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Influence of fire on edge vegetation in an Atlantic Forest remnant in Brazil

Influência das queimadas sobre a vegetação de borda de um remanescente de Mata Atlântica no Brasil

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Abstract

Fires and habitat fragmentation are responsible for devastating large ecosystems around the biosphere. The increasing use of remote sensing allows fire patterns to be identified and plays an essential role in preventing fires. In this context, this study aimed to describe the variation in evidence of fire between the edge and the interior of an Atlantic Forest remnant in southeastern Brazil and infer its effects on vegetation. Fire records were acquired between 2010 and 2020 from the *Instituto Nacional de Pesquisas Espaciais* database and United States Geological Survey satellite images. For each scene, the images were processed and the normalized difference vegetation index (NDVI) was calculated. To assess the variation, records were classified and compared according to the year, month, hours, and habitat type (edge and interior). To verify the influence of fires on vegetation, simple linear regressions were performed based on the fire risk due to the NDVI-year-habitat interaction. The data included 748 fire records, with the highest occurrences from April to August, and 51% of the fires occurred between 15h and 20h, indicating periods with more intense solar radiation. The relationship between fire risk and NDVI-year-habitat was significant ($F = 30.35$; $R^2 = 0.26$; $p < 0.0001$), and the edges were more vulnerable to fire risk. This study shows that in an Atlantic Forest remnant, areas with lower vegetation indices, such as edges, are more vulnerable to fire than areas with dense forest vegetation.

Keywords: Fire ecology; Habitat fragmentation; Remote sensing; Serra da Tiririca State Park.

Resumo

As queimadas e a fragmentação de habitat são responsáveis por devastar grandes ecossistemas da biosfera. O uso crescente de sensoriamento remoto desempenha um papel essencial na prevenção das queimadas, permitindo que estas sejam identificadas. Considerando o contexto, este estudo teve como objetivo descrever a variação das evidencias de queimadas entre a borda e o interior de um remanescente de Mata Atlântica no sudeste do Brasil e inferir seus efeitos sobre a vegetação. Para tal fim, foram adquiridos registros de queimadas entre 2010 e 2020 do banco de dados do Instituto Nacional de Pesquisas Espaciais e imagens de satélite do *United States Geological Survey*. Para cada imagem, foram processados e calculados os índices de vegetação por diferença normalizada (NDVI). Para avaliar a variação de queimadas, os registros foram classificados e comparados de acordo com o ano, mês, hora e tipo de habitat (bordas e interior). Para verificar a influência das queimadas sobre a vegetação, foram realizadas regressões lineares simples com base no risco de fogo sobre a interação NDVI-ano-habitat. Os dados incluíram 748 registros de queimadas, com as maiores ocorrências entre abril a agosto, e 51% das

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queimadas ocorreram entre 15h e 20h, indicando períodos de radiação solar mais intensa. A relação entre risco de fogo e NDVI-ano-habitat foi significativa (F = 30,35; R2 = 0,26; p < 0,0001), e as bordas, como esperado, foram mais vulneráveis ao risco de fogo. Este estudo mostra que em um remanescente de Mata Atlântica, áreas com índices de vegetação mais baixos, como bordas, são mais vulneráveis ao fogo do que áreas com vegetação florestal densa.

Palavras-chave: Ecologia do fogo; Fragmentação de habitat; Sensoriamento remoto; Parque Estadual da Serra da Tiririca.

INTRODUCTION

The synergy between fires and habitat fragmentation is responsible for devasting huge areas across the Neotropics (Cochrane, 2001; Cochrane & Laurance, 2002; Brando et al., 2012). Correspondingly, the interaction between fires and droughts causes abrupt increases in plant mortality, including large forest areas and small remnants (Numata et al., 2017). At the regional level, in addition to destroying biodiversity, fires are associated with increases in greenhouse gas (GHG) emissions (Zeri et al., 2016) that cause environmental pollution and worsen respiratory diseases (Souza et al., 2012). At the local level, fires deplete the soil, reduce the infiltration of water underground and, in many cases, cause deaths, accidents, and property loss (Instituto Nacional de Pesquisas Espaciais, 2021). It is estimated that between 1999 and 2018, more than 16 million forest fires occurred throughout Brazil, which mainly affected large rainforest biomes, such as the Amazon and Atlantic Forest (Silva Junior et al., 2020). In 2020 alone, around 223 thousand fires occurred in Brazil, 12.7% more than in 2019 (Instituto Nacional de Pesquisas Espaciais, 2021), associating this fire activity with anthropogenic influences on the climate and land use changes (Barros et al., 2021).

Among anthropic disturbances in forests ecosystems, habitat fragmentation is one of the most striking and is constantly threatening global biodiversity through the formation of new edges (Laurance et al., 2006). Edges, also known as transition zones, are very important because they exhibit unique ecological patterns (Ries et al., 2004). The environmental changes associated with the boundaries of fragments are known as edge effects. Edges and their effects have been extensively studied in different contexts (Murcia, 1995; Harper et al., 2005; Laurance et al., 2011). Half of the tropical forests are 500 m from an edge, including about 20% of the remnants that are 100 meters from an edge (Haddad et al., 2015). In the Amazon biome, up to 50,000 km of new edges are created each year (Broadbent et al., 2008), and in the Brazilian Atlantic Forest, more than 80% of the fragments are <50 ha, and almost half the remaining forest is <100 m from its edges (Ribeiro et al., 2009). Many edge effects are dynamic at space-time scales (Ries et al., 2004). The intensity of edge effects increases based on factors that promote variabilities, such as fragment size, edge age, vegetation structure, functional traits and fire (Cochrane & Laurance, 2002; Cadenasso et al., 2003; Magnago et al., 2015). While most studies about this subject require an uninterrupted effort of time and money, new approaches using predictive technologies, such as remote sensing, are increasingly used in ecological studies (Chave et al., 2019).

The use of remote sensing and geographic information systems in forest dynamics study is a low-cost alternative for forest monitoring (Chave et al., 2019). Since it provides information based on satellite images (Campbell & Wynne, 2011), remote sensing can be used to analyze different parameters from different strata based on the incorporation of optical technologies (Richards, 1999). In addition, this technology makes it possible to process large amounts of data, correlate band spectra, and calculate vegetation indices for large areas (Lu, 2006). Thus, it is likely that studies using these methods will clearly explain the nature of vegetative features and their interaction with environmental parameters (Peng et al., 2012). However, using these methods for fires is often limited to large scales, such as studies of real-time detection (INPE, 2021) and chrono-spatial analyses (Silva Junior et al., 2020; Gois et al., 2020; Barros et al., 2021). Studies at small scales are less common (Nova et al., 2021), and studies about habitat variation as a predictor of fire are rare (Almeida et al., 2020).

Therefore, it is vital to conduct predictive studies that use remote sensing for small remnants (Guedes et al., 2020). There is a lack of knowledge about the influence of fires on edges and the relationships in biomes threatened by anthropogenic disturbances, such as the Atlantic Forest (Myers et al., 2000; Tabarelli et al., 2010) that currently occupies only 12.4% of its original coverage (SOS Mata Atlântica & INPE, 2019). In this sense, this study aimed to describe the variation in evidence of fire between the edge and the interior of an Atlantic Forest remnant and infer its effects on vegetation. The hypothesis tested here is that the remnant edges are more vulnerable to fire risk than the interior of the forest.

MATERIAL AND METHODS

Study area

This study was conducted in the Serra da Tiririca remnant, one of the main sectors of Serra da Tiririca State Park (PESET). This protected area, surrounded by anthropic occupation, is located between 22º48'– 23º00'S and 42º57' – 43º02'W in Niterói and Maricá, Rio de Janeiro State (Figure 1), and was created in 1991 (State Law 1901; November 29, 1991; Rio de Janeiro, 1991). The study area is 1788 ha. It is in the Atlantic Forest biome and is a dense submontane rain forest with some rocky outcrops (Barros, 2008). Serra da Tiririca is a floristically heterogeneous area that includes sections in different successional stages (Barros, 2008). The remnant predominantly includes plant species such as *Gallesia integrifolia* (Spreng.) Harms, *Guapira opposita* (Vell.) Reitz and *Astronium graveolens* Jacq. (Barros, 2008), whereas forest edges are floristically characterized by *Piptadenia gonoacantha* (Mart.) J. F. Macbr., *Machaerium hirtum* (Vell.) Stellfeld and *Pseudopiptadenia contorta* (DC.) G.P. Lewis & M.P. Lima (Machado et al., 2021). The regional climate is humid and hot, with heavy rains in the summer and a dry season in the winter (Aw type in the Köppen classification, updated in Alvares et al., 2013). The average annual temperature is 23.7°C, the average annual rainfall is ~1172 mm, and the average annual relative humidity is ~ 80% (Instituto Nacional de Meteorologia, 2021). The soil is mainly formed by Agrisols, Cambisols, and Lithosols (Instituto Estadual do Ambiente, 2015).

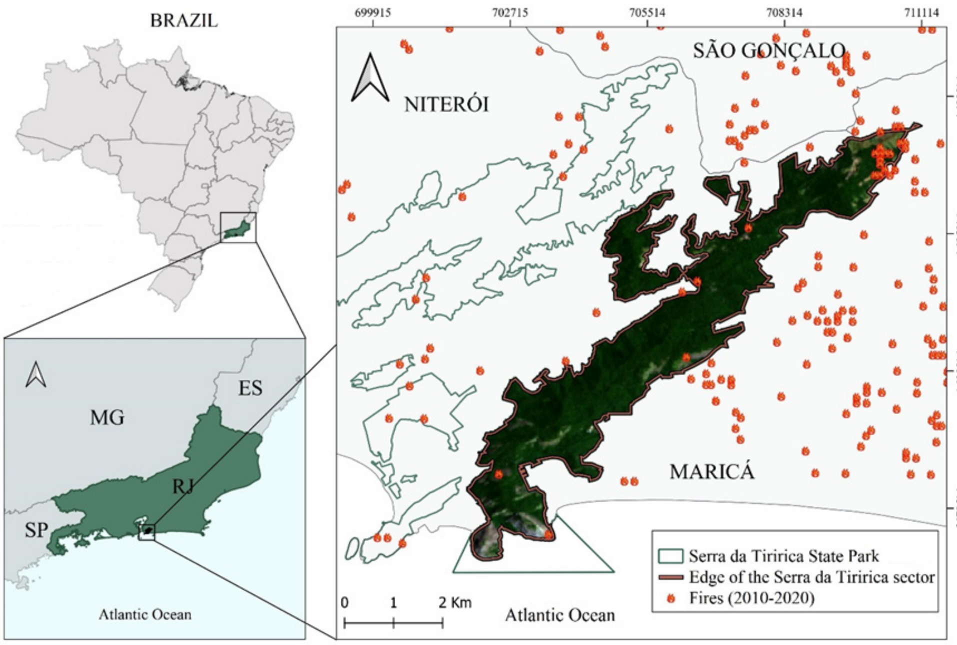

Figure 1. Map and location of the fires in and surrounding Serra da Tiririca from 2010 to 2020.

Data collection and processing

Firstly, PESET fire records were surveyed by extracting data from the BDQueimadas – INPE (Instituto Nacional de Pesquisas Espaciais, 2021), filtering records of fires that occurred between January 2010 and December 2020, at a distance of 5 km around PESET (Figure 1). The satellites selected in the survey were the following: AQUA-MT, AQUA-MM, NOAA-15, NOAA-18, NOAA-19, NOAA-19D, NOAA-20, NPP-375, TERRA-MM, and TERRA-MT. All records were submitted to screening to avoid duplicate records from different satellites; redundant information was discarded. The coordinates and fire risk were the primary information extracted from the fire records. The latter is an attribute that indicates the susceptibility of vegetation to fire. This susceptibility is correlated to vegetation type, days without rain in a location, maximum temperature, minimum relative humidity, latitude, topography, and presence of local fire (Instituto Nacional de Pesquisas Espaciais, 2021). Since some records of fires did not have values for the attribute fire risk, it was necessary to infer the values through imputations for missing data using the Amelia II package in the statistical environment R 4.0.5 (Honaker et al., 2011; R Core Team, 2021).

Secondly, the coordinates of the fire records were converted to points (shapefile). They were then interpolated from the fire risk attribute by the inverse distance weighting (IDW) deterministic method (Shepard, 1968) in the program QGIS 3.16.15 (QGIS Development Team, 2021). In this study, the term fires refer to hot spots, burns, fire pixels, or fire foci.

Thirdly, satellite images of Serra da Tiririca were acquired from the United States Geological Survey (USGS) database (United States Geological Survey, 2021). Six TIFF images were obtained, with minimal presence of clouds, a spatial resolution of 30 m, a temporal resolution of 16 days, and orbit-point 217-76 of the Landsat 5 TM, Landsat 7 EMT, and Landsat 8 OLI/TIRS satellites, acquired for the dry seasons between 2010–2020 (Table 1).

Table 1. Details of satellite products purchased from the United States Geological Survey (USGS).

Year	Satellite – Sensors	Date of acquisition
2010	Landsat 5 – TM	08/26/2010
2012	Landsat 7 – EMT	09/08/2012
2014	Landsat 8 - OLI/TIRS	08/21/2014
2016	Landsat 8 - OLI/TIRS	08/26/2016
2018	Landsat 8 - OLI/TIRS	09/01/2018
2020	Landsat 8 - OLI/TIRS	07/20/2020

Using the software QGIS, the images were processed with the Semi-Automatic Classification Plugin 7.8.17 (SCP) (Congedo, 2020) and the dark object subtraction (DOS) method was applied for atmospheric correction of the bands of the near-infrared (NIR) and red (RED) spectra. To verify the areas with vegetation, band compositions were performed and the spectral index, normalized difference vegetation index (NDVI) calculated, using the Equation 1 in Rouse et al. (1973):

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{1}$$

Subsequently, all new layers generated from processing the NDVI were cut from the extension of the polygon (shapefile) of Serra da Tiririca and used for the analysis and creation of maps. All maps were generated from the Geographic Coordinate System and Datum SIRGAS 2000 UTM zone 23 S.

For data sampling, initially the edge was delimited at 50 m away from the perimeter limit of Serra da Tiririca in the interior direction of the remnant (Figure 1). Then, two types of habitats were defined: edge and interior. Using the QGIS random points tool, 200 random points were requested with a minimum distance of 50 m from each other, divided evenly between the edge and interior. The values for the fire risk interpolation and the NDVI values of the six layers were extracted from the 200 generated points using the complement Point Sampling Tool 0.5.3. Finally, the data were sorted, and a matrix was created with the extraction values.

Data analysis

To describe the variation of the fires, all records around PESET were counted and the percentage of records by satellite was verified. Then, only the fire records for the Serra da Tiririca remnant were selected (including those up to 25 m from the edge) and those compared between the type of habitat through the number of records per year and a monthly and hourly proportion of fires.

To determine the influence of fires on the vegetation of Serra da Tiririca, the response variable (fire risk) and the explanatory variable (NDVI) were submitted to a normality analysis (Shapiro-Wilk test) (Razali & Wah, 2011). Since they did not meet the assumptions of the test, they were transformed into logarithmic or square root values and submitted to new tests. Even after the transformations, the new values did not meet the assumptions, so they were analyzed using non-parametric tests. Subsequently, to assess significant differences between fire risk and NDVI depending on the habitat type, a Wilcoxon test was conducted (Fagerland & Sandvik, 2009). Also, an analysis of variance (ANOVA) and Tukey test were conducted to determine differences between the NDVI as a function of years. Simple linear regressions for the fire risk on NDVI per habitat type were performed and validated the regressions with an F test and correlation coefficient (R^2). Additionally, a simple linear regression model was generated of fire risk on the NDVI-year-habitat interaction and validated the prediction model with a covariance analysis (ANCOVA) and R^2. With the model's prediction, a fire risk map of Serra da Tiririca was constructed using the raster calculator in QGIS. For all statistical analyses, we adopted a significance level of $p < 0.05$. All statistical analyses were conducted in R.

RESULTS AND DISCUSSION

Between 2010 and 2020, 748 fires occurred around Serra da Tiririca State Park. Of these, most were captured by the satellite NPP-375 (69%), followed by NOAA-20 (23%) and AQUA-MT (6%). Thirty-three fires were found in the Serra da Tiririca sector, 22 for the edges, and 11 for the forest interior. The years with the highest records were 2014 and 2017 for edges and 2015 and 2019 for the interior. The months with the highest records were April, August, and October for the edges and May and July for the interior. No fires were recorded for March and November. Finally, 51% of the fires occurred between 15h and 20h, followed by 36% between 00h and 05h. No records were found for the 05h to 10h time interval.

Several regional studies report a trend toward the pattern of variation identified in this study (Clemente et al., 2017; Gois et al., 2020; Barros et al., 2021; Christo et al., 2021; Silva Junior et al., 2020). The fire records reported here, are part of a significant increase in Brazil´s number of environmental satellites (Instituto Nacional de Pesquisas Espaciais, 2021) and, consequently, fire records in recent decades. An increase in fires is observed mainly in the dry season (winter) and in the afternoon (Caúla et al., 2015). Also, the increase in fire incidence between 2014 and 2017 could be associated with meteorological oscillations correlated with the *El Niño* and *La Niña* phenomena (Andrade et al., 2019). In addition, records in these months and hours could be explained by the low volumes of precipitation and high solar radiation (Centro de Previsão de Tempo e Estudos Climáticos, 2021; Instituto Nacional de Meteorologia, 2021). Aldersley et al. (2011) explain that areas with higher precipitation and high humidity are less likely to have fires.

In the visual variation of vegetation generated by the NDVI, a greater concentration of large areas is in the North and South ends of Serra da Tiririca, with values between -1 and 0.2. In contrast, the forest interior had areas with values between 0.6 and 1 (Figure 2). A possible explanation for this variation is the change in forest landscape by anthropization. In Serra da

Tiririca, the land has been used and occupied by humans since prehistoric times (Kneip, 1995). Nonetheless, it was only between the 18th and 20th centuries that human activities increased to the point where the forest was devastated and the landscape anthropized due to intense charcoal production (Oliveira et al., 2020), monocultures, and real estate growth (Barros, 2008). Currently, as in other protected areas, Serra da Tiririca is surrounded by a buffer zone with limited human activity, which is a strategy to reduce the creation of new edges (Lima & Ranieri, 2018). However, protected areas, particularly in Rio de Janeiro State, have high densities of fires on their edges (Barros et al., 2021).

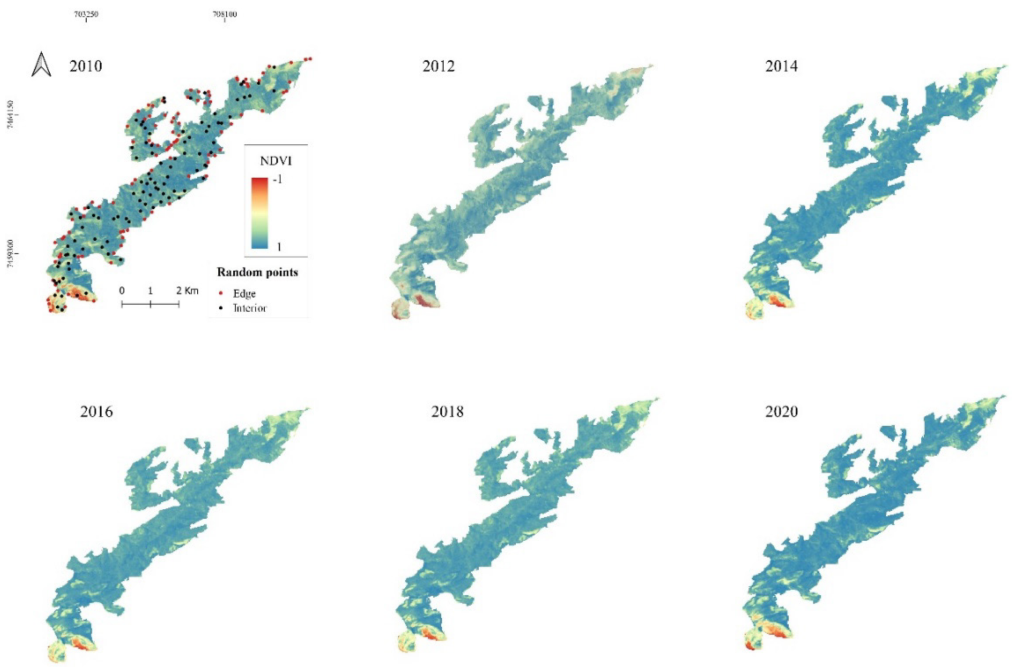

Figure 2. Biannual maps of the normalized difference vegetation index (NDVI) variation between 2010–2020 in Serra da Tiririca, and visualization of the random points selected in this study. NDVI values without vegetation (-1 to 0), vegetation with some deficiency (0 to 0.33), moderately healthy vegetation (0.33 to 0.66), and healthy vegetation (0.66 to 1).

Only fire risk showed significant variation between habitats ($z = 263574$; $p < 0.0001$), with a median value of 0.72 ± 0.15 for the edges and 0.69 ± 0.14 for the interior, although the variation of NDVI by habitat type was not significant ($z = 170485$; $p = 0.11$). Nevertheless, there is variation in the values for years in both areas (Figure 3a), with low rates for 2010 and 2016. Likewise, the Tukey test generated from the variance of the NDVI as a function of the years showed significantly different means for 2010–2012 (diff = -0.05; $p = 0.0025$), 2010–2016 (diff = 0.16; $p < 0.0001$), 2010–2020 (diff = 0.17; $p < 0.0001$), 2012–2016 (diff = 0.21; $p < 0.0001$) and 2012–2020 (diff = 0.22; $p < 0.0001$) (Figure 3b).

The relationship between fire risk and NDVI by habitat type was low but significant (Figure 3c) for both the edges ($F = 38.36$; $R^2 = 0.06$; $p < 0.0001$) and interior ($F = 15.02$; $R^2 = 0.02$; $p = 0.0001$). The prediction model's analysis of covariance indicates significant differences in the intercepts for fire risk due to the NDVI-year-habitat interaction ($F = 30.35$; $R^2 = 0.26$; $p < 0.0001$) (Figure 3d). Despite the low values for the correlation coefficient, negative values were also observed for the interaction of the estimated coefficients and high significance for the p-value (Table 2).

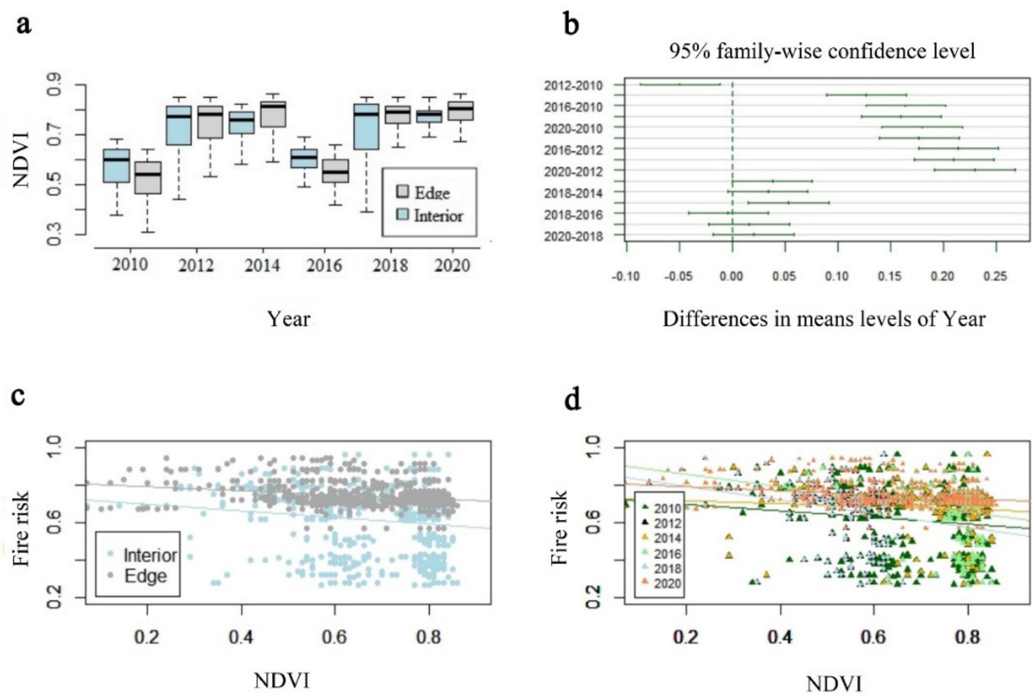

Figure 3. Different graphs representing the relationship and interaction between fire risk, normalized difference vegetation index (NDVI), year, and habitat. Boxplots show the variability of NDVI by year and habitat type. Limits of boxes cover the 1st and 3rd quartiles, and the upper and lower whiskers cover the entire data (a). Tukey test to compare differences in means of NDVI between years (b). Relationships between fire risk values and NDVI according to the habitat type (c) and year (d).

Table 2. Simple linear regression model generated from the relationship between fire risk and the interactions among predictor variables. Negative parameters indicate negative effects and positive parameters indicate positive effects. p ≤ 0.0001 '***', 0.001 '**'. SE = standard error.

Model = Fire risk ~ NDVI:Year:Habitat		
	Estimate (SE)	**p > (t)**
(Intercept)	0.82 (0.02)	<0.001***
NDVI:2010:Edge	-0.13 (0.04)	0.0011**
NDVI:2012:Edge	-0.14 (0.04)	0.0011**
NDVI:2014:Edge	-0.11 (0.03)	0.0007***
NDVI:2016:Edge	-0.10 (0.03)	0.0011**
NDVI:2018:Edge	-0.10 (0.03)	0.0012**
NDVI:2020:Edge	-0.09 (0.04)	0.0011**
NDVI:2010:Interior	-0.35 (0.04)	<0.001***
NDVI:2012:Interior	-0.38 (0.03)	<0.001***
NDVI:2014:Interior	-0.27 (0.03)	<0.001***
NDVI:2016:Interior	-0.27 (0.03)	<0.001***
NDVI:2018:Interior	-0.27 (0.03)	<0.001***
NDVI:2020:Interior	-0.26 (0.03)	<0.001***
NDVI:2020:Interior	-0.26 (0.03)	<0.001***

The vulnerability of edges to fire occurs because the boundaries of forest remnants are often dry, juxtaposed to pastures prone to fire, and deforested (Cochrane & Laurance, 2002). Prediction models indicate that the relationship between fires and vegetation cover is usually strongly correlated (Díaz-Delgado et al., 2003; Van der Werf et al., 2010; Van Wees et al., 2021).

However, prediction models with high variability are generated from the relationship of more than one explanatory variable (Jongman et al., 1995), which could clarify that although significant, the model in this study explained 26% of the variation of fire risk for the NDVI-year-habitat interaction. Otherwise, it is known that digital image processing and spatial modeling have become essential to monitor and combat fires (Soares et al., 2016), especially when analyzing vegetation indices over a time series performed by NDVI. However, the low frequency of records for a variable in an area could induce a local trend in an interpolation (Greene & Daniels, 2017). This could help explain why the fire risk is critical for the rock formation area in the Southern end of Serra da Tiririca (Figure 4). In addition to having low vegetation cover, this area has one fire record in the ten years and the record has the highest fire risk value (Instituto Nacional de Pesquisas Espaciais, 2021).

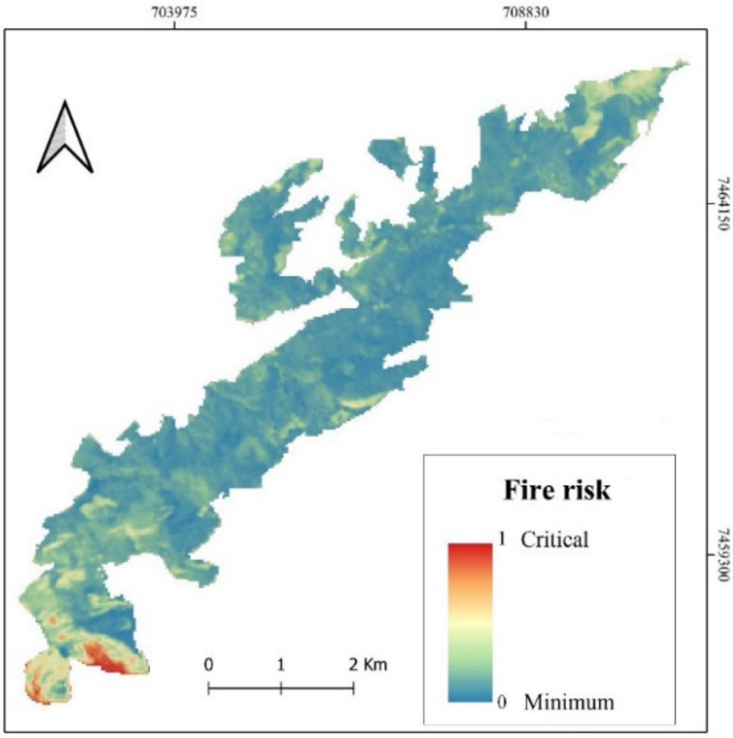

Figure 4. Fire risk map of Serra da Tiririca. Fire risk: minimum (0.00-0.15), low (0.15-4.00), medium (0.40-0.70), high (0.70-0.95), and critical (> 0.95 -1.00).

The spatial projection of the model on the fire risk map (Figure 4) reveals that the North and South ends, such as edges and the interior close to the edges, are more vulnerable to fire risk (0.7-1) than the interior far from the edges (0-0.4). One of the factors responsible for the vulnerability of tropical forests to fire is the type of vegetation (Cochrane & Laurance, 2002). In Serra da Tiririca the floristic heterogeneity is remarkable, particularly the arboreal vegetation, bromeliads, cacti on the slopes, and grasses and other herbs in the surroundings (Barros, 2008; Verçoza & Bastos, 2013; Vasconcelos et al., 2019). Grasses (family Poaceae), often treated as invasive species, grow mainly in areas with high rates of anthropic disturbance and are often correlated with fires (Cano-Crespo et al., 2015). In Serra da Tiririca, alien species, such as 'capim-gordura' (*Melinis Multiflora* Beauv.) and 'capim-colonião' (*Panicum maximum* Jacq), and a native species, 'sapê' (*Imperata brasiliensis* Trin.), are notable in anthropic areas. They grow on the edges and are also abundant in many areas within the remnant (Barros, 2008). In the fire risk map of this study, these places have medium- and high-risk index values.

Here, it was found that areas with a lower vegetation cover, mainly on the edges, are more susceptible to fire than areas of the forest interior. Although there is a lower frequency of fires in dense rainforests, specifically in Serra da Tiririca, it was possible to observe the same local pattern in other Atlantic Forest remnants (Guedes et al., 2020). In this sense, it is necessary to know the dynamics of fires and their consequences, and this study could serve as an important tool to prevent fires and manage PESET. The fire risk map depicts not only the areas that have been the most vulnerable to fire but also areas that should be monitored in the future. Nevertheless, it is vitally important to conduct additional modeling studies with new biotic and abiotic variables to better understand the ecology of the remnant.

CONCLUSIONS

The analyses of the fires between 2010 and 2020 on the variation of the vegetation indices of Serra da Tiririca indicates that areas with lower indices, such as edges and places with more grasses and other herbs, are more vulnerable to fire than areas with dense forest vegetation. Among the years with the highest records for Serra da Tiririca, 2014 and 2017 stand out, when the *El Niño/La Niña* meteorological phenomena occurred. The months with the highest incidence correspond to winter, when there is less precipitation and greater solar radiation. Further, 51% of the fires occurred between 15h and 20h. This study also contributes a fire risk map for Serra da Tiririca, which could assist in preventing and managing fires in Serra da Tiririca State Park.

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