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MAPPING OF FIRE SUSCEPTIBILITY IN THE HYDROGRAPHIC SUB-BASIN OF THE MÉDIO JAGUARIBE, CEARÁ, BRAZIL

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ABSTRACT

Wildfires are a major environmental concern, especially in regions prone to dry conditions and high temperatures. The Médio Jaguaribe Hydrographic region, located in Ceará, Brazil, faces significant challenges related to fire risk due to its semi-arid climate and vegetation types. This study aims to assess the susceptibility to wildfires in the Médio Jaguaribe Hydrographic region using Geographic Information System (GIS) methods. The analysis considers land variables (land use and cover, slope, elevation, soil exposure), climate variables (temperature and precipitation), and anthropogenic factors (proximity to roads). Temperature data were obtained from meteorological stations (2009 – 2024), while precipitation data were collected from ten rainfall stations (1988 – 2024). Proximity to highways was analyzed using shapefile data provided by the Brazilian Institute of Geography and Statistics (IBGE). The study applied the IDW interpolation method to create raster layers for temperature, precipitation, and proximity to roads, and weighted each variable using eigenvectors to determine their influence on fire risk. The results reveal that areas with pastureland and agricultural land present the highest susceptibility to wildfires, while bodies of water have the lowest risk. The analysis of terrain orientation, slope, and elevation further highlights critical areas at risk. The findings provide valuable insights for the management of wildfire risks in the region, with implications for environmental planning and policy-making. Identifying areas most at risk can help inform preventative measures and mitigate the impact of wildfires.

Descriptors: Monitoring, Fire Vulnerable Areas, jaguaribe Hydrographic Region

1 INTRODUCTION

Fire is a natural phenomenon in the Earth System that has shaped the landscape of many of Earth's biomes for millions of years. These fire emissions, and the subsequent sequestration fluxes of around seven billion tonnes of CO2 peryear resulting from post-fire vegetation recovery, are major fluxes in the carbon cycle (Jones et al., 2022).

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Global warming is expected to alter wildfire potential and fire season severity, but the magnitude and location of change is still unclear. Despite Brazil's long-standing "Zero Fire" policy and the sanctions established by law, nearly 20% of the country's territory was affected by fires between 1985 and 2020 (Faria, 2023).

In this context, remote sensing may offer distinct advantages for this in comparison to traditional site-based approaches, as a powerful tool in this scenario, allowing for continuous observation and monitoring of large areas with high temporal and spatial resolution (Gale et al., 2021). Using satellites equipped with thermal and optical sensors allows for the identification of temperature anomalies that indicate the presence of fire outbreaks, even in hard-to-reach areas.

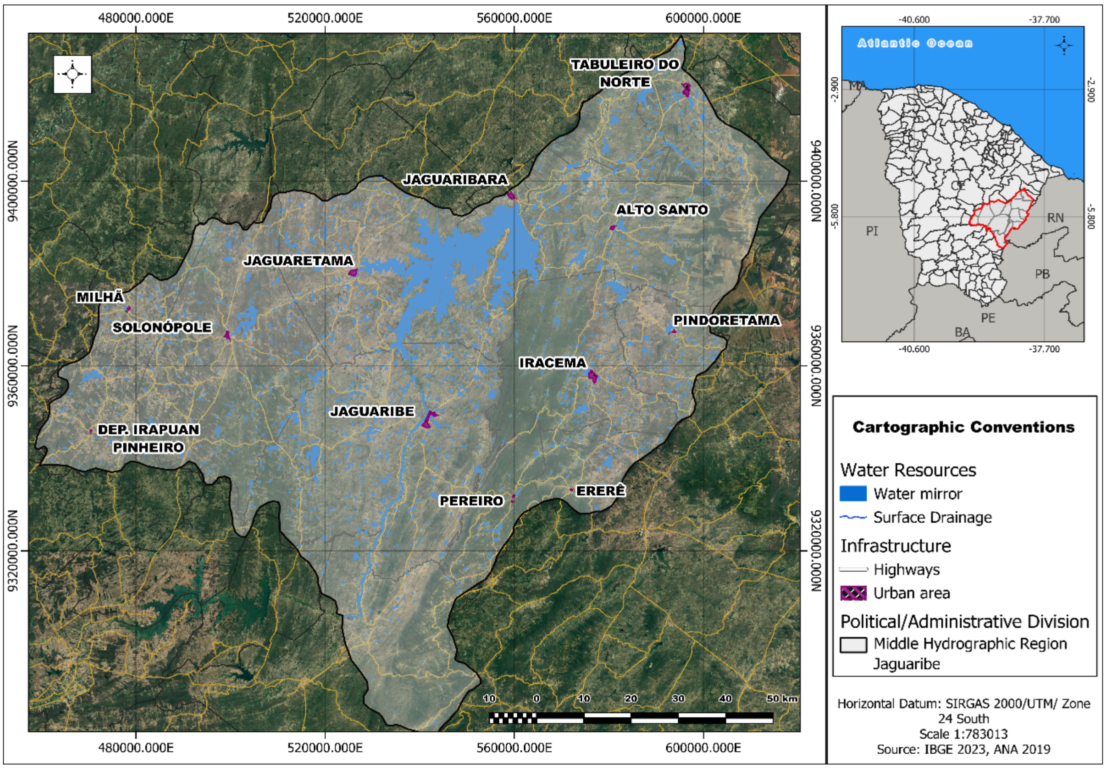
This article aims to analyze the temporal distribution and to assess the fire risk by creating susceptibility maps for forest fire occurrence taking into account land variables (land use and cover, slope, elevation, soil exposure); climate variables (temperature and precipitation) and anthropogenic variables (proximity to roads), through Geographic Information System (GIS) methods in the Médio Jaguaribe Hydrographic region, located in Ceará, Brazil.

2 MATERIALS AND METHODS

2.1 Jaguaribe River Hydrographic Region characterization

The Médio Jaguaribe Hydrographic Region covers an area of 72,645 km², located between parallels 4°30' and 7°45' S and meridians 37°30' and 41°00'W. It is subdivided into five regions: Alto Jaguaribe, Salgado, Médio Jaguaribe, Banabuiú and Baixo Jaguaribe. The Jaguaribe valley extends around 633 km and covers approximately 72,000 km2 (Figure 1).

Figure 1. Location of the hydrographic basin of the Jaguaribe River.



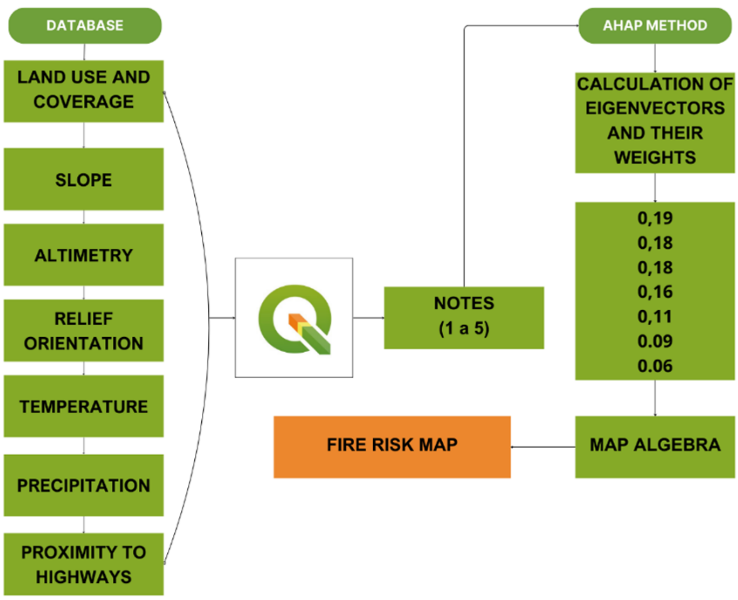
In the region, there are four climatic types: humid, sub-humid, semiarid, and arid, and three types of transition: humid to sub-humid, sub-humid to semiarid, and semiarid to arid (IBGE, 2023). The vegetation includes open shrubby Caatinga, dense shrubby Caatinga, Carrasco, Cerrado, vegetation complex of the coastal zone, arboreal Caatinga, riparian forest with carnauba, maritime evergreen swamp forest, dry forest, cerradão, and rainforests (Costa et al., 2010).

The study region has a large area of soils undergoing desertification and weakened, along with a socioeconomic history based on monoculture and extensive cattle ranching, which has culminated in the state of degradation.

2.2 Data Processing

The wildfire risk map was developed using QGIS 3.30 software, which was used for algebraic analysis based on land variables (land use and cover, slope, elevation, soil exposure); climate variables (temperature and precipitation) and anthropic variables (proximity to roads). The variables were classified with levels ranging from 1 to 5 for fire risk: 1 - very low, 2 - low, 3 - moderate, 4 - high, and 5 - very high. The weights were obtained which aims to justify whether the levels corresponding and reality (Figure 2).

Figure 2. Methodological process for wildfire risk map generation.



Source: Authors (2024).

2.3 Analytic Hierarchy Process (AHP)

The calculation of eigenvectors to determine the weights of each variable was conducted according to Falcão (2013). Initially, a criteria weighting matrix was created, allowing for comparison between them. This resulted in important values ranging classified as 1 - equal; 2 - slightly equal; 3 - somewhat better; 4 - moderately better; 5 - better; 6 - much better; 7 - significantly better; 8 - critically better and 9 - absolutely better.

Next, the values assigned to each criterion in the matrix were summed, and the overall total was calculated. With this sum, the eigenvector was derived by dividing the sum of the criterion weights by the overall total. This eigenvector value was then used in map algebra, following the equation:

W = ((Land Use * 0.19) + (Slope * 0.18) + (Elevation * 0.18) + (Altimetry * 0.16) + (Temperature * 0.11) + (Precipitation * 0.09).

3 RESULTS AND DISCUSSION

Land Variables

Land use and land cover data were downloaded from the MapBiomas in raster format from collection 9.0. Exposed soil was assessed based on the region's vegetative cover, ranging from environments with high vegetative vigor to low vegetative vigor, as well as different land use types, such as pasture, agriculture, crops, mosaics of uses, and urban areas. Grades and weights were assigned according to the degree of fire risk.

Using QGIS 3.30, it was possible to delineate the study area, resulting in 12 classes of land use and cover: Forest Formation, Savanna Formation, Grassland Formation, Pasture, Land Use and Occupation, Urban Area, Exposed Soil, Mining, Aquaculture, Water Resources, Temporary Crops and Permanent Crops.

The Digital Elevation Model (DEM) from the Copernicus website of the European Space Agency (ESA, 2024) was used to calculate the slope. The terrain slope was extracted in degrees using the raster analysis and slope tools in QGIS software, as it is understood that as the degree of inclination increases, the speed of fire propagation also increases (Soares; Batista, 2007).

The altitude class was obtained from the ESA database, 2024, based on the Digital Elevation Model (DEM), where it can be observed that the altitude varies from 28 to 835 meters. Using the aspect tool in QGIS software, it was possible to extract the direction of the relief from the Digital Elevation Model (DEM). The results indicated that the direction of the relief varies from 0 to 360 degrees, allowing for the classification of orientations into North, East, South, and West. All land variables have been classified according to the level of fire risk (Table 1).

Table 1. Classification of land variables according to fire risk.

Land Variables	Level
Land Use and Cover	
Forest Formation	2
Savanna Formation	4
Grassland Formation	4
Pasture	5
Land Use and Occupation	5
Urban Area	5
Exposed Soil	4
Mining	5
Aquaculture	5

Water Resources	1
Temporary Crops	5
Permanent Crops	5
Slope	
< 0º	1
1° - 16º	2
17° - 32º	3
33° - 48º	4
> 65º	5
Elevation	
< 28 m	5
29 – 230 m	4
231 – 432 m	3
432 – 633 m	2
> 835 m	1
Relief	
0 - North	5
90 - East	2
180 - South	1
270 - West	4
360 - North	5

Source: Authors (2024).

Climate Variables

The air temperature data were obtained from weather stations Meteorological Foundation of Ceará, located in the municipality of Jaguaribe at -5.90 Latitude and -38.62 Longitude, from 2009 to 2024, and in the area at -6.18 Latitude and -38.64 Longitude, from 2015 to 2024. The IDW interpolation method was used to create a raster layer indicating temperature intensity.

The precipitation data, in turn, were collected from 10 rain gauge stations located in the study area, specifically in the localities of Alto Santo, Aquinópoles, Bastiões, Canidezinho, Caraúbas, Castanhão, Comunidade de Baixo, Irapuã, Joaquim Távora, and Riacho do Sangue, with a temporal range from 1988 to 2024. The data were averaged for each station, then plotted in QGIS software, and subsequently. The IDW interpolation method was used to identify areas with higher precipitation. All climate variables have been classified according to fire risk level (Table 2).

Table 2. Classification of climate variables according to fire risk.

Climate Variables	Level
Temperature	
< 28,7 °C	1
28,82 °C	2

28,9 °C	3
29,07 °C	4
29,17 °C	5
Precipitation	
< 79 mm	5
80 – 94 mm	4
95 – 109 mm	3
110 – 124 mm	2
125 – 139 mm	1

Source: Authors (2024).

Anthropogenic Variable

The road proximity data were obtained from the Brazilian Institute of Geography and Statistics – IBGE (2023), through the continuous database in shapefile format. In QGIS software, the shapefile data were converted into raster format, and then, using the r.grow.distance tool, the distance from roads within the study area was calculated. The roads were also classified according to fire risk, as shown in Table 3.

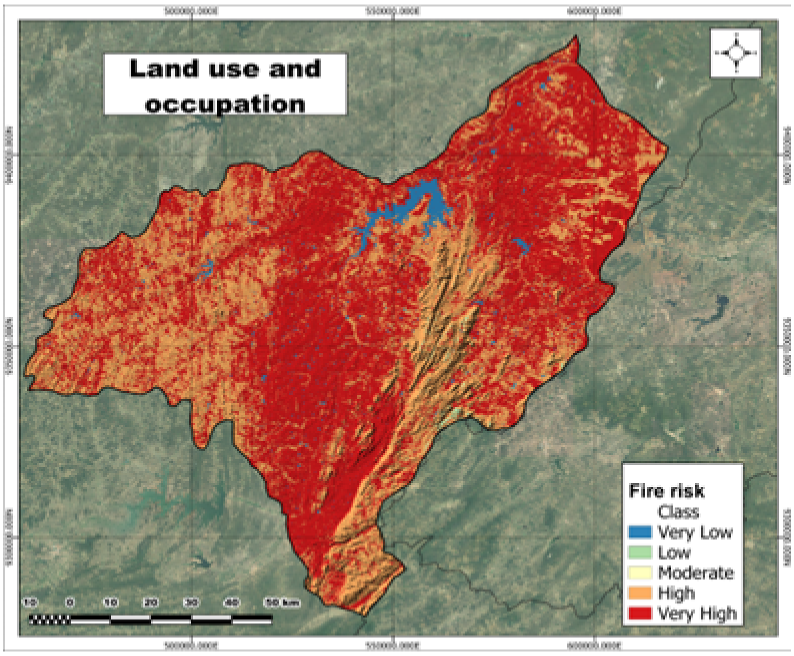
Table 3. Classification of anthropic variables according to fire risk.

Anthropogenic Variable	**Level**
Roads proximity	
< 0 m	5
0 - 2927 m	4
2928 - 5855 m	3
5856 - 8783 m	2
> 11711 m	1

Source: Authors (2024).

The types of land use and coverage affect the dynamics of fire propagation, as a result of its different uses, such as human activities, which are one of the active causes of fire risk (Ronie et al., 2021). The "Very Low" risk was characterized only by the water reservoir. On the other hand, the "Very High" risk was evident in much of the region, serving as a significant warning for environmental management in this area (Figure 3).

Figure 3. Fire susceptibility map according to slope.



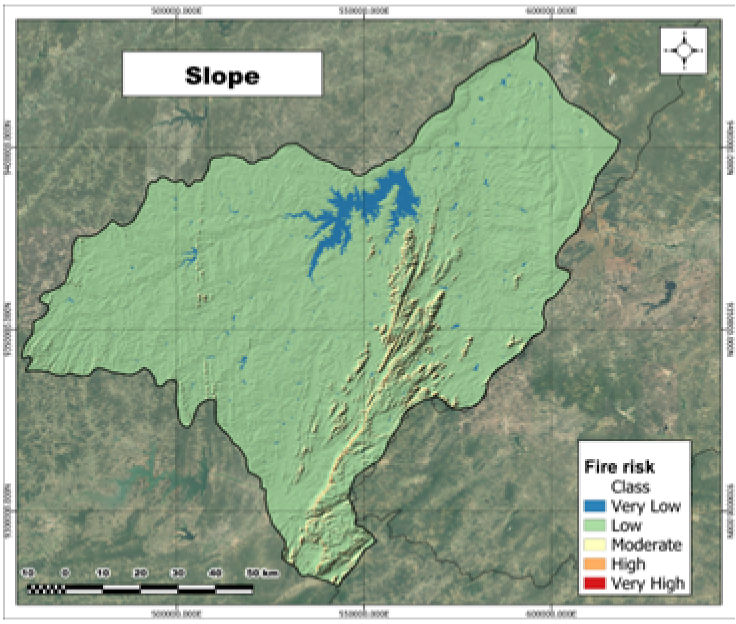
Source: Authors (2024).

According to Ronie et al. (2021), vegetation characteristics are one of the main factors contributing to forest fires due to the amount of material available as fuel for fire spread. The authors also identified, when analyzing different types of land use and vegetation cover, that the class with the lowest risk is water bodies, while agricultural and pasture areas present the highest risk, corroborating the findings of this study.

It was found that most fire susceptibility is in pastureland, covering 45.52% and classified as "Very High" fire risk, followed by permanent crops (10.7%) and temporary crops (2.5%). In the "High" category, the Savanna Formation stands out, occupying 39.21% or an area of 4,192 km². In the "Low" category, the Forest Formation is prominent, with 0.26% and an extent of 28 km².

Altitude represents a variable that influences fire risk due to its relationship with relative humidity. Figure 4 presents the fire risk classes according to slope. It is observed that the study area mostly has low susceptibility, with 9,847 km², and moderate susceptibility, with 4,620 km². Following this, the "Very Low" class covers 3,146 km² (17.0%), "High" (488 km²), and "Very High" (5 km²).

Figure 4. Fire susceptibility map according to slope.

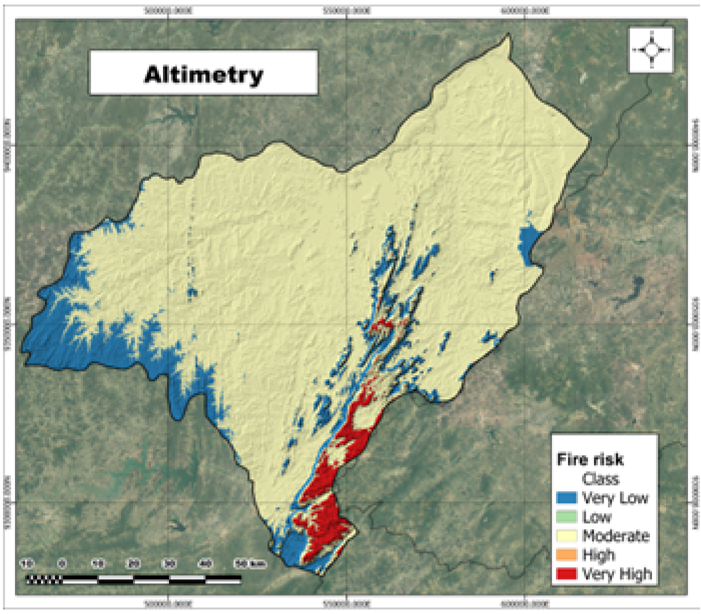


Source: Authors (2024).

Torres et al. (2017) describe that the steeper the slope, the greater the susceptibility to fire occurrences. Moreira et al., (2020) report that the terrain is a key factor influencing climate and vegetation, which in turn affects the fuel material, leading to a tendency for fire to spread more rapidly on slopes and more slowly on declines.

The risk classes of the study area according to altitude indicate that the majority of the region is classified with low fire risk. Specifically, approximately 9,040 km² corresponds to "High" susceptibility, 1,356 km² to "Moderate" susceptibility, and 297 km² is categorized as "Very High" susceptibility (Figure 5).

Figure 5. Fire susceptibility map according to altitude.



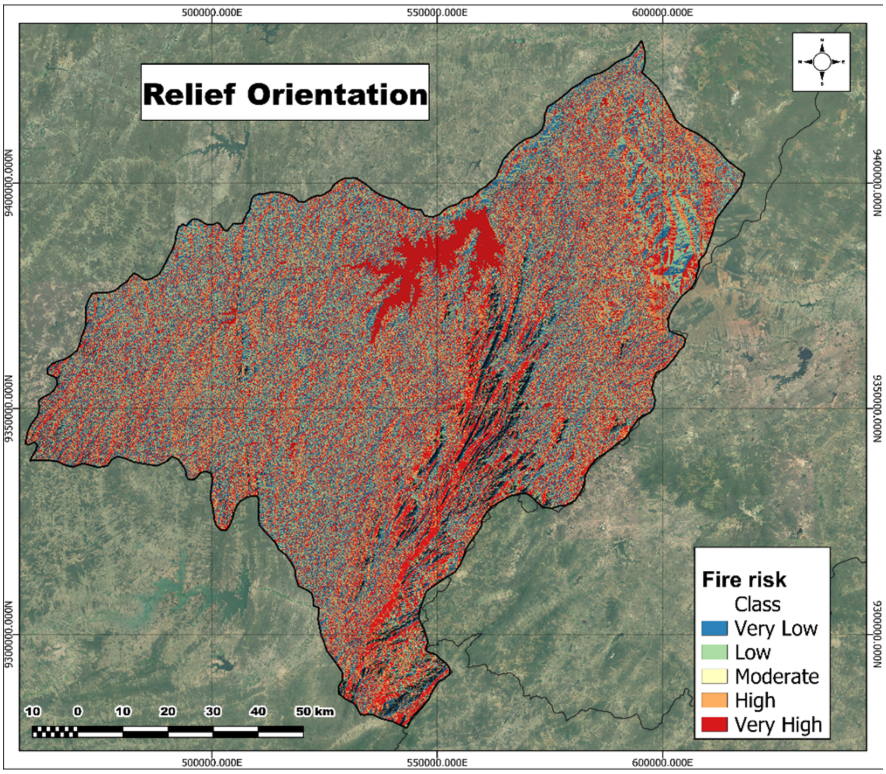
Source: Authors (2024).

According to Torres et al. (2018), altitude plays an important role in fire occurrences, with humidity tending to decrease with increasing altitude. In this sense, Fernandes, Hacon and Novais (2019) explain that variation in altitude influences the risk of fires, as there is a direct relationship with air humidity. In other words, altitude indirectly affects the humidity of the combustible material, consequently resulting in a reduction in the risk of fire occurrence.

Low-elevation regions tend to have longer wildfire risk seasons compared to higher elevations. Mountain tops and valley bottoms exhibit distinct burning conditions during the day due to air currents and fire propagation conditions, with the situation being different at night.

Regarding the terrain orientation, in the study area, the North direction stands out (3,243 km²), as it receives the highest solar radiation, followed by the South (2,757 km²) and East (2,507 km²) directions, classified as "Very High," "Very Low," and "Low," respectively, in terms of fire susceptibility (Figure 6). In the Southern Hemisphere, north-facing slopes receive more sunlight, consequently transmitting more heat. The west-facing slope is the second most exposed to sunlight, followed by the east direction. The south-facing slope receives the least heating (Ribeiro et al., 2007).

Figure 6. Fire susceptibility map according to terrain orientation.

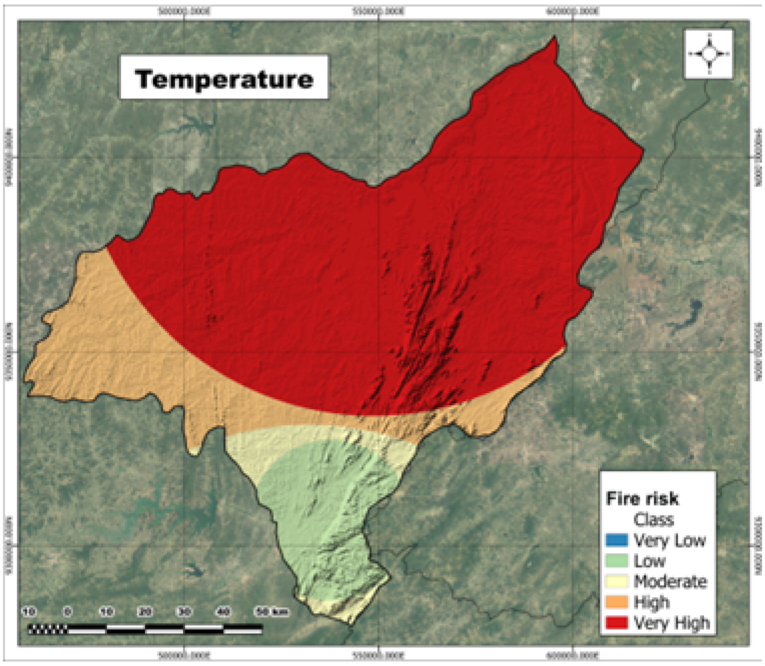


Source: Authors (2024).

The relationship between climatic conditions and the occurrence of forest fires, the author emphasizes that high temperatures, combined with low relative humidity, increase the evaporation rate of vegetation (Silva; Vasconcelos; Costa, 2023). This makes the vegetation drier and, consequently, provides more fuel material, favoring the spread of fires. Additionally, prolonged dry periods, often accompanied by intense heat, create a favorable environment for the ignition and rapid propagation of fires, particularly in areas with high amounts of combustible material.

High temperatures and low relative humidity, wind speed is another important climatic factor in the spread of forest fires. Strong winds can intensify the flames, carrying embers to nearby areas and promoting the rapid expansion of the fire. The predominant classes stand out as ranging from “Very Low” to “Very High” fire risk (Figure 7).

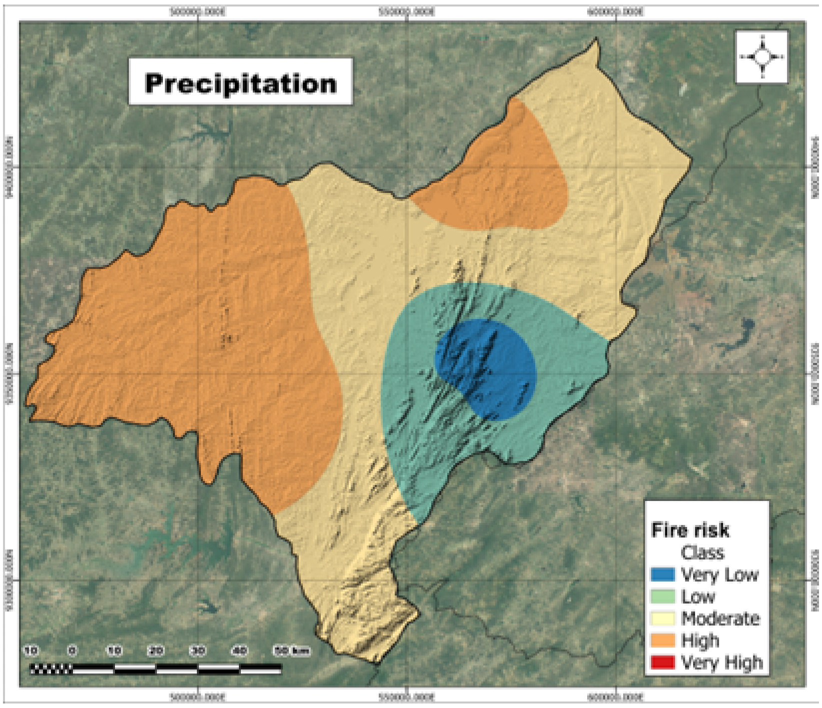
Figure 7. Fire susceptibility map according to ambient temperature.



Source: Authors (2024).

The precipitation distribution of the study area and its respective fire risk level are presented, with an average precipitation classified as “Moderate” (4,368 km²) to “High” (4,341 km²). This classification is attributed to missing precipitation data and the low rainfall index the region receives throughout the year. Correlated with precipitation data obtained from the Data Collection Platforms (PCD) of the Cearense Foundation of Meteorology and Water Resources (FUNCEME), the average precipitation for the Médi Jaguaribe Basin was 742.15 mm for the year 2023, and the number of heat spots, for instance, in the month of October, was 538 (Figure 8).

Figure 8. Fire susceptibility map according to precipitation data.



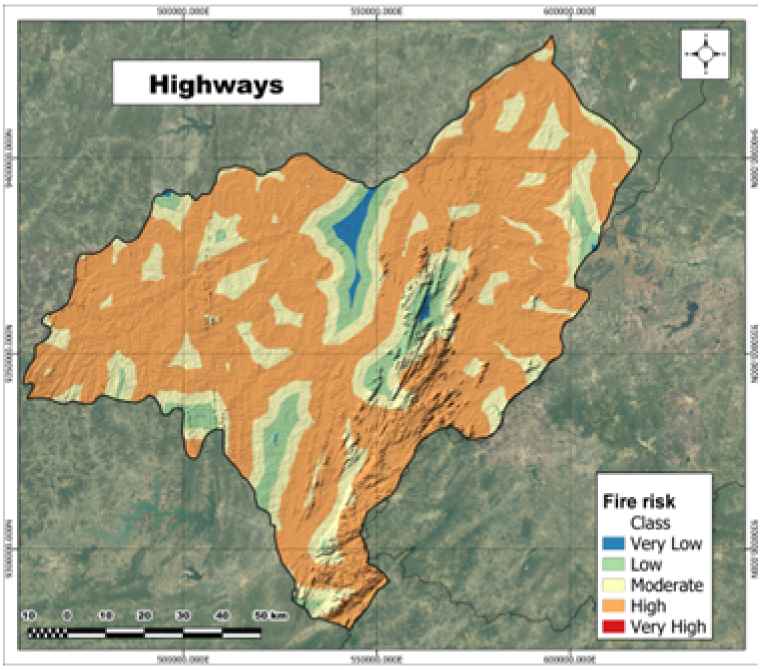
Source: Authors (2024).

According to Eugênio (2021), precipitation is directly and indirectly related to the occurrence of forest fires. The quantity and distribution of precipitation are determining factors for the onset, duration, and end of the highest fire risk season (Soares; Batista, 2007). Torres (2006) states that the months with higher precipitation are those that have the lowest number of fires, as the increased water content in the system prevents the formation of dry fuel material. On the other hand, the months with the greatest water deficit have a higher number of forest fire cases.

In the Brazilian semiarid region, the influence of precipitation and winds is more significant concerning wildfires. In this study, an average of the variables for all months (January to December) of the year was calculated. However, in Ceará, it is observed that most rainfall occurs in the first semester, with a more significant period lasting approximately four months (February to May), known as the rainy season. In the second semester, these regions experience only sporadic rainfall, insufficient to maintain low vegetation fire risk levels, accompanied by an increase in wind incidence, which further exacerbates the conditions for the occurrence of wildfires and heightens the need for attention in Ceará's areas.

Ribeiro et al. (2007), when observing their study area, identified that it is surrounded by highways and narrow internal roads with car and pedestrian traffic. Even though this traffic is low, there is an impact that, no matter how small, should not be ignored in fire zoning work. The largest extension of the study area (7,451 km²) corresponds to the "High" fire risk class due to proximity to highways, followed by 2,353 km² with "Moderate" risk and 773 km² with "Low" risk (Figure 9).

Figure 9. Fire susceptibility map according to proximity to highways.

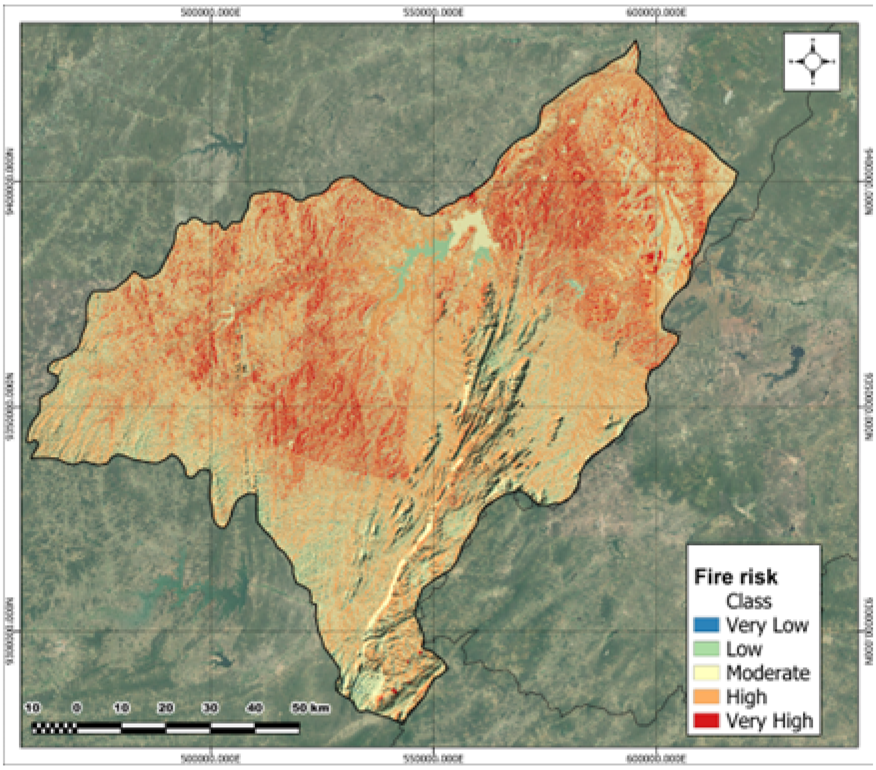


Source: Authors (2024).

Considering both natural and anthropogenic factors, it can be highlighted that the study area presents a high propensity for wildfire risk due to its natural vulnerability to fire processes. This vulnerability is amplified by anthropogenic factors that accelerate the spread of fires, especially in areas with irregular land use and occupation, as well as in regions with vegetation of high combustible potential.

The mapping the areas vulnerable to fire risk revealed that the northern portion of the Médio Jaguaribe Hydrographic Region is the most susceptible to such occurrences. Meanwhile, the central and southern areas exhibit a range of risk levels, from very high to moderate. The data reveals that around 23% of the region is classified as having a “Very High” risk of forest fires, while 56% of the area is at risk “High”. Also, only 19% of the region presents a “Moderate” risk, and a small fraction, approximately 0.44%, corresponds to areas with a “Very Low” to “Low” risk for fires, as shown in Figure 10.

Figure 10. General map of fire risk vulnerability in the Middle Jaguaribe region.



Source: Authors (2024).

4 CONCLUSION

Based on the analysis conducted, it is concluded that the of Médio Jaguaribe Hydrographic Region has significant vulnerability to wildfire risk, with spatial susceptibility variations that reflect both natural characteristics and the impacts of human activities. The northern portion stands out for its higher propensity for fire, requiring increased attention in preventive and firefighting policies. The central and southern areas, while also presenting high-risk levels, vary in intensity and suggest the need for mitigation strategies appropriate to each vulnerability level. The mapping conducted serves as a crucial tool for environmental planning and management, contributing to the conservation of natural resources and the protection of local communities against the impacts of wildfires.

CONFLICT OF INTEREST

there is no conflict interest in the present research

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