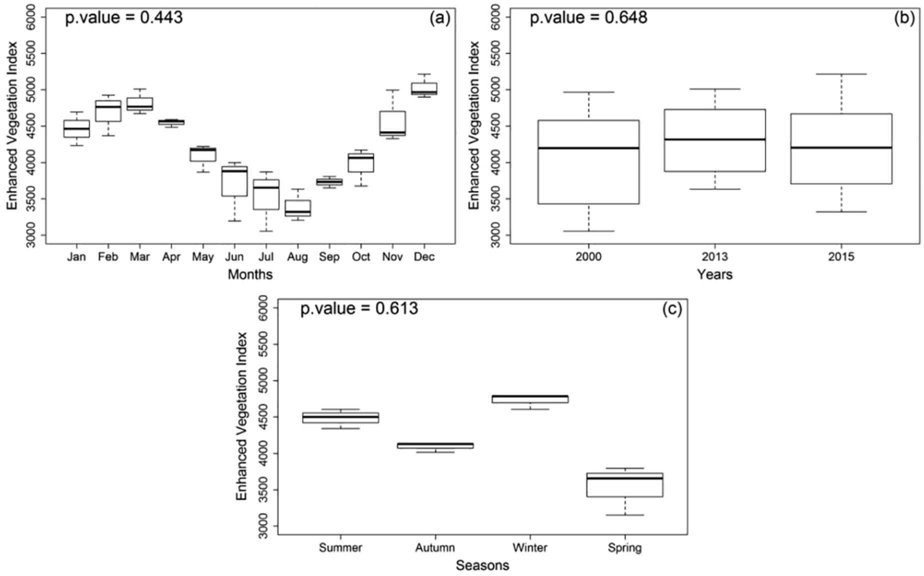


Fig. 5. Boxplot of the average EVI values for the monthly (a), annual (b) and seasonal (c) scales based on the Kruskal-Wallis test ($p < 0.05$) for the SRJ, Brazil.

foci, especially in 2015, which is possibly associated with low economical activities in that region of the state (Medeiros Junior, 2013) (Figs. 3 and 4).

4.2. EVI evaluation for the SRJ

The evaluation of fire foci is of great importance to the conservation of natural resources, whether on a local, regional, or global scale because they represent changes in the thermal pattern that can negatively affect the environment, society, and the economy (Graczyk et al., 2017). Besides, geoprocessing tools have become essential to monitor fire foci, conserve ecosystems in tropical forests, and prevent forest fires (Toomey et al., 2011; Soares et al., 2016).

Comparatively, 2015 registered the increase of more than 50% the number of fire foci compared to 2013 (Figs. 3, 4 and 5a). The period from 2013 to 2014 registered low precipitation in the Southeast region of Brazil, while in 2015, a very strong El Niño event that reached up to 2.6 in the Oceanic Niño Index (ONI) scale, may have influenced temperature, air humidity, and rainfall, besides the activity of sources of carbon sinks (oceans and vegetation) (IPCC, 2007; Frank et al., 2015; Braga and Molion 2018; Sobral et al., 2019).

In spring, the interquartile range of EVI was remarkable throughout the time series, especially concerning the 1st quartile, with greater variation of EVI. It is noteworthy that at this time of year there is high variability in rainfall records due to the performance of meteorological systems in multi-scale rain producers (Brito et al., 2017). Regarding symmetry, only the summer season stood out from the others, as it demonstrated that the EVI in the SRJ was symmetrical in the studied period, unlike the other stations with asymmetric distribution. This symmetry in summer is due to the strong relationship of dependence between vegetation vigor and rainfall regime in the SRJ (Gois et al., 2016; Costa et al., 2017). Comparatively, the monthly and seasonal EVI scales in the SRJ were highly variable during the study period, except for the annual scale (Fig. 5a–c).

Even in the most optimistic carbon emissions scenarios, probably by the year 2100, the planet's average temperature will increase by at least 2 °C (IPCC, 2014). Wu et al. (2015) point out that, for the eastern coast of South America (Atlantic Rainforest), the effects of radiation will be the first perceived impact with climate change. South American forest ecosystems are more vulnerable to climate change than other ecosystems because drastic changes in climate patterns can accelerate the loss of ecosystem resilience, leading to another steady-state in the density of vegetation cover (Anjos and Toledo, 2018). Nevertheless, it is expected for the Atlantic Forest future climate changes due to global warming, but these changes will be less representative when compared to the direct effect of land-use change (Salazar et al., 2015).

In this study, the ecosystems in the Ombrophylous and Seasonal forests showed a decrease in average EVI values (Figs. 6a and 7). This may also suggest that areas best suited to warmer and drier environments may be slightly expanding into environments that are historically occupied by moist forests. However, pioneer formations and transitional forests grew in the area during the study period, suggesting an increase in the average EVI values (Figs. 6a and 7). Particularly in the dry periods (March to September), the rays of the sun have wider angles in these regions, and this contributes to increased radiation exposure and results in longer days, resulting in higher temperatures in practically the entire Southeast region of Brazil. The exceptions are high altitude areas where temperatures are milder during all seasons (Caúla et al., 2015, 2016; Clemente et al., 2017a,b).

The increase in temperature and evapotranspiration (ET) reduces the amount of water in the soil, even when rainfall does not decrease significantly, which can trigger the replacement of the current biomes by others more adapted to climate change, i.e., tropical savannahs replacing tropical forests; (Nobre et al., 2008; Scarano and Ceotto, 2015), and possibly also tropical rainforests. Some of the scenarios that are predicted as effects of climate change on tropical vegetation suggest that forests and savannas could represent alternative stable states, implying critical transitions in the stability points of these biomes (Santos et al., 2017).

4.3. Orbital products and public conservation policies applied to the Atlantic forest

The use of RS technology provides a practical and economical means for assessing the spatial variability of natural resources in large areas. Due to the high spatial resolution (Xue and Su, 2017; Xie et al., 2008) of vegetation cover (Formigoni et al., 2011) and of meteorological parameters (MODIS), which are fundamental requirements for research on global climate variability, this study used the MCD12Q1 (Caúla et al., 2016; Clemente et al., 2017a) orbital product to assess both themes. This orbital product has been the main source of information, since there is no on-site monitoring, and the fire brigade only record fires via the Fire Occurrence Report (FOR) (Oliveira-Júnior et al., 2017).

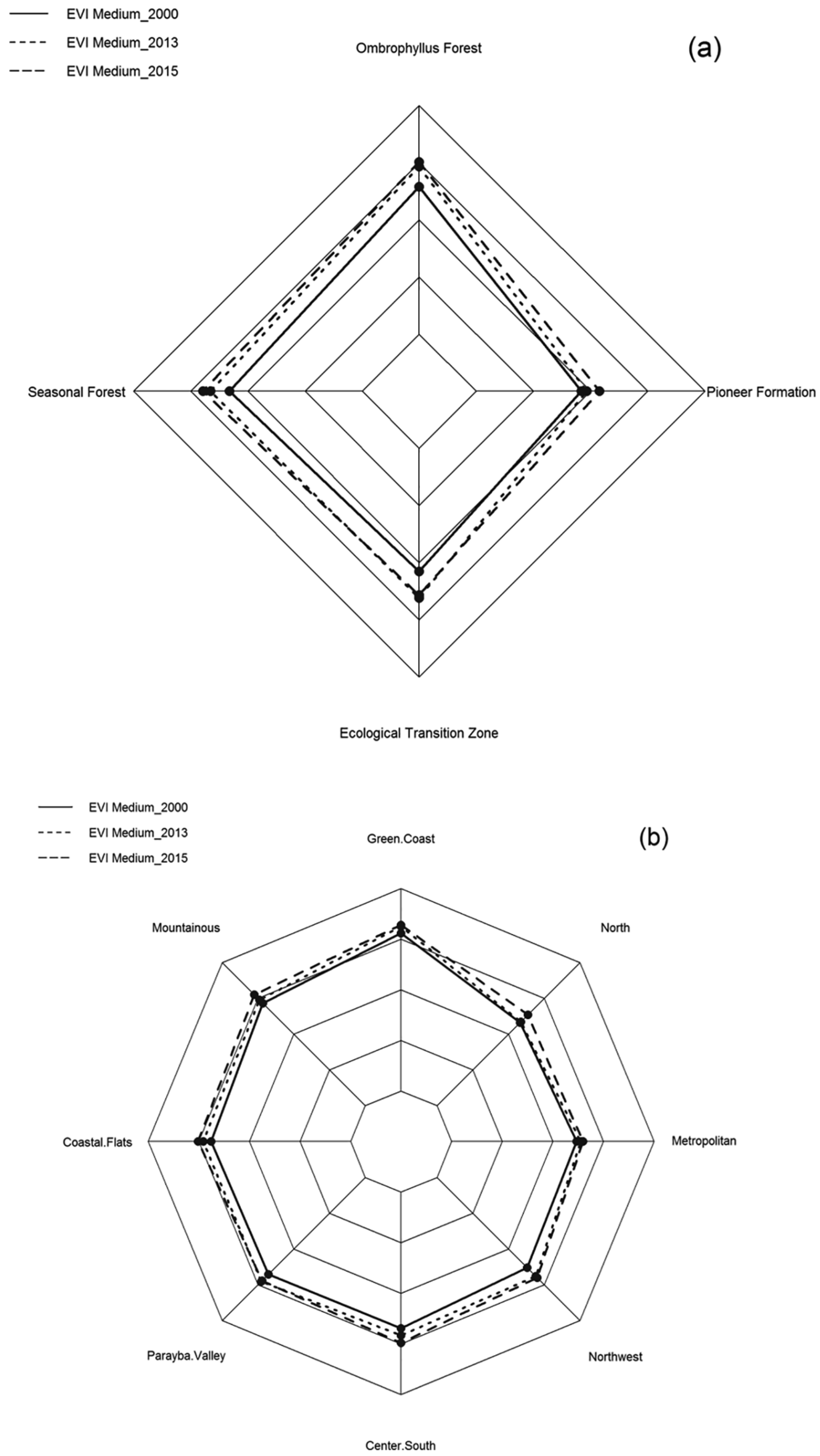


Fig. 6. Radar diagram for the average annual EVI (2000, 2013, and 2015) considering (a) Atlantic Forest physiognomies and (b) Administrative regions in the SRJ, Brazil.

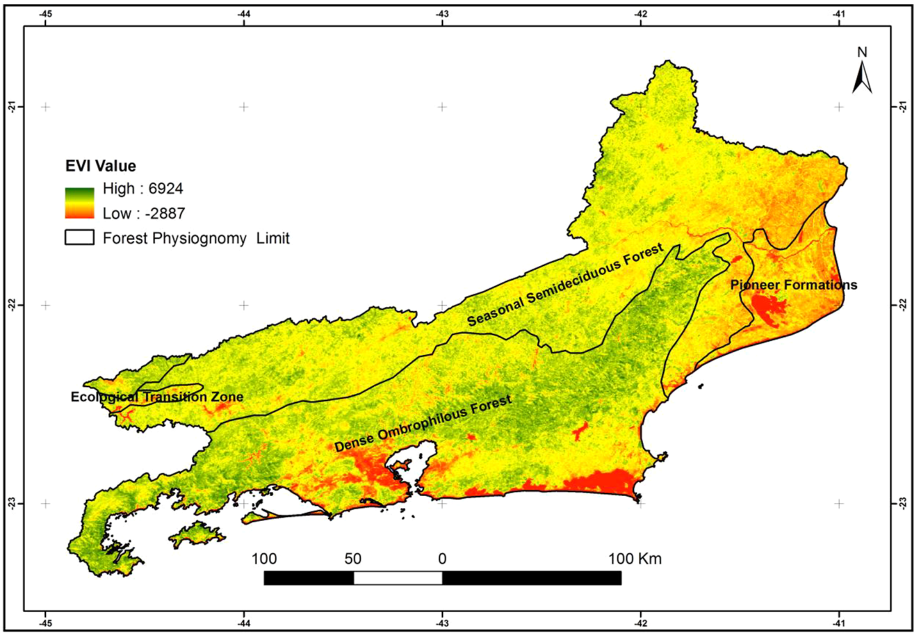


Fig. 7. Average annual EVI values for the Atlantic Forest ecosystems in the year 2015.

Another relevant issue is that the fire hazard index (FHI) monitoring does not cover the whole region, since it depends on a homogeneous and consistent series of automatic meteorological stations data, not yet available in Brazil. The main drawback is that the fire foci data is an estimate of the occurrence of burnings and forest fires from orbital sensors that perform the imaging of the terrestrial surface. In the case of the time series used in the study, AVHRR (Advanced Very High-Resolution Radiometer) and MODIS. The AVHRR performs the radiation detection to remotely determine the surface temperature, which in the case of the fire foci is Land Surface Temperature (LST) > 47 °C. This may provide non-existent data, for example, granites, water, buildings or industrial parks (Caúla et al., 2015, 2016). MODIS has low spatial resolution, especially when compared to Landsat images. However, many of the changes in forest cover occur on a 250-meter pixel compatible scale (Townshend and Justice, 1988).

There is no single vegetation spectral classification index ideal for all plant typologies. EVI and NDVI (Normalized Difference Vegetation Index) are the most commonly used indexes and may present good adjustments in most of the thematic classes (Gois et al., 2016; Silva et al., 2019). However, NDVI is more accurate for chlorophyll, whereas EVI is more effective for canopy structural variations, plant physiognomy and crown architecture (Huete et al., 2002), according to this study. Nevertheless, one of the characteristics inherent in the use of vegetation indices obtained by MODIS sensor products is the presence of noise that is caused by atmospheric interference (cloud cover) or by relatively high angles of incidence of the sensor.

However, the lack of certainty about the impact of climate change on the planet (Canhos et al., 2008; Gobbo et al., 2016), especially in ecosystems of the Atlantic Forest, represents an obstacle in assessing the vulnerability and impact of climate change and implementing

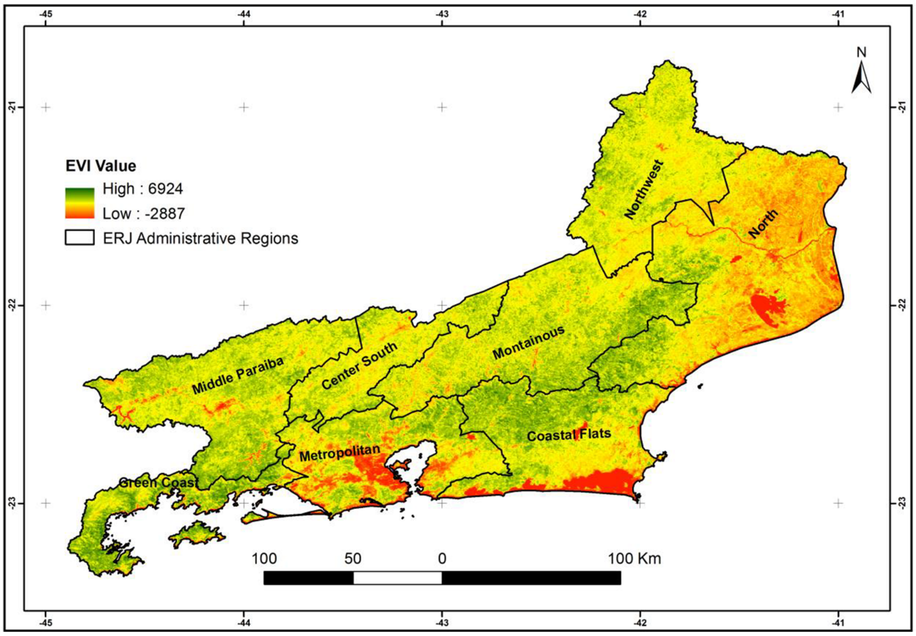


Fig. 8. Average annual EVI values for the different administrative regions in the SRJ in the year 2015.

adaptation and mitigation measures (Nobre et al., 2008; Krug, 2008). The process of forest fragmentation has created a pattern of forest remnants that are surrounded by a matrix of agricultural land, pastures, artificial forests (eucalyptus or pine) and urban areas where more than 80% of the fragments are < 50 ha (Ribeiro et al., 2009; Scarano and Ceotto, 2015). Since in intensely anthropic landscapes, forestry regeneration is not expected to lead to a forest structure that is similar to most of the conserved ecosystems, at least not without active investment in restoration and in physical (floods, droughts, fires), biological (physiological and behavioral patterns of species), ecological (bio-invasions, extirpations, and extinction), and socioeconomic systems, which especially affect the most vulnerable populations (e.g. epidemics, reduction in food supply) (D'Albertas et al., 2018).

5. Conclusion

A high variability in the density of fire foci was observed in the SRJ over 15 years, especially during the dry years of 2013–2014 followed by the Super El Niño of 2015, and the most fire foci were observed in the driest months (fall and winter). The North and Metropolitan regions of Rio de Janeiro are the main areas with an increase in fire foci density, with a corresponding reduction in the EVI index associated to the transformations that have been taking place in land use and occupation patterns. In these regions, highlights for activities associated with fire foci related to agricultural activities and urbanization processes (e.g. burning of fossil fuels). The value of the EVI suggests a transformation in the forest cover in the SRJ, especially between the more open physiognomies (Ecotones and Pioneer formations) and the more closed (Ombrophylous forest) areas. Fire foci monitoring associated with the EVI applied at different scales in the SRJ is of paramount importance to direct the application of mitigation measures against potential future losses and damage associated with the impact of climate change and can be a good tool for planning and managing natural resources in the Atlantic Forest.

Using this study, new research should be conducted to evaluate the significant changes in the structure and functioning of the ecosystems of the Atlantic Forest considering the fire foci occurrence. Therefore, the expansion of interdisciplinary studies regarding different branches of ecology (landscape, ecosystems, and communities), climatology, and geotechnology are necessary to assess the impact of global climate change in the ecosystems of the SRJ, Brazil.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The second author thanks the Coordination of Improvement of Higher Education Personnel (CAPES) for a postdoctoral fellowship during the Post-Graduation Program in Environmental Technology (PGTA) at the Universidade Federal Fluminense (UFF). We also thank the anonymous reviewers who contributed to improving the manuscript.

References

Anderson, L.O., Oliveira, L.E., Aragão, C., Lima, A., Shimabukuro, Y.E., 2005. Detecção de cicatrizes de áreas queimadas baseada no modelo linear de mistura espectral e imagens índice de vegetação utilizando dados multitemporais do sensor MODIS/TERRA no estado do Mato Grosso, Amazônia brasileira. Acta Amaz. 35, 445–456.

Anjos, L.J.S., Toledo, P.M., 2018. Measuring resilience and assessing vulnerability of terrestrial ecosystems to climate change in South America. PLOS One 19, e0194654.

Artaxo, P., Dias, M.A.F.S., Nagy, L., Luizão, F.J., Cunha, H.B., Quesada, C.A.N., Marengo, J.A., Krusche, A., 2014. Perspectivas de pesquisas na relação entre clima e o funcionamento da floresta Amazônica. Cienc. Cult. 66, 41–46 (Accessed on 22 July, 2018).

Bergamin, R.S., Bastazini, V.A.G., Vélez-Martin, E., Debastiani, V., Zanini, K.J., Loyola, R., Müller, S.C., 2017. Linking beta diversity patterns to protected areas: lessons from the Brazilian Atlantic Rainforest. Biod. Conserv. 26, 1557–1568.

Braga, H.A., Molion, L.C.B., 2018. A Seca de 2013/2014 na Região Sudeste do Brasil. Anuário do Instituto de Geociências –. UFRJ 41, 100–107.

Brito, T.T., Oliveira-Júnior, J.F., Lyra, G.B., Gois, G., Zeri, M., 2017. Multivariate analysis applied to monthly rainfall over Rio de Janeiro state, Brazil. Meteorol. Atmos. Phys. 129, 469–478.

Canhos, V.P., Siqueira, M.F., Marino, A., Canhos, D.A.L., 2008. Análise da vulnerabilidade da biodiversidade brasileira frente às mudanças climáticas globais. Parcerias Estratégicas 27, 113–148.

Caúla, R.H., Oliveira-Júnior, J.F., Lyra, G.B., Delgado, R.C., Heilbron Filho, P.F.L., 2015. Overview of Fire Foci Causes and Locations in Brazil Based on Meteorological Satellite Data from 1998 to 2011. Environ. Earth Sci. 74, 1497–1508.

Caúla, R.H., Oliveira-Júnior, J.F., Lyra, G.B., Delgado, R.C., Heilbron Filho, P.F.L., Oliveira-Júnior, J.F., Gois, G., Delgado, R.C., Pimentel, L.C.G., Teodoro, P.E., 2016. Nonparametric statistics applied to fire foci obtained by meteorological satellites and their relationship to the MCD12Q1 product in the state of Rio de Janeiro Southeast, Brazil. Land Degrad. Dev. 28, 1056–1067.

Centro de Previsão do Tempo e Estudos Climáticos – CPTEC. Monitoramento dos focos de calor. http://sigma.cptec.inpe.br/queimadas/v_antiga/index_old.php (Accessed on 15 January 2018).

Chen, K., Huang, L., Zhou, L., Ma, Z., Bi, J., Li, T., 2015. Spatial analysis of the effect of the 2010 heatwave on stroke mortality in Nanjing, China. Nature 5, 10816.

Clemente, S.S., Oliveira Júnior, J.F., Louzada, M.A.P., 2017a. Focos de Calor na Mata Atlântica do Estado do Rio de Janeiro. Rev. Bras. Meteorol. 32, 669–677.

Clemente, S.S., Oliveira Júnior, J.F., Louzada, M.A.P., 2017b. Focos de calor do bioma Mata Atlântica no estado do Rio de Janeiro: uma abordagem de gestão e legislação ambiental. Rev. Ciên. Agroamb. 15, 159–174.

Constanza, R., D'arge, R., De Groot, R.S., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., Van Den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

Cook, K.H., Vizy, E.K., 2008. Effects of 21st-century climate change on the amazon rainforest. J. Clim. 21, 542–560.

Corlett, R.T., 2015. The anthropocene concept in ecology and conservation. Trends Ecol. Evol. 30, 36–41.

Costa, W.L.B., Braga, C.C., Alcântara, C.R., Costa, A.S., 2017. Phenological dynamics of vegetation using the enhanced vegetation index (EVI) in regions of Bahia State. JHRS 7, 399–407.

D'albertas, F., Costa, K., Romitelli, I., Barbosa, J.M., Vieira, S.A., Metzger, J.P., 2018. Lack of evidence of edge age and additive edge effects on carbon stocks in a tropical forest. For. Ecol. Manag. 407, 57–65.

De Keersmaecker, D., Lhermitte, S., Tits, L., Honnay, O., Somers, B., Coppin, P., 2015. A model quantifying global vegetation resistance and resilience to short-term climate anomalies and their relationship with vegetation cover. Global Ecol. Biogeogr. 24, 539–548.

Dickson, A.J., 2017. A molybdenum-isotope perspective on Phanerozoic deoxygenation events. Nat. Geosci. 10, 721–726.

Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA. Banco de produtos MODIS. https://www.modis.cnptia.embrapa.br/geonetwork/srv/pt/main.home (Accessed on 15 January, 2018).

Environmental System Research Institute Inc. ESRI. ArcGIS desktop: Kernel Density. Available in http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/kernel-density.htm (Accessed on January 18, 2018).

Fernandes, B.C., Coura, P.H.F., Sousa, G.M., Avelar, A.S., 2011. Avaliação Geoecológica de Susceptibilidade à Ocorrência de Incêndios no Estado do Rio de Janeiro, Brasil. Floresta Ambient. 18, 299–309.

Formigoni, M.H., Xavier, A.C., Lima, J.S.S., 2011. Análise temporal da vegetação na região do Nordeste através de dados EVI do MODIS multi-temporal. Ci. Fl. 21, 1–8.

Frank, D., Reichstein, M., Bahn, M., Frank, D., Mahecha, M., Smith, P., Thonicke, K., van der Velde, M., Vicca, S., Babst, F., Beer, C., Buchmann, N., Canadell, J., Ciais, P., Cramer, W., Ibrom, A., Miglietta, F., Poulter, B., Rammig, A., Seneviratne, S., Walz, A., Wattenbach, M., Zavala, M., Zscheischler, J., 2015. Effects of climate extremes on the terrestrial carbon cycle: concepts, processes and potential future impacts. Glob. Change Biol. 8, 2861–2880.

Franklin, J.M., Serra-Diaz, J., Syphard, A.D., Regan, H.M., 2016. Global change and terrestrial plant community dynamics. PNAS 113, 3725–3734.

Fundação SOS Mata Atlântica. Regeneração de remanescentes florestais na Mata Atlântica – 1985 a 2015. https://www.sosma.org.br/105842/estudo-inedito-traca-panorama-da-regeneracao-florestal-na-mata-atlantica (Accessed on 22 May, 2018).

Fundação SOS Mata Atlântica. Atlas da Mata Atlântica. https://www.sosma.org.br/projeto/atlas-da-mata-atlantica/ (Accessed 08 February, 2019).

Garbin, M.L., Saiter, F.Z., Carrijo, T.T., Peixoto, A.L., 2017. Breve histórico e classificação da vegetação capixaba. Rodriguésia 68, 1883–1894.

Gobbo, A.D.A., Garcia, R.F., Amaral, A.A., Eugenio, F.C., Alvarez, C.R.S., Luppi, A.S.L., 2016. Uso da Terra no Entorno do PARNA-Caparaó: Preocupação com Incêndios Florestais. Floresta Ambient. 23, 350–361.

Gois, G., Delgado, R.C., Oliveira-Júnior, J.F., Teodoro, P.E., Souza, T.C.O., 2016. EVI2 Index Trend Applied to the Vegetation of The State of Rio de Janeiro Based on Non-Parametric Tests and Markov Chain. Biosci. J. 32, 1049–1058.

Graczyk, D., Pińskwar, I., Kundzewicz, Z.W., Hov, Ø., Førland, E.J., Szwed, M., Choryński, A., 2017. The heat goes on—changes in indices of hot extremes in Poland. Theor. Appl. Climatol. 129, 459–471.

Huete, A., Didan, K., Miura, T., Rodriguez, E.T., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213.

Hurteau, M.D., Bradford, J.B., Fulé, P.Z., Taylor, A.H., Martin, K.L., 2014. Climate change, fire management, and ecological services in the southwestern US. For. Ecol. Manag. 327, 280–289.

Instituto Brasileiro de Geografia e Estatística – IBGE. IBGE Cid@dades https://cidades.ibge.gov.br (accessed on 06 january, 2018). 445 Instituto Nacional de Pesquisas Espaciais – INPE. BDQueimadas. https://prodwwwqueimadas.dgi.inpe.br/bdqueimadas (Accessed on 15 January, 2018).

Intergovernmental Panel on Climate Change – IPCC. 2001. Summary for policymakers: climate change 2001: impacts, adaptation, and vulnerability. [S.l.: s.n.], 17 p. http://www.ipcc.ch/ipccreports/tar/wg2/pdf/WGII_TAR_full_report.pdf (Accessed on 12 March, 2018).

IPCC, 2007. Summary for Policymakers. In: Metz, B O.R., Davidson, P.R., Bosch, R., Meyer Dave, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Kingdom and 2007 Cambridge University Press, Cambridge, United New York, NY, USA.

IPCC, 2012. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge University Press: Cambridge, UK, and New York, NY, USA, 582 pp.

IPCC, 2014. Synthesis Report. In: Core Writing Team, Pachauri, R.K. and Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, 151 pp.

Johann, J.A., Rocha, J.V., Duft, D.G., Lamparelli, R.A.C., 2012. Estimativa de áreas com culturas de verão no Paraná, por meio de imagens multitemporais EVI/Modis. Pesq. Agropec. Bras. 47 (1295–471), 1306.

Joly, C.A., 2007. Biodiversidade e mudanças climáticas: contexto evolutivo, histórico e político. Ambient. Soc. 10, 169–172.

Krug, T., 2008. Impacto, vulnerabilidade e adaptação das florestas à mudança do clima. Parcerias Estratégicas 13, 43–72.

Laschefski, K.A., Dutra, C., Doula, S.M., 2012. A legislação ambiental como foco de conflitos: uma análise a partir das representações sociais da natureza dos pequenos agricultores em Minas Gerais, Brasil. Soc. Nat. 24, 405–418.

Lucena, A.J., Rotunno, O.C., Peres, L.F., França, J.R.A., 2012. A evolução da ilha de calor na região metropolitana do Rio de Janeiro. Revista Geonorte 2, 8–21.

Machado, C.C., Silva, B.B., De Albuquerque, M.B., Galvincio, J.D., 2014. Estimativa do balanço de energia utilizando imagens TM – Landsat 5 e o algoritmo SEBAL no litoral sul de Pernambuco. Rev. bras. meteorol. 29, 55–67.

Marques, A.A.B., Schneider, M., Peres, C.A., 2016. Human population and socioeconomic modulators of conservation performance in 788 Amazonian and Atlantic Forest reserves. PeerJ 4, e2206.

Martinelli, G., Valente, A.S.M., Maurenza, D., Kutschenko, C., Judice, D.M., Silva, D.S., Fernandez, E.P., Martins, E.M., Barros, F.S.M., Sfair, J.C., Santos Filho, L.A.F., Abreu, M.B., Moraes, M.A., Monteiro, N.P., Pietro, P.V., Fernandes, R.A., Hering, R.L.O., Messina, T., Penedo, T.S.A., 2013. Avaliação de risco de extinção de espécies da flora brasileira. In: Martinelli, G., Moraes, M.A. (Eds.), Livro vermelho da flora do Brasil. CNC Flora, Jardim Botânico do Rio de Janeiro, Rio de Janeiro, pp. 60–84.

Medeiros Junior, H., 2013. Desconcentração econômica e atratividade regional no estado do Rio de Janeiro entre 2000–2010. Cadernos do Desenvolvimento Fluminense 1, 23–52.

Mittermeier, R.A., Turner, W.R., Larsen, F.W., Brooks, T.M., Gascon, C., 2011. Global biodiversity conservation: the critical role of hotspots. In: Zachos, F.E., Habel, J.C. (Eds.), Biodiversity Hotspots. Springer, Berlin, pp. 3–22.

Nehren, U., Kirchner, A., Sattler, D., Turetta, A.P., Heinrich, J., 2013. Impact of natural climate change and historical land use on landscape development in the Atlantic Forest of Rio de Janeiro, Brazil. An. Acad. Bras. Ciênc. 85, 497–518.

Nobre, C.A., Sampaio, G., Salazar, L., 2008. Cenários de mudança climática para a América do Sul para o final do século 21. Parcerias Estratégicas 29, 19–42.

Oliveira, M.J., Baptista, G.M.M., Carneiro, C.D.R., Vecchia, F.A.S., 2015. História geológica e ciência do clima: métodos e origens do estudo dos ciclos climáticos na Terra. Terræ 12, 03–26.

Oliveira-Júnior, J.F., Sousa, G.M., Nunes, M.T.O., Fernandes, M.C., Tomzhinski, G.W., 2017. Relationship between SPI and ROI in Itatiaia National Park. Floresta Ambient. 24, e20160031.

Pettitt, A.N., 1979. A non-parametric approach to the change-point problem. Appl. Stat. 28, 126–135.

Pinto, L.P., Bedê, L., Paese, A., Fonseca, M., Paglia, A., Lamas, I., 2006. Mata Atlântica Brasileira: os Desafios para Conservação da Biodiversidade de um Hotspot Mundial. In: Rocha, C.F.D., Bergallo, H.G., Sluys, M.V., Alves, M.A.S. (Eds.), Biologia da Conservação: essências. São Carlos, RiMa, pp. 1–28.

Development Core, R., Team, 2018. Language and Environment for Statistical Computing. R Foundation for Statistical Computing. R Foundation, Vienna (Accessed on 15 May, 2018).

Ribeiro, M.C., Metzger, J.P., Martensen, A.C., Ponzoni, F.J., Hirota, M.M., 2009. The Brazilian Atlantic Forest: How much is left, and how is the remaining forest distributed? Implications for conservation. Biol. Conserv. 142, 1141–1153.

Sahana, M., Sajjad, H., 2019. Vulnerability to storm surge flood using remote sensing and GIS techniques: a study on Sundarban Biosphere Reserve. India Rem. Sens. Appl. Soc. Environ. 13, 106–120.

Salazar, L.F., Nobre, C.A., Oyama, M.D., 2015. Climate change consequences on the biome distribution in tropical South America. Glob. Planet. Change 128, 103–119.

Santana, C.A.S., Freitas, W.K., Magalhães, L.M.S., 2015. Estrutura e similaridade em florestas urbanas na região metropolitana do Rio de Janeiro. Interciência 40, 479–486.

Santos, J.F.C., Mendonça, B.A.F., Araújo, E.J.G., Andrade, C.F., 2017. Fragmentação florestal na Mata Atlântica: o caso do município de Paraíba do Sul, RJ, Brasil. R. Bras. Bioci. 15, 151–158.

Saxe, H., Cannell, M.G.R., Johnsen, Ø., Ryan, M.G., Vourtilis, G., 2001. Tree and forest functioning in response to global warming. New Phytol. 149, 369–400.

Scarano, F.R., Ceotto, P., 2015. Brazilian Atlantic forest: impact, vulnerability, and adaptation to climate change. Biodivers. Conserv. 24, 2319–2331.

Scholze, M., Knorr, W., Arnell, N.W., Prentice, I.C., 2006. A climate-change risk analysis for world ecosystems. PNAS 103, 13116–13120.

Silva, V.S., Salami, G., Silva, M.I.O., Silva, E.A., Monteiro Júnior, J.J., Alba, E., 2019. Methodological evaluation of vegetation indexes in land use and land cover (LULC) classification. Geol. Ecol. Landscapes (Accessed on 20 May, 2019).

oares, T., B. O., Resende, F.C., Gabriel, P., 2016. Distribuição espacial dos focos de calor em Unidades de Conservação de Minas Gerais no período de 2007 a 2012. UD y la Geomática 11, 39–45.

Sobral, B.S., Oliveira- Júnior, J.F., Gois, G., Pereira Junior, E.R., Terassi, P.M.B., Muniz Junior, J.G.R., Lyra, G.B., Zeri, M., 2019. Drought characterization for the state of Rio de Janeiro based on the annual SPI index: trends, statistical tests and its relation with ENSO. Atmos. Res. 220, 141–154.

Sun, W., Kooijmans, L.M.J., Maseyk, K., Chen, H., Mammarella, I., Vesala, T., Levula, J., Keskinen, H., Seibt, U., 2018. Soil fluxes of carbonyl sulfide (COS), carbon monoxide, and carbon dioxide in a boreal forest in southern Finland. Atmos. Chem. Phys. 18, 1363–1378.

Tomzhinski, G.W., Coura, P.H.F., Fernandes, M.C., 2011. Avaliação da Detecção de Focos de Calor por Sensoriamento Remoto para o Parque Nacional de Itatiaia. Bio. Bras. 1, 201–211.

Toomey, M., Roberts, D.A., Still, C., Goulden, M.L., McFadden, J.P., 2011. Remotely sensed heat anomalies linked with Amazonian forest biomass declines. Geophys. Res. Lett. 38, 1–5.

Townshend, J.R.G., Justice, C.O., 1988. Selecting the spatial resolution of satellite sensors required for global monitoring of land transformations. Int. J. Remote Sens. 9, 187–236.

Tozato, H.C., Mello-Théry, N.A., Vicent, D., 2015. Impactos das mudanças climáticas na biodiversidade brasileira e o desafio em estabelecer uma gestão integrada para a adaptação e mitigação. RGPP 5, 309–1268.

Van der Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Mu, M., Kasibhatla, P.S., Morton, D.C., De Fries, R.S., Jin, Y., Van Leeuwen, T.T., 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). Atmos. Chem. Phys. 10, 11707–11735.

White, B.L.A., White, L.A.S., 2016. Queimadas controladas e incêndios florestais no Estado de Sergipe, Brasil, entre 1999 e 2015. Floresta 46, 561–570.

Williams, A.A.J., Karoly, D.J., Tapper, N., 2001. The sensitivity of Australian fire danger to climate change. Clim. Change 49, 171–191.

Wu, D., Zhao, X., Liang, S., Zhou, T., Huang, K., Tang, R., Zhao, W., 2015. Time-lag effects of global vegetation responses to climate change. Glob. Change Biol. 21, 3520–3531.

Xie, Y., Sha, Z., Yu, M., 2008. Remote sensing imagery in vegetation mapping: a review. J. Plant Ecol. 1, 9–23.

Xue, J., Su, B., 2017. Significant remote sensing vegetation indices: a review of developments and applications. J. Sens. https://doi.org/10.1155/2017/1353691. (Accessed on 20 May, 2019).

Yuan, W., Piao, S., Qin, D., Dong, W., Xia, J., Lin, H., Chen, M., 2018. Influence of vegetation growth on the enhanced seasonality of atmospheric CO_2. Global Biogeochem. Cycles 32, 32–41.

Zalasiewicz, J., Waters, C.N., Summerhayes, C.P., Wolfe, A.P., Barnosky, A.D., Cearreta, A., Crutzen, P., Ellis, E., Fairchild, J.J., Gałuszka, A., Haff, P., Hajdas, I., Head, M.J., Assunção, A., do Sul, J.A.I., Jeandel, C., Leinfelder, R., McNeill, J.R., Neal, C., Odada, E., Oreskes, N., Steffen, N., Syvitski, J., Vidas, D., Wagreich, M., Williams, M., 2017. The working group on the anthropocene: summary of evidence and interim recommendations. Anthropocene 19, 55–60.

Zar, J.H., 1999. In: Biostatistical Analysis, fourth ed. Prentice-Hall, New Jersey, pp. 469.