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# FIRE DANGER IN THE SUPPLY AREAS OF HYDROELECTRIC RESERVOIRS UNDER THE RESTORATION PROCESS IN THE SOUTH OF MINAS GERAIS, BRAZIL

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# FIRE DANGER IN THE SUPPLY AREAS OF HYDROELECTRIC RESERVOIRS UNDER THE RESTORATION PROCESS IN THE SOUTH OF MINAS GERAIS, BRAZIL

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**ABSTRACT**

The partial or complete loss of vegetation cover triggers an increase in surface runoff, erosion, and sedimentation of water bodies, including reservoirs for hydroelectric power generation, reducing their life expectancy. To control or mitigate this issue, ecological restoration interventions should prioritize the recovery of areas most vulnerable to these processes, such as springs. Conversely, wildfires cause damage to vegetation cover and hinder ecological restoration and/or natural regeneration processes. Therefore, this study aimed to identify - with the aid of Geographic Information Systems - the temporal and spatial likelihood of fire occurrences in spring recharge areas undergoing ecological restoration and contributing to hydroelectric reservoirs in southern Minas Gerais, Brazil. The findings indicated that the months with the highest probability of wildfire occurrences were August and September (accounting for 66% of cases), requiring increased attention to prevention efforts. Furthermore, locations most susceptible to fires (steeper slopes, more flammable vegetation, and higher anthropogenic use) should be treated as priorities for both prevention and ecological restoration actions.

**KEYWORDS:** Fire ecology, Recovery of degraded areas, Forest hydrology

## 1. INTRODUCTION

Natural ecosystems play a pivotal role in the regulation of microclimate, the control of river flow, and biogeochemical cycles (Honda and Durigan, 2017). Several studies support the correlation between changes in land use and cover, and the quality and quantity of water resources within the same basin (Kändler et al., 2017; Liu et al., 2019; Costa et al., 2022).

The partial or complete loss of vegetation cover triggers an increase in runoff, frequency, and magnitude of flood events, soil vulnerability to water erosion, and increased sedimentation rates in river channels or reservoirs (Yan et al., 2022; Riquetti et al., 2023).

The risk of reservoir sedimentation diminishes their lifespan and effectiveness. This natural phenomenon, driven by water erosion, is associated with the watershed's characteristics in terms of topography, lithology, vegetation cover, hydrology, and also human activities that can promote or amplify soil loss (Terêncio et al., 2020).

To control or mitigate this issue, restoration interventions should prioritize the recovery of soil and vegetation in the most fragile locations, in exposed areas, and along stretches of the basin subject to greater surface runoff and, therefore, exposed to higher risks of erosion and sedimentation. In this manner, springs and sloped terrains should be primarily protected. For this purpose, forests, savannas, or grasslands, if properly restored, can also perform the protective function, which increases with the expansion of the area rehabilitated adjacent to the water body (Honda and Durigan, 2017).

Conversely, wildfire incidents contribute to the depletion of forest canopies, thereby expediting erosional processes through enhanced surface water flow. This phenomenon also poses significant challenges to the initiation of ecological restoration efforts (Kändler et al., 2017; Liu et al., 2019; Costa et al., 2022). Consequently, a comprehensive understanding of the spatial and temporal patterns of fire events is imperative for the effective reach and success of restoration methodologies (Sivrikaya et al., 2024).

The fire severity within forest landscapes exerts a profound influence on the post-fire ecological dynamics, shaping the vegetative community's structure and successional patterns, as well as wildlife population behaviors. Specifically, the intensity of the blaze plays a critical role in seedling emergence, activation of the soil's seed reservoir, and arboreal seed dispersal, which collectively dictate the successional pathways and recuperation velocities of the forest ecosystem (Guo et al., 2024).

Despite numerous studies on the mapping of wildfire susceptibility (Torres et al., 2017a, b; Santana Neto et al., 2022, 2023; Pagadala et al., 2024; Sivrikaya et al., 2024), and the determination of the most likely period of occurrence (Pinto et al., 2021; Popovic et al., 2021; Scarff et al., 2021), there is a lack of research that utilizes information about the most susceptible locations and most probable periods to support ecological restoration projects.

Given the presented data, this study's objective was to identify the most probable period and the locations most susceptible to wildfires within a basin undergoing ecological restoration, specifically in areas that replenish springs-feeding hydroelectric plant reservoirs in southern Minas Gerais. The study posits three hypotheses: firstly, that periods of pronounced water scarcity correlate with the highest probability of wildfires; secondly, that slopes with increased solar exposure (north and west facing) and sparse vegetation (herbaceous types) exhibit greater susceptibility to fires; and thirdly, that assigning weights to predictive variables (such as land use categories, aspect of slopes, and inclination) based on historical fire occurrences will yield more precise susceptibility maps.

## 2. MATERIAL AND METHODS

### 2.1. Study area

The study was conducted across 39 municipalities situated in the Sub-basin of the Rio Grande, in the southern region of the state of Minas Gerais (Figure 1). The region, encompassing approximately 20,000 km², serves as a recharge area for aquifers that supply the reservoirs of the Furnas and Peixoto Hydroelectric Plants. Agriculture (41%) and Pasture (34%) represent the primary land uses and cover within the basin.

Insert here Figure 1

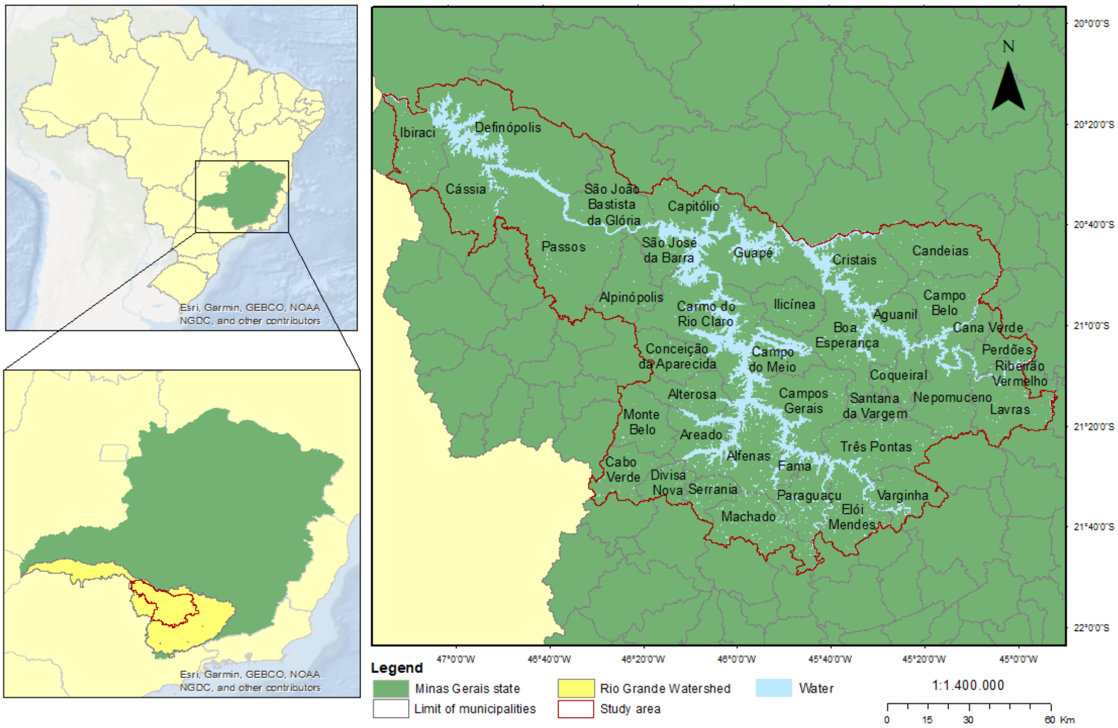


Figure 1 – Study area location in the Rio Grande Watershed, in the southern region of the Minas Gerais state, Brazil

The region is located in the ecotone between the Cerrado and the Atlantic Forest, featuring a mesothermal climate with humid summers, classified as Cwa according to the Köppen climate classification. The average temperature ranges from 22.9°C in January to 16.3°C in June, and the monthly accumulated precipitation is 283 mm in January and 17 mm in August (INMET, 2024).

A total of 182 plots were designated for ecological restoration in spring recharge areas throughout the basin. The selection of these plots took into account the availability and willingness of landowners to undertake recovery efforts. The total area of the plots was approximately 218 hectares, with an average of 1.2 hectares per plot. Before planting, the areas were fenced off to facilitate subsequent planting and necessary treatments for soil amendment and ant control.

## 2.2. Dataset

The fire occurrence data were extracted from the Instituto Nacional de Pesquisas Espaciais (INPE) Burned Area Database (BDQueimadas), filtered for the period from January 1, 2012, to December 31, 2022, using the reference satellite AQUA_M-T (MODIS sensor).

The Digital Elevation Model (DEM), which provided information on the terrain's slope and its aspect, was developed from altimetric data obtained from the Shuttle Radar Topographic Mission (SRTM) with a spatial resolution of approximately 30 meters. The data were accessed through the Earth Explorer digital platform, developed by the United States Geological Survey (USGS).

The land use and cover data were obtained from the digital platform MapBiomas (Collection 8 of 2022), which provides spatial resolution mosaics of 30 meters.

**2.3. Analysis**

To determine the most likely period for fire occurrences, the monthly averages of occurrences were compared using the Scott Knott (SK) test at a 5% probability level in the R software. This test was selected for its suitability in grouping means, as it ensures no overlap between the results of the groups (Pinto et al., 2021).

The susceptibility cartograms were generated using ArcGIS 10.8.1 software, employing a multicriteria approach for the integration of cartographic databases. In the construction of the ignition susceptibility cartogram, data on land use and cover, as well as slope solar exposure, were integrated, each weighted at 50%. For the propagation susceptibility cartogram, the ignition susceptibility cartogram, weighted at 66%, was combined with terrain slope information, which was assigned a 34% weight (Torres et al., 2014; Torres et al., 2017a, b).

The weights assigned to each class in the integration process (Table 1) were determined based on the density of fire occurrences within each class from 2012 to 2022 in the study area. Consequently, the class with the highest density of fire foci per km² received a weight of 10, and the others were assigned proportional weights. This method is employed because the significance of each variable in wildfire occurrences varies according to the specific territorial context of the region under study (Torres et al., 2014; Torres et al., 2017a, b).

Table 1 – Basin area, focus density, and weights of each class in the elaboration of wildfire susceptibility cartograms

| Class | Total area ($km^2$) | No. Focus | No. focus/ $km^2$ | Weight |
|---|---|---|---|---|
| Land use and cover | | | | |
| Forest Formation | 2,236.46 | 304 | 0.14 | 2 |

| | | | | |
|---|---|---|---|---|
| Savanna Formation | 266.15 | 69 | 0.26 | 4 |
| Silviculture | 175.43 | 45 | 0.26 | 4 |
| Wetland vegetation | 125.35 | 34 | 0.27 | 4 |
| Grassland | 322.62 | 145 | 0.45 | 7 |
| Pasture | 6,906.50 | 956 | 0.14 | 2 |
| Agriculture | 8,220.06 | 1,449 | 0.18 | 3 |
| Non-Vegetated Area | 41.41 | 7 | 0.17 | 2 |
| Urbanized Area | 218.74 | 61 | 0.28 | 4 |
| Water Bodies | 1,315.71 | 38 | 0.03 | 0 |
| Rocky outcrop | 212.39 | 144 | 0.68 | 10 |
| Slope | | | | |
| 0-3º | 2,037.20 | 224 | 0.11 | 3 |
| 3-8º | 4,208.19 | 748 | 0.18 | 4 |
| 8-20º | 9,410.99 | 1.509 | 0.16 | 4 |
| 20-45º | 3,942.37 | 656 | 0.17 | 4 |
| 45-75° | 371.19 | 96 | 0.26 | 6 |
| >75º | 36.80 | 15 | 0.41 | 10 |
| Aspect | | | | |
| Plain | 1,159.59 | 45 | 0.04 | 2 |
| North (337.5 - 22.5º) | 2,451.04 | 432 | 0.18 | 10 |
| East (22.5 - 157.5º) | 6,903.24 | 1.091 | 0.16 | 9 |
| South (157.5 - 202.5º) | 2,121.36 | 386 | 0.17 | 9 |
| Werst (202.5 - 337.5º) | 7,371.51 | 1.294 | 0.18 | 10 |

To validate the efficiency of the generated susceptibility cartograms, the foci of the 3,208 wildfires occurrences within the studied period were overlaid on them, and the density of foci per area for each susceptibility class was defined

Once the ignition and propagation susceptibilities for the study region were established, the polygons of each of the 182 plots of the ecological restoration project were plotted on the generated cartograms, thus defining the areas of the plots within each of the wildfire susceptibility classes.

## 3. RESULTS

The hypotheses regarding the period of occurrences and the most susceptible areas were confirmed. The findings delineated three distinct periods concerning the probability of occurrences (Figure 2), with 66% of the fires occurring in August and September, identifying this as the most probable period for an ignition source to develop into a wildfire, averaging 98 occurrences per month during the analyzed period. The second intermediate group (July and October) accounted for 24% of the occurrences with an average of 35 occurrences per month, and the third group, comprising the remaining eight months, recorded 10% of the occurrences with an average of three occurrences per month.

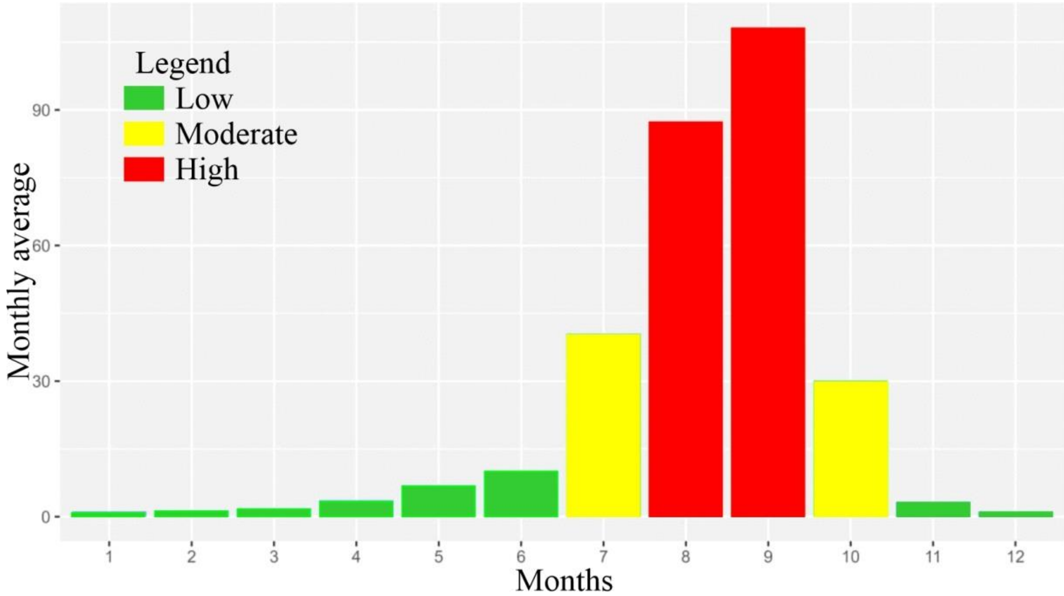


Figure 2 – Monthly probability of wildfire occurrences in the study area. Equal colors present equal averages by the Scott Knott test at a 5% probability

Upon analyzing the entire basin (Table 1), the majority of the 3,208 wildfire occurrences happened in areas classified as agriculture (44.56%) and pasture (29.4%). However, when considering the size of the area of each land use and cover class, the areas with the highest density of fire foci per square kilometer were rocky outcrops (0.68 foci/km²) and grassland formations (0.45 foci/km²).

When the wildfire occurrences are segmented according to the three time periods identified in Figure 2, the behavior concerning land use and cover remains similar to the annual analysis presented in Table 1. The only exception is during the period from November to June, where the urbanized area class exhibited the highest density of fire foci per area.

The density of fire foci per square kilometer increased with the terrain's slope. Regarding the aspect, the majority of occurrences were on West-facing slopes (40%) and East-facing slopes (34%), with West and North-facing slopes (both with 0.18 foci/km²) having the highest density of occurrences per area (Table 1).

The generated maps of ignition and propagation susceptibility (Figure 3A) exhibited similar patterns, with the majority of the study area classified as low susceptibility, followed by moderate and high. Although the highest numbers of fire foci were in areas of low ignition susceptibility (58%) and propagation susceptibility (59%), and the lowest in areas of high ignition susceptibility (2%) and propagation susceptibility (3%), the density of foci per area showed higher values for areas classified as high susceptibility for both ignition and propagation. The average density of foci for the study area was 0.16 foci/km² within the analyzed period. The density of foci per area for the high ignition susceptibility class was twice that of the low susceptibility class, and the high propagation susceptibility density was almost six times greater than that of the low (Table 2).

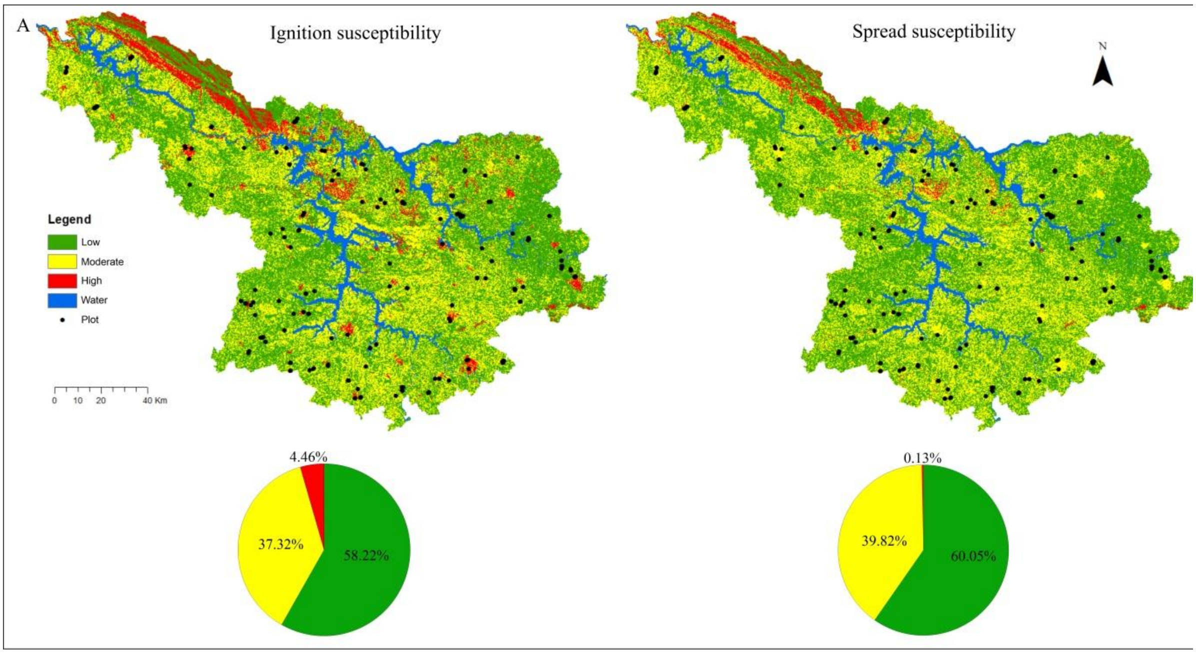


Figure 3 – Ignition susceptibility and wildfire propagation of the plots in forest restoration

Table 2 – Area of the classes, number of focuses, and focus density/area in each class of wildfire susceptibility

| Class | Area (km$^2$) | Area (%) | Focus | Focus/km$^2$ |
|---|---|---|---|---|
| Ignition susceptibility | | | | |
| Low | 11,741.20 | 55.60 | 1,552 | 0.13 |
| Moderate | 7,071.51 | 37.83 | 1,323 | 0.19 |
| High | 1,228.11 | 6.57 | 333 | 0.27 |
| Propagation susceptibility | | | | |
| Low | 1,.919.40 | 56.56 | 1,522 | 0.13 |
| Moderate | 7,465.02 | 39.93 | 1,203 | 0.16 |
| High | 656.4 | 3.51 | 483 | 0.74 |
| Total | 20,040.82 | 100.00 | 3,208 | 0.16 |

Regarding the plots undergoing ecological restoration (Figure 3B), their susceptibilities to ignition and propagation were similar, with a slight predominance of areas classified as high ignition susceptibility (9.70 ha) compared to those classified as high propagation susceptibility (3.00 ha). The majority of the plots are located in areas of low ignition susceptibility (126.90 ha) and low propagation susceptibility (128.90 ha) for wildfires. The second most representative class was that of moderate ignition susceptibility (81.36 ha) and propagation susceptibility (86.82 ha).

## 4. DISCUSSION

The delineation of regions highly vulnerable and temporal windows where an ignition source is likely to initiate and propagate a fire significantly enhances the precision of preventive, detection, and suppression strategies in wildfires (Torres et al., 2018). These strategies can be tailored to specify the exact location, optimal timing, and effective intervention methods (Torres et al., 2017).

August and September, which record the highest number of occurrences, coincide with the most problematic period for fire outbreaks in the southeastern region of Brazil, as well as in most of the country (Pinto et al., 2021). The increased number of incidents during this period can be attributed to the dominance of high-pressure systems in the region (Torres and Machado, 2012), coupled with dry conditions and high solar radiation, which enhance evapotranspiration and, consequently, the availability of forest fuel for combustion (Bedia et al., 2015; Huijnen et al., 2016; He et al., 2024). The moisture content of forest fuel is identified in the literature as the most critical characteristic for increasing its flammability (Popovic et al., 2021; Scarff et al., 2021). Greater availability of combustible materials increases the likelihood of an ignition source starting a wildfire (Torres et al., 2018). The establishment of an intermediate season (July and October) also differs slightly from that in the southeastern region of Brazil, where the intermediate season comprises the months of June and October (Pinto et al., 2021).

The peak period for fire occurrences also coincides with the time of the most extensive use of fire in agricultural activities (Ying et al., 2021; Pagadala et al., 2024). Fire has been a vital agricultural tool for thousands of years, and its application in agricultural fields is a common practice for burning crop residues, controlling weeds, and rejuvenating the soil and pasture quality (Shyamsundar et al., 2019). However, when not conducted safely, these burnings act as a potential ignition source for larger-scale fires. Moreover, the increased human activity in these areas for various agricultural tasks heightens the risk of ignition (Arnell et al., 2019).

Although the highest number of ignitions is often recorded in agricultural areas, other studies have found that cultivated lands, such as farms and pastures, are less prone to fires compared to other herbaceous and shrubby vegetation areas like savannas and degraded lands with invasive plants (Pagadala et al., 2024). Finer fuels present in herbaceous vegetation ignite more easily compared to their thicker counterparts, owing to their greater responsiveness to atmospheric moisture conditions (Bajoco et al., 2017; Hanes et al., 2019). This accounts for the higher density of fire hotspots per square kilometer observed in this study in rocky outcrops and grassland formations.

The study area's rocky outcrops are adorned with herbaceous vegetation adapted to the substrate-imposed conditions and are also found in conjunction with the region's more sloped areas. The inclination factor improves the propagation efficiency in the direction of the slope (Lacerda et al., 2022; Guo et al., 2024), as it enhances fuel drying through more effective heat transfer to the adjacent upper parts (Mitsopoulos et al., 2019), corroborating our results that show a greater density of ignition points per square kilometer in steeper terrains.

Beyond the influence of slope, the Aspect modulates the desiccation rates of fuel moisture, thereby increasing ignition susceptibility and facilitating the propagation of fire. In the Southern Hemisphere, north-facing slopes, which receive the most solar energy, are the most susceptible to fire occurrences, followed by west, east, and south-facing slopes (Torres et al., 2017a). The topography of the study area predominantly aligns in a north-south direction, explaining the prevalence of west and east-facing slopes. The foci densities per square kilometer exhibited minimal variation across different slope orientations, suggesting that aspect does not significantly influence fire events in the region, which contrasts with findings from other studies in Minas Gerais (Torres et al., 2014; Torres et al., 2017a, b). This discrepancy may be due to the study region's smaller areas of slopes that are more (North) and less (South) susceptible to fires, and the larger areas of slopes with intermediate susceptibility (West and East).

The susceptibility cartograms for ignition and propagation, as well as the susceptibility assessments of the 182 plot areas, demonstrated a consistent trend with a predominance of areas classified as low-susceptibility and a minority classified as high-susceptibility. This observation, coupled with the increased focus density per square kilometer in high-risk areas, validates the effectiveness of the susceptibility maps developed for the study region (Torres et al., 2014; Torres et al., 2017a, b).

However, it should be emphasized that an area classified as highly susceptible does not guarantee the occurrence of a fire, just as an area deemed low susceptibility does not ensure the absence of one. Other factors must be considered, such as the likelihood of occurrences related to meteorological conditions; therefore, the fire danger only materializes when the most susceptible areas coincide with the most probable times (Yin et al., 2024).

Conversely, the hazard of fire does not necessarily predict its occurrence; considering that 97% of fires in Brazil are anthropogenic, an initial flame is required to trigger the process (Costa et al., 2023). High-danger situations indicate an increased ease with which an ignition source can start a wildfire compared to low-danger scenarios. This also explains the higher density of foci per area in urbanized regions between November and June, when the more humid seasons require greater activation energy (Torres et al., 2018), and domestic waste burning may provide this initial energy more efficiently than other negligent causes (Aximoff et al., 2020).

The method used in this study to assign weights to variables, aiming to reflect their influence on recorded occurrences, proves effective in defining susceptibility to fires. Therefore, these maps require unique information from each region to enhance their efficiency. The significance of the local level for the success or failure of certain actions implies that the principles and measures adopted must be tailored to the actual and specific intervention characteristics derived from the particular territorial context (Torres et al., 2017). Thus, the more accurate the fire occurrence records in a given region, the more precise the value assignments to the influences that variables have on the initiation and spread of fire, and the more effective the prevention, detection, and firefighting actions will be. Locations identified as having a higher susceptibility to fires may receive special attention regarding prevention and early detection actions, especially during the most likely period of occurrences.

Finally, it is important to note that, legally, the State of Minas Gerais allows planned use of fire for agrosilvopastoral or phytosanitary purposes on rural properties, as regulated by the Joint Resolution SEMAD/IEF No. 2,988, dated July 24, 2020. The 'Authorization for Controlled Burning' document ensures that the request has been approved by the environmental authority and includes its reverse side recommendations to be followed for the correct use of fire and to prevent wildfires (Minas Gerais, 2020). In this context, educating rural producers to use fire more safely, especially when legally authorized and in situations of greater fire danger, as well as monitoring and supervising the execution of burns, can reduce the occurrences of wildfires. This facilitates ecological restoration processes and the natural regeneration of vegetation, consequently reducing impacts on water resources and other ecosystem services provided by forest remnants.

## 5. CONCLUSIONS

The research has identified the period and places most conducive for an ignition source to initiate and propagate a wildfire within spring areas undergoing ecological restoration. Drier meteorological conditions and heightened susceptibility increase the likelihood of fire occurrences, yet anthropogenic influence is a critical determinant in the ignition of wildfires. Defining the months with the highest probability of wildfire occurrences can guide the timing of preventative measures in the restoration plots, such as area clearance in June and the escalation of monitoring and awareness efforts in subsequent months, diminishing the necessity for action from November onwards

Areas with increased ignition susceptibility should prioritize interior plot cleaning to mitigate combustible materials, whereas regions with elevated propagation susceptibility should focus on perimeter cleaning.

The prevalence of incidents in agricultural and pasture lands necessitates targeted campaigns to raise awareness among rural producers regarding the safe utilization of fire, contingent upon authorization from environmental authorities.

The degree of danger, whether high or low, should not dictate the omission of preventative measures in low-risk scenarios. Instead, scheduled execution of activities should commence in June, starting with high-susceptibility areas, followed by medium, and concluding with low-susceptibility regions for forest fires.

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**Declaração de contribuição dos autores**

Fillipe Tamiozzo Pereira Torres - prepared the paper. Shauanne Dias Pancieri - data and map production. Vicente Paulo Santana Neto - technical review and translation. Vinicius Barros Rodrigues - data tabulation.

**Declaração de conflito de interesse**

Os autores declaram que não há conflito de interesse.

**Declaração de disponibilidade de dados da pesquisa**

Todo o conjunto de dados de apoio aos resultados deste estudo foi publicado no próprio artigo.