

Assessing wildfires susceptibility: lithology, vegetation, biomass, and lineaments in the Morro da Pedreira, Brazil, Minas Gerais

Avaliação da suscetibilidade a incêndios florestais: litologia, vegetação, biomassa e lineamentos no Morro da Pedreira, Brasil, Minas Gerais

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RESUMO

Objetivo da investigação: Identificar como a litologia, a biomassa seca, a vegetação, a topografia, os lineamentos e os fatores antrópicos influenciam a dinâmica dos incêndios florestais e determinam a suscetibilidade ao fogo na Área de Proteção Ambiental Morro da Pedreira, fornecendo suporte técnico ao planejamento ambiental, à prevenção e ao manejo integrado do fogo.

Metodologia: A pesquisa foi conduzida por meio de técnicas de geoprocessamento e sensoriamento remoto. Foram analisados dados de biomassa seca, cobertura vegetal e realizada análise fotogeológica para identificar lineamentos estruturais. A integração desses dados permitiu mapear áreas de maior suscetibilidade ao fogo e compreender os padrões de propagação. Além disso, realizou-se análise espacial da distribuição de focos de calor em relação à rede de acesso da área de estudo, incluindo trilhas e estradas.

Resultados: Verificou-se que a orientação dos lineamentos, a litologia, a vegetação, a biomassa seca e o declive do terreno influenciam significativamente a propagação do fogo. Observou-se forte correlação entre os focos de calor e áreas com maior acessibilidade, como trilhas e estradas, evidenciando a contribuição das atividades humanas. As áreas mais suscetíveis foram identificadas e mapeadas, oferecendo base metodológica para o manejo integrado do fogo.

Originalidade/Valor: O estudo amplia o conhecimento sobre a dinâmica de incêndios florestais na Serra do Espinhaço Meridional, integrando variáveis naturais e antrópicas em uma abordagem multidisciplinar. Os resultados fornecem subsídios técnicos para a conservação dos ecossistemas, a proteção da biodiversidade, a segurança da infraestrutura e da população local, além de contribuir para a prevenção de grandes incêndios que ameaçam os recursos naturais.

Palavras-chave: Geoprocessamento; Sensoriamento remoto; Suscetibilidade ao fogo; Manejo integrado do fogo; Incêndios florestais.

ABSTRACT

Research Purpose: To identify how lithology, dry biomass, vegetation, topography, lineaments, and anthropogenic factors influence wildfire dynamics and determine fire susceptibility in the Environmental Protection Area Morro da Pedreira, providing technical support for environmental planning, prevention, and integrated fire management.

Methodology: The research was conducted using geoprocessing and remote sensing techniques. Dry biomass data and vegetation cover were analyzed, and photogeological analysis was performed to identify structural lineaments. The integration of these data enabled the mapping of areas with greater fire susceptibility and the understanding of propagation patterns. Additionally, spatial analysis of heat spot distribution was carried out in relation to the study area's access network, including trails and roads.

Findings: It was found that lineament orientation, lithology, vegetation, dry biomass, and terrain slope significantly influence fire propagation. A strong correlation was observed between heat spots and areas with greater accessibility, such as trails and roads, evidencing the contribution of human activities. The most susceptible areas were identified and mapped, providing a methodological basis for integrated fire management.

Originality/Value: The study expands knowledge about wildfire dynamics in the Southern Espinhaço Range, integrating natural and anthropogenic variables in a multidisciplinary approach. The results provide technical support for ecosystem conservation, biodiversity protection, infrastructure and local population safety, and contribute to the prevention of large wildfires that threaten natural resources.

Keywords: Geoprocessing; Remote sensing; Fire susceptibility; Integrated fire management; Wildfires.

1. Introduction

The Environmental Protection Area (EPA) Morro da Pedreira, located in the Southern Espinhaço Range (SER), plays a key role in environmental conservation. Covering eight municipalities, the region is an important destination for ecotourism, especially the Serra do Cipó National Park (NP). The EPA Morro da Pedreira is part of the geological context of the SER, made up of rocks from the Basal Complex and the Rio Paraúna, Espinhaço and São Francisco Supergroups (Jansen, 2013; Joncew & Campanha, 2025).

However, the conservation unit faces a critical challenge: wildfires. These events are aggravated by various factors, such as the presence of dry biomass, steep terrain, prevailing east-west winds, long periods of drought, inappropriate use of fire and disorderly occupation of the territory.

Given this context, it is crucial to assess the susceptibility of the EPA Morro da Pedreira to fires in order to protect the ecosystem and local communities. The proximity of the region to Belo Horizonte accentuates tourist pressure and contributes to disorderly occupation, factors that increase the risk of wildfire.

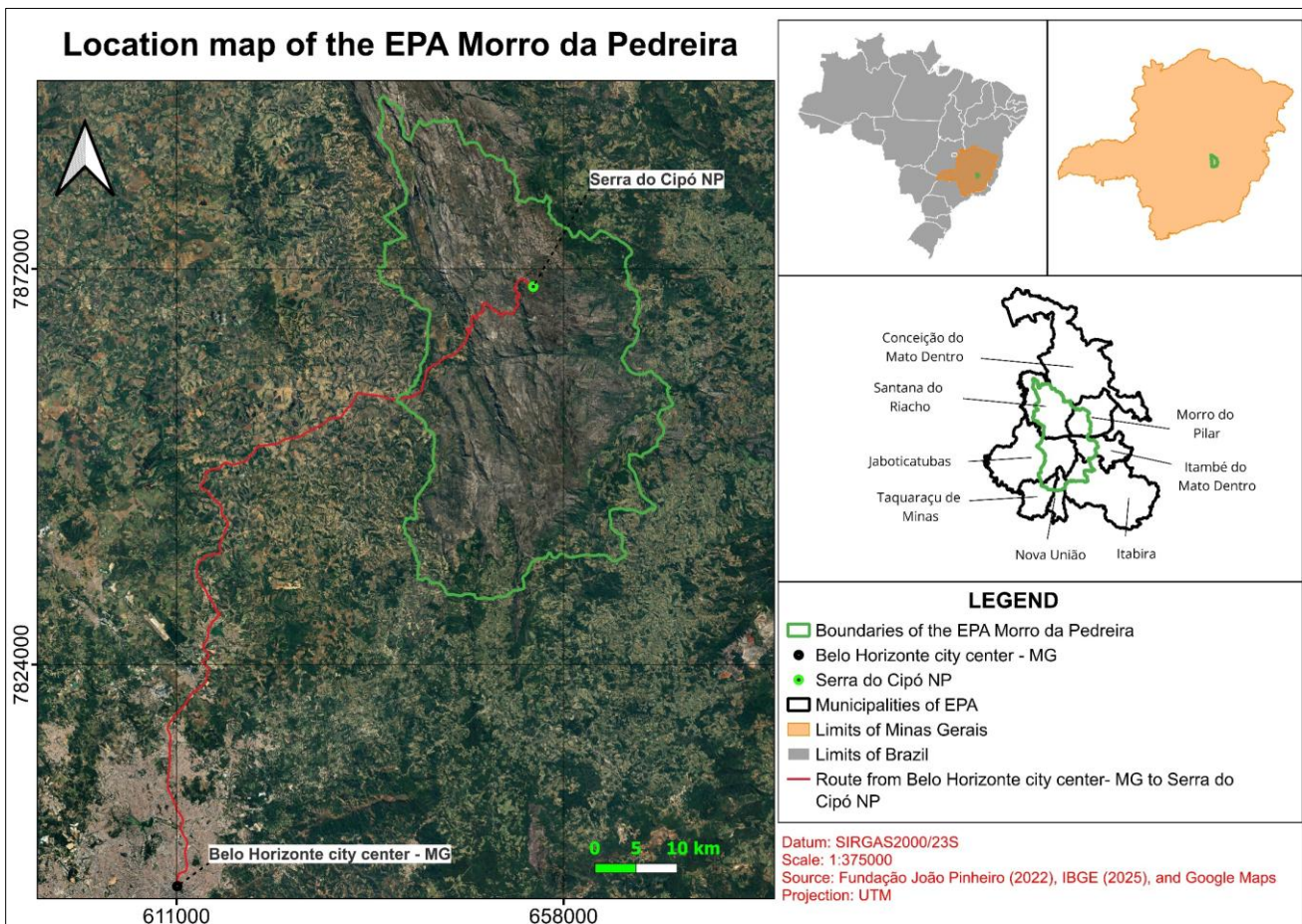
This study uses remote sensing techniques to integrate information on vegetation, dry biomass, lithology and photogeological lineaments in order to identify vulnerable areas and develop strategies for prevention and integrated fire management (MIF). The aim is to promote the conservation of the EPA and reduce the impacts caused by wildfire.

1.1. Location

The EPA Morro da Pedreira is located in the Espinhaço Range, in Minas Gerais, encompasses, according to Chico Mendes Institute for Biodiversity Conservation (ICMBio, 2022), the municipalities of Santana do Riacho, Jaboticatubas, Taquaraçu de Minas, Nova União, Conceição do Mato Dentro, Itabira, Itambé do Mato Dentro and Morro do Pilar. The region's main reference point is the Serra do Cipó NP and it can be reached from the center of Belo Horizonte, about 121 kilometers from the Alto Palácio gate of the Serra do Cipó NP. Figure 1 illustrates the recommended route.

The route starts at Afonso Pena Avenue, number 680. Head towards Amazonas Avenue and turn left onto Espírito Santo street. Continue along do Contorno Avenue and access the East Viaduct, following Cristiano Machado Avenue. Next, enter highway MG-010 heading toward Lagoa Santa and proceed until you reach the Juquinha statue, a tourist attraction located in Santana do Riacho. From this point, continue northeast on highway MG-010 for approximately 3.3 kilometers until reaching the Alto Palácio gate of Serra do Cipó NP.

Figure 1
 Characterization of the study area and access routes



Source: Elaborated by the authors

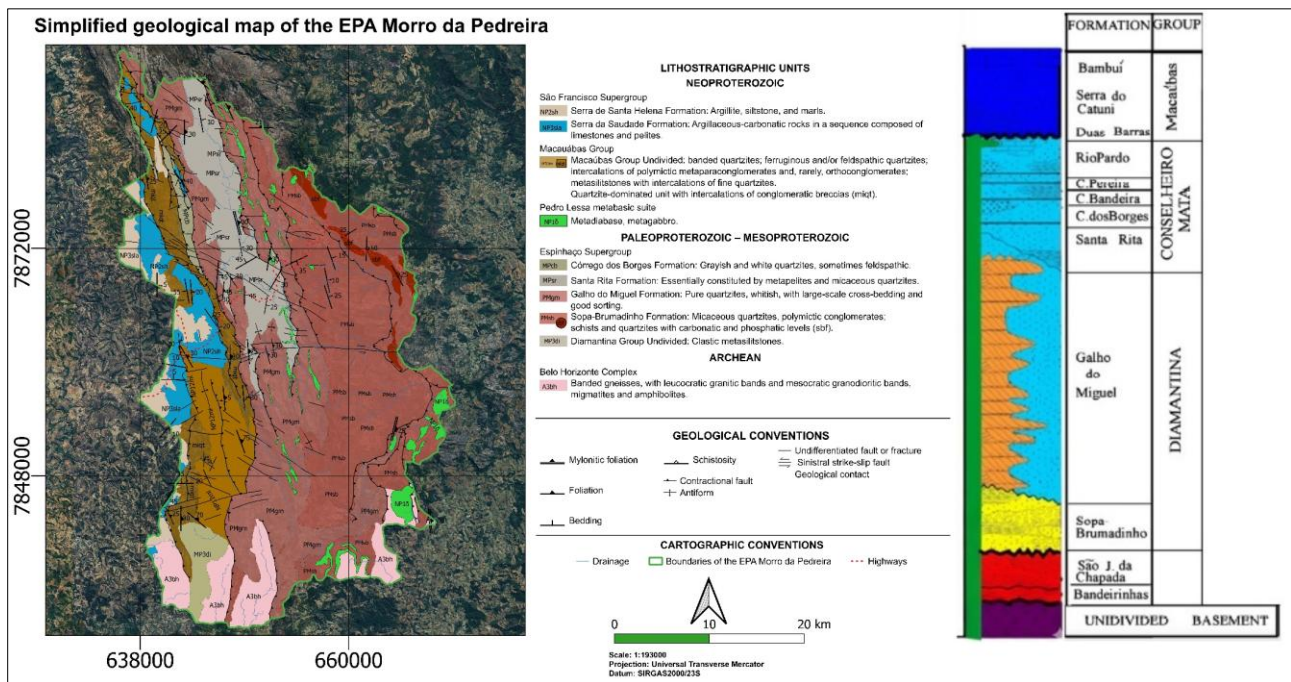
2. Regional Geology

2.1 Stratigraphy

The geological context of the SER is characterized by a basement predominantly composed of granites, gneisses, and migmatites. Over this crystalline basement lie volcano-sedimentary and metasedimentary rocks belonging to the Rio Paraúna, Espinhaço, and São Francisco Supergroups (Jansen, 2013; Joncew & Campanha, 2025). Figure 2 illustrates the spatial distribution of these geological units and the regional stratigraphy.

Figure 2

Schematic map of the EPA geological, with the stratigraphic column corresponding to the SER



Modified from: UFMG et al. (2012); UFMG et al. (2014); Tuller et al. (2010); Padilha et al. (2000); Chemale Jr et al. (2012).

2.1.1. Basal Complex

The Basal Complex, according to Santos (2015), is made up of granites, migmatites, gneisses and restricted bodies of amphibolites. According to Machado et al. (1989), the position of this geological unit is Archean, and it has been dated at approximately 2839 ± 14 Ma by the U/Pb method in zircons in the Goveia Granite.

2.1.2. Rio Paraúna Supergroup

Defined by Fogaça et al. (1984), the Rio Paraúna Supergroup is divided into two groups: the Pedro Pereira Group, with metavolcanites and metasediments remaining from a greenstone belt, and the Costa Sena Group, composed of schists, quartzites and metavolcanics. U-Pb dates on zircons indicate ages of 2971 ± 16 Ma for the metasediments of the Pedro Pereira Group and 2049 ± 16 Ma for the metavolcanics of the Costa Sena Group (Machado et al., 1989).

2.1.3. Espinhaço Supergroup

The main unit of the SER is the Espinhaço Supergroup, subdivided by Dossin et al. (1985) into two groups: the Diamantina Group, which came to include the Banderinha Formation after the revision by Almeida Abreu (1993), and the Conselheiro Mata Group.

Diamantina Group

The Diamantina Group is made up of the Bandeirinha, São João da Chapada, Sopa-Brumadinho and Galho do Miguel Formations (Almeida Abreu, 1993).

Bandeirinha Formation

The Bandeirinha Formation is composed of fine-grained quartzites, with colors ranging from pink to red, displaying medium-scale, high-angle cross-stratification, as described by Benitez (2009). According to Machado et al. (1989) this Formation was deposited around 1752 ± 2 Ma.

São João da Chapada Formation

The São João da Chapada Formation comprises fine to coarse grained quartzites interbedded with pelitic layers and lenses of metaconglomerates containing quartzite and quartz pebbles. These quartzites typically display structures such as planar-parallel stratification, tabular cross-stratification, and ripple marks. Intercalations of hematitic phyllite, associated with the described metasediments, suggest syn-sedimentary magmatism (Egger, 2006). According to Chemale Jr. et al. (2012), U-Pb zircon dating from hematitic phyllites yields an age of 1703 ± 12 Ma.

Sopa-Brumadinho Formation

The Sopa-Brumadinho Formation is characterized by a transition from the medium to coarse grained quartzites of the São João da Chapada Formation to fine-grained, micaceous quartzites, which exhibit low-angle planar and cross-stratification, interbedded with phyllites and metasilites. Polymictic metaconglomerate lenses composed of quartzite, phyllite, and quartz pebbles are common and frequently associated with diamond occurrences (Egger, 2006). The base of the Sopa-Brumadinho Formation has an estimated age of approximately 1180 Ma, based on U-Pb dating of the tuffaceous matrix in a conglomerate from the extraction zone (Chemale Jr. et al., 2010).

Galho do Miguel Formation

The Galho do Miguel Formation is predominantly made up of fine quartzite, characterized by high textural and mineralogical maturity (Egger, 2006).

Conselheiro Mata Group

The Conselheiro Mata Group is made up of the following Formations: Santa Rita, Córrego dos Borges, Córrego da Bandeira, Córrego Pereira and Rio Pardo Grande.

According to Egger (2006), the Santa Rita Formation records a progressive deepening of the water column in the basin, with its base composed of fine quartzites interbedded with metapelites, while the top is dominated by metasilites and phyllites, along with lenses of fine quartzites and local conglomerates. The Córrego dos Borges Formation consists of white-grayish micaceous quartzites with fine to medium granulation, displaying planar-parallel laminations marked by submillimetric levels of iron oxides, as well as cross-bedding truncated by wave action. The Córrego da Bandeira Formation is composed of fine quartzites that gradually transition into gray metasilites, with lenses of phyllites. The Córrego Pereira Formation features fine quartzites interbedded with metapelites, which become more abundant toward the top. Finally, the Rio Pardo Grande Formation is

characterized by the predominance of metasiltites, phyllites and quartzites arranged in rhythmic intercalations, as well as containing lenses of dolomitic marbles.

2.1.4 Pedro Lessa Suite

The Pedro Lessa Suite is characterized mainly by medium-grained metagabbros, which occur as dikes, sills, and stocks, typically oriented in a north-south direction (Uhlein, 1991). U-Pb isotopic analyses of baddeleyite and zircon from these rocks indicate crystallization ages of approximately 906 ± 2 million years, as determined by Machado et al. (1989).

2.1.5 São Francisco Supergroup

The São Francisco Supergroup is made up of two groups: the Macaúbas Group and the Bambuí Group.

Macaúbas Group

The Macaúbas Group is mainly composed of diamictites with a sandy-clay matrix and varied clasts (Tuller et al. 2010). Oliveira et al. (1987, as cited in Tuller et al., 2010) divided it into two units: the undivided, formed by quartzites with intercalations of conglomerates, as well as metasiltites alternating with quartzites; and the Quartzite, characterized by quartzites with intercalations of conglomeratic breccias. At the base of this unit, Pb/U ages of zircons indicate around 900 Ma, estimating the maximum age of deposition (Babinski et al., 2012).

Bambuí Group

The group is predominantly composed of carbonate sequences, with intercalations of pelitic units (Lima et al., 2007). At the base of the unit, Babinski et al. (2007) estimated the age of deposition at 740 ± 22 Ma.

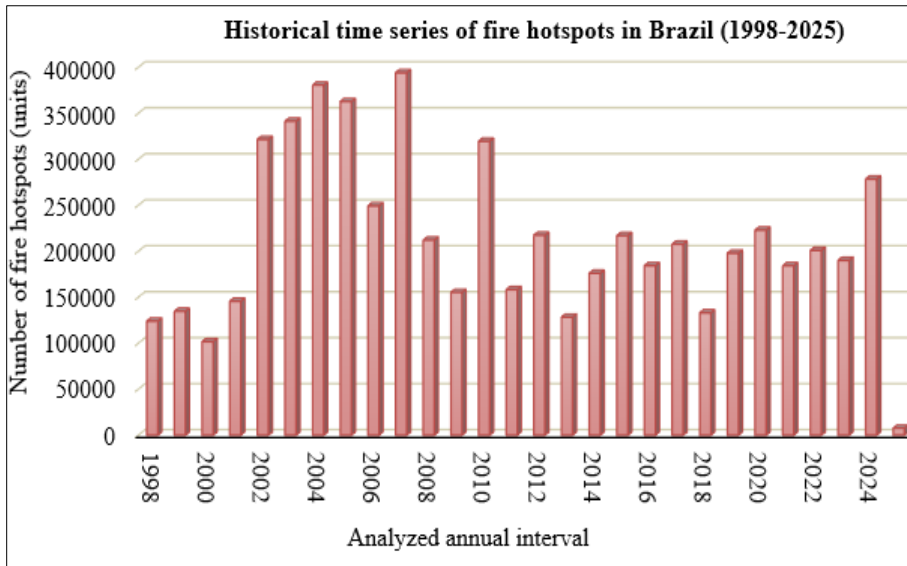
3. History Of Burning

3.1. Brazil

About 1% of wildfires in Brazil originate from natural causes, primarily lightning strikes during convective thunderstorms with intense electrical activity. These strikes can ignite wildfires in dry vegetation, particularly during periods of low humidity and high dry biomass. Other natural agents, such as spontaneous chemical reactions in the soil or ignition from concentrated solar radiation, are extremely rare. The remaining 99% of wildfires are caused by human activities, closely associated with economic practices, especially in areas of agricultural expansion (Moura, 2024).

The historical time series of active fire hotspots detected by satellites in Brazil from 1998 to 2025, according to data from the National Institute for Space Research (INPE, 2025), is presented in Figure 3.

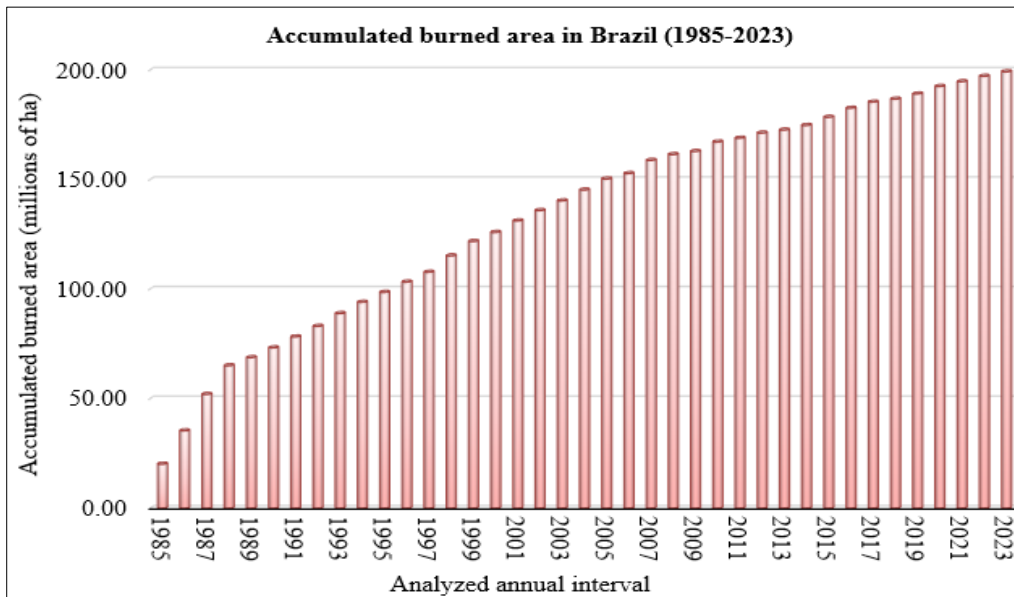
Figure 3
Temporal distribution of fire hotspots in Brazil



Source: INPE (2025)

Additionally, the total accumulated burned area across Brazilian territory from 1985 to 2023, based on the MapBiomas (2023), is shown in Figure 4.

Figure 4
Temporal evolution of accumulated burned areas in Brazil



Source: MapBiomas (2023)

The integrated analysis of this data reveals clear patterns of increase and decrease over time, both in the frequency of fires and in the territorial extension affected, demonstrating a strong correlation between the two indicators.

In 2002, for example, according to Climanálise (2002), the drought caused by the El Niño phenomenon (2002-2003), combined with the use of fire to prepare the soil (especially for growing cotton and beans) in the north and northeast of the country, contributed to the intensification of fires. The peaks in 2003 and 2004 were strongly

associated with the high rates of deforestation in the Amazon, the result of the opening up of areas through land grabbing and invasions, followed by burning to clear the land (França, 2024).

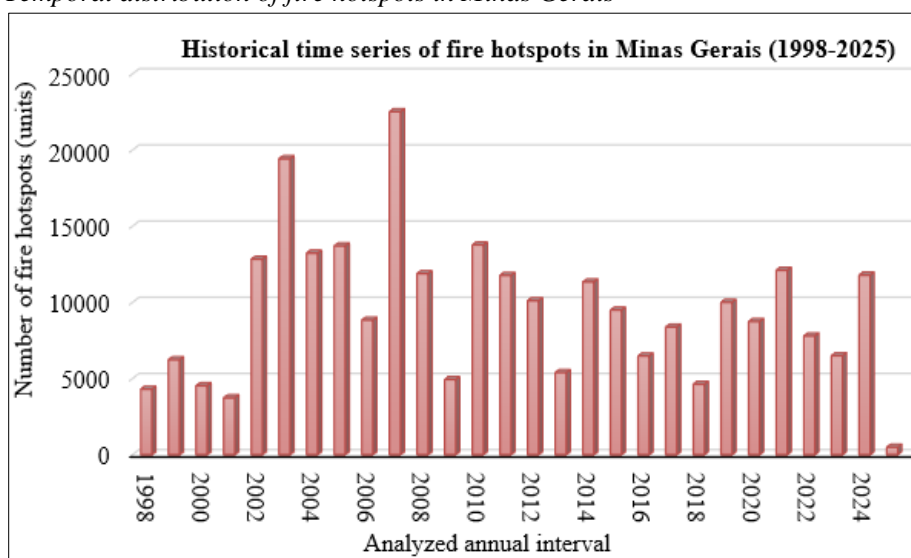
In 2005, an extreme drought, linked to high temperatures in the tropical North Atlantic (National Geographic Brasil, 2021), favored new increases in fire hotspots. A similar situation was repeated in 2010, when the combination of intense droughts and deforestation significantly aggravated fire records. However, the highest peak ever recorded occurred in 2007, driven by the appreciation of agricultural commodities and livestock, as well as high deforestation in the Amazon region (Butler, 2007).

In this context, Law No. 14,944/2024, which establishes the National Policy for Integrated Fire Management, delineates guidelines for the controlled utilization of fire as a sustainable management tool (Brasil, 2024). The legislation acknowledges two distinct modalities: controlled burns, executed pursuant to prior authorization and technical oversight by environmental agencies within designated areas, and prescribed burns, oriented toward environmental conservation via the strategic reduction of dry biomass, thereby averting large-scale wildfires. The law's objective is to harmonize the mitigation of forest fire impacts with the appreciation of fire as a traditional Brazilian practice, ensuring its application as an environmentally efficient tool.

3.2. Minas Gerais

The historical evolution of wildfires in Minas Gerais through two key indicators: the number of fire hotspots recorded between 1998 and 2025, using data from INPE (2025), and the total accumulated burned area between 1985 and 2023, based on information from MapBiomass (2023). Over the years, the number of fire hotspots showed considerable fluctuations, with significant peaks in 2003 and 2007. By April 3, 2025, 491 fire hotspots had already been recorded in the state, as shown in Figure 5.

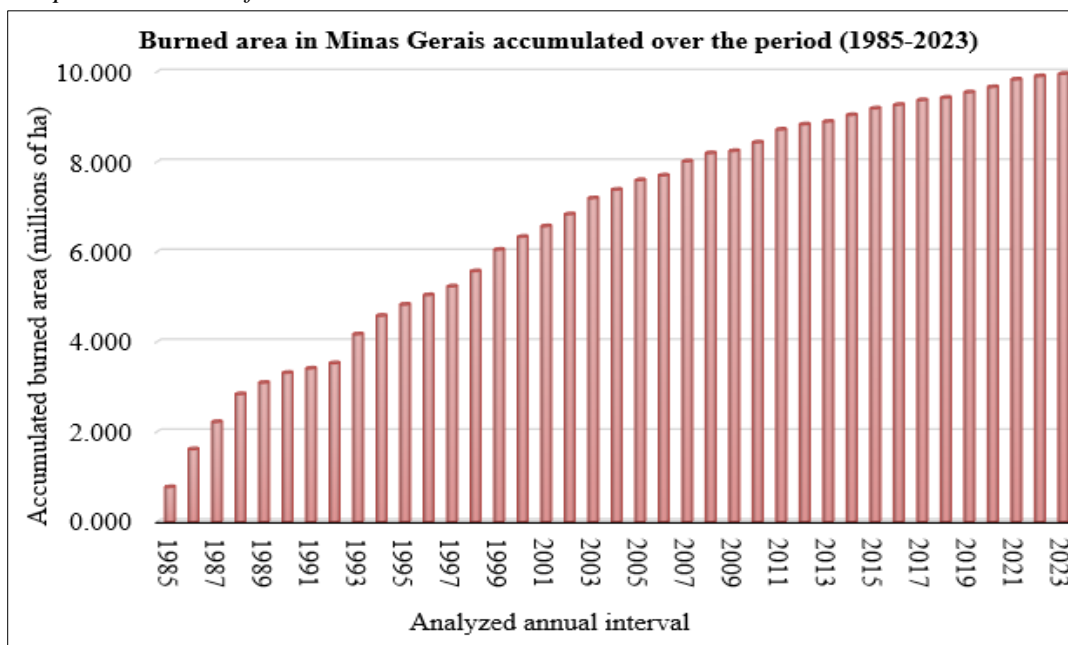
Figure 5
Temporal distribution of fire hotspots in Minas Gerais



Source: INPE (2025)

The accumulated burned area grew from 0.7 million hectares in 1985 to more than 10 million hectares in 2023, with a much sharper increase starting in the 2000s coinciding with the periods that recorded the highest number of fire hotspots. Figure 6 illustrates this evolution of the accumulated area.

Figure 6
Temporal evolution of accumulated burned areas in Minas Gerais



Source: MapBiomass (2023)

Since the late 1970s, Minas Gerais' Cerrado, the state's predominant biome, has been converted into pastures and crops, driven by programs such as the Japanese-Brazilian Cooperation Program for the Agricultural Development of the Cerrados (PRODECER) (Genaro & Chelotti., 2013; Latuf et al., 2022). Between 1985 and 2023, fire consumed around 9954 million hectares in Minas Gerais, which represents 17,07% of the state's territory. This advance has brought important environmental impacts, such as deforestation, reduced humidity and changes in the rainfall regime, factors that favor the spread of fires, especially in years of severe drought, such as 2003, 2010 and 2014. The Cerrado was the most affected biome, with 31.2% of its area affected, and the Triângulo Mineiro and Alto Paranaíba mesoregion, an important agribusiness hub, had 31.3% of its area impacted between 2001 and 2020 (Latuf et al., 2022).

The expansion of agricultural production in Minas Gerais, especially sugar cane, coffee and milk, accompanied the increase in global demand for these commodities in 2007. In the same period, there was a peak in fire hotspots, indicating that the situation in Minas Gerais reflects the national trend of an increase in fires in parallel with the expansion of agribusiness.

However, attributing responsibility for this scenario exclusively to the agricultural sector would be reductionist. Other factors contribute to the worsening situation, such as climate change, which intensifies droughts, and shortcomings in inspection and prevention policies, including the absence of practices such as prescribed burning and environmental education. Furthermore, Andrade (2024) highlights evidence of fires allegedly linked to

economic interests, including mining. Preservation areas, such as the Moeda and Curral Ranges, have experienced wildfires possibly associated with the so-called scorched earth theory. This theory refers to the intentional burning of native vegetation to clear access and facilitate mineral prospecting and extraction.

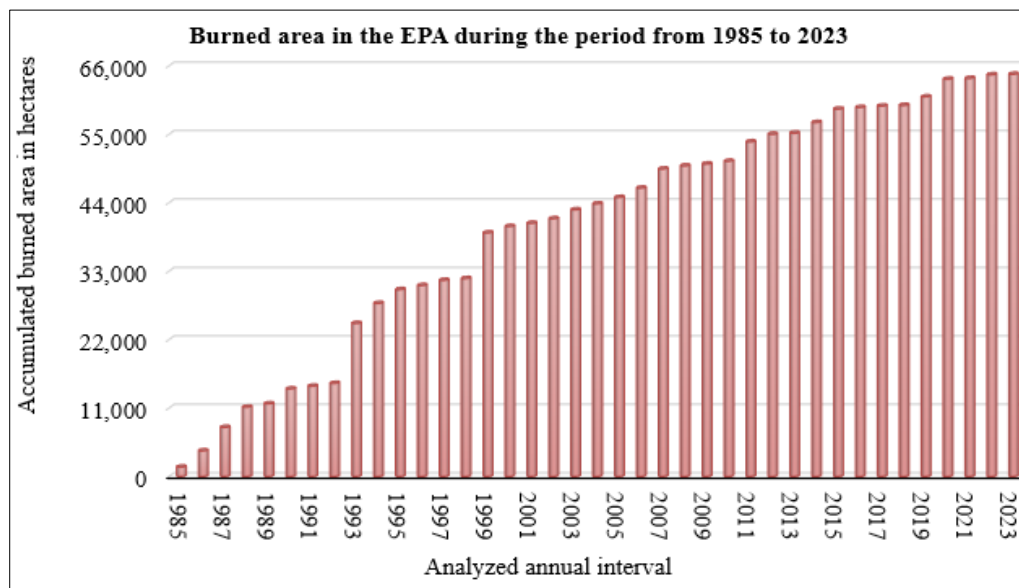
It is important to note that, according to the Military Environmental Police and the State Civil Defense, more than 90% of vegetation fires in Minas Gerais are human-caused (AMDA, 2024).

So, while the correlation between the advance of agribusiness and the increase in fires in Minas Gerais is clear, it is not exclusive. Tackling this problem requires an integrated approach that involves strengthening environmental enforcement, implementing preventive policies, encouraging sustainable practices, and rigorously investigating the interests behind the fires, especially in protected areas.

3.3. EPA Morro da Pedreira

Analysis of fire data from MapBiomias (2023) and INPE (2025) in the EPA Morro da Pedreira reveals a significant increase in the total area affected by fires over time. Between 1985 and 2023, the accumulated burned area exceeded 64,000 hectares, which corresponds to about 48.6% of the EPA's total area. A more pronounced acceleration trend can be seen from the 2000s onward, possibly associated with the intensification of human activities and climate change, which make the environment more prone to fires, as can be seen in Figure 7.

Figure 7
Temporal evolution of accumulated burned areas in EPA Morro da Pedreira



Source: MapBiomias (2023)

The average annual burning rate can be estimated by dividing the total area burned by the number of years analyzed, as shown in Equation 1:

$$\text{Average rate} = \frac{64653}{38} \approx 1701.4 \text{ hectares per year} \quad (1)$$

If this average rate is maintained over the next 20 years (until 2043), it is estimated that another 34028 hectares could be burned, bringing the total area affected to around 98681 hectares, equivalent to 74.9% of the EPA. This projection reinforces the urgency of immediate interventions to reduce the frequency and extent of fires, as such impacts would imply the loss of biodiversity, soil degradation, compromised springs, and greater vulnerability to new fires. The urgency of actions such as intensive monitoring, environmental education and ecological restoration is therefore evident.

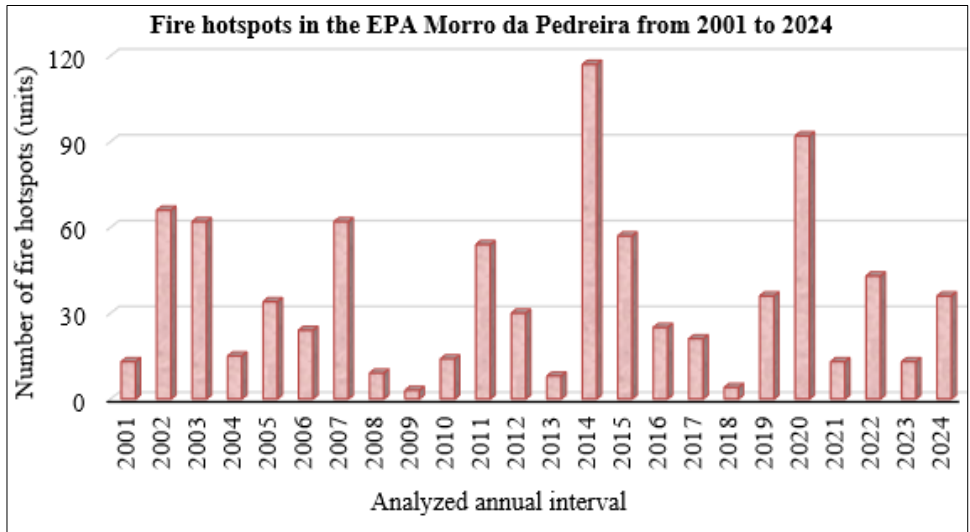
It is important to note that this projection is based on a constant average rate, which is a simplification of reality. Factors such as public policies, climate change or increased human activity could significantly alter this trend. In addition, areas that have already been burned may suffer a recurrence of fires, which would not increase the total accumulated area, but would aggravate environmental degradation.

The annual data on fire hotspots between 2001 and 2024 shows significant fluctuations, with notable peaks in 2014 and 2020. The year 2014 was marked by an extreme drought, considered the worst in a century, according to the newspaper *Estado de Minas* (2014), which favored the spread of large fires, reflecting the higher number of fire hotspots recorded by INPE. Despite the occurrence of the first prescribed burns that year, the predominant ignition was of anthropogenic origin.

In 2020, although there were no records of severe drought in the National Water Agency's (ANA, 2020) Drought Monitor, the number of fire hotspots increased significantly. Possibly the COVID-19 pandemic has compromised environmental monitoring, contributing to the increase of illegal burning and other disorderly human actions, such as the expansion of agricultural practices.

On the other hand, years such as 2015 and 2021 showed significant drops in fire hotspots. In 2015, it is plausible that the reduction is associated with the lower availability of dry biomass, resulting from the large fires that occurred in 2014, as well as the possible impacts of the MIF actions in the region. In the case of 2021, it can be hypothesized that the partial resumption of on-site activities, accompanied by the strengthening of inspection, has contributed to the reduction in fire hotspots (ICMBio, 2022), in addition to the lower accumulation of remaining dry biomass. Figure 8 shows the temporal distribution of fire hotspots data in the EPA from 2001 to 2024.

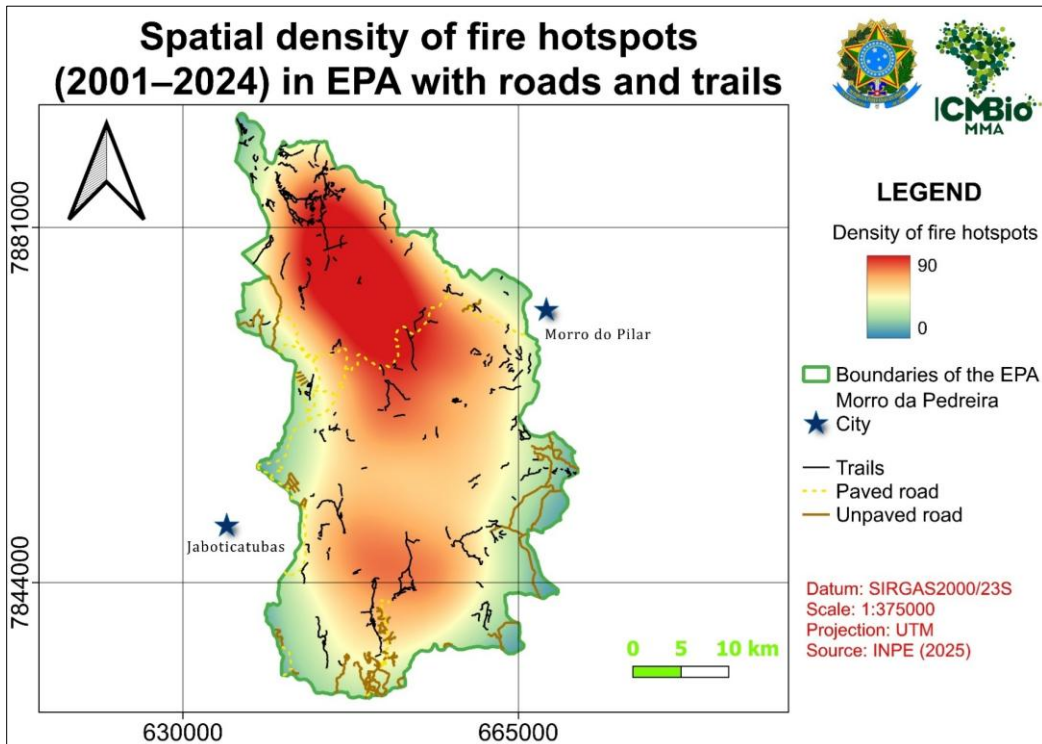
Figure 8
Temporal distribution of fire hotspots in the EPA Morro Pedreira



Source: INPE (2025)

The spatial analysis of fire hotspots density in the EPA, from 2001 to 2024, reveals a strong correlation between areas with higher fire recurrence and the network of roads and trails. This overlap suggests that the intensive use of these pathways is directly linked to wildfires, particularly in regions with high accessibility and visitation within the conservation unit, as shown in Figure 9.

Figure 9
Spatial density of fire hotspots (2001–2024) in EPA displaying spatial frequency patterns in relation to roads and trails



Source: Elaborated by the authors

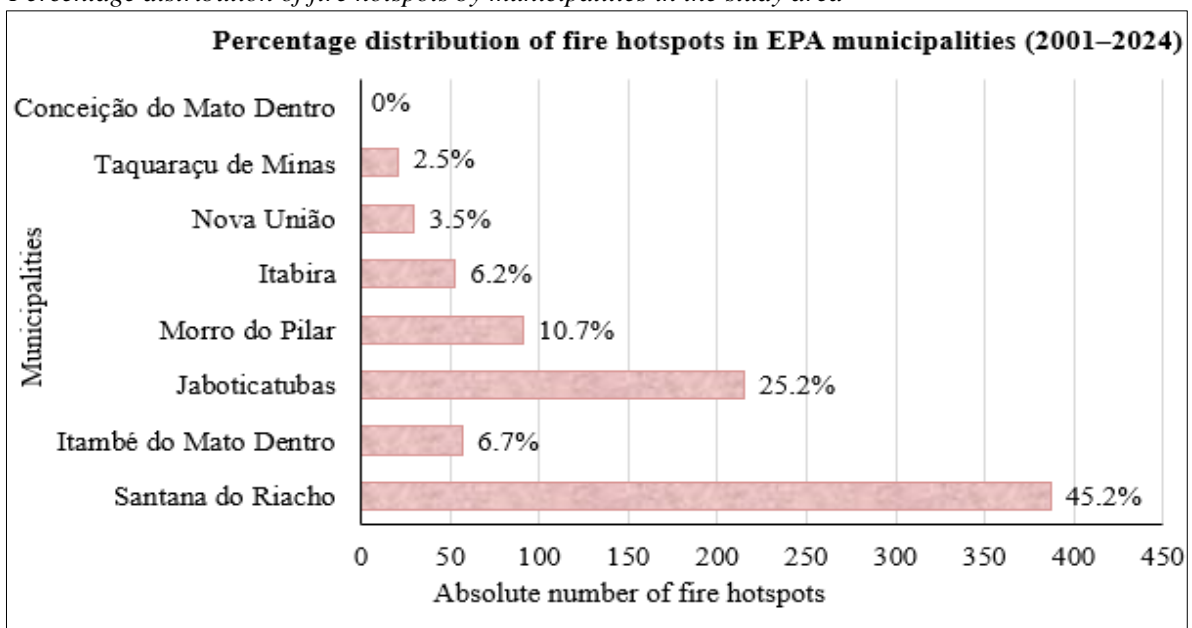
A plausible hypothesis for this pattern is the impact of unregulated tourism, characterized by visitors lacking environmental awareness, insufficient continuous monitoring, and infrastructure unsuitable for the area’s environmental sensitivity (ICMBio, 2022). Practices such as lighting campfires, improper waste disposal, vehicle traffic in vulnerable areas, and movement through dry, highly flammable vegetation may act as accidental or negligent ignition sources.

The most critical areas, located in the NNE and SSW quadrants, exhibit the highest density of fire hotspots, coinciding with extensive road infrastructure and human presence. This scenario underscores the role of unregulated tourism and unplanned urban expansion in the dynamics of wildfires.

Consequently, integrated policies for fire prevention and control are essential, focusing on tourism regulation, continuous monitoring of sensitive areas, environmental education, and strengthened enforcement.

As for the municipal distribution of fire hotspots, the municipality of Santana do Riacho stands out, with 45.2% of the records, followed by Jaboticatubas (25.2%) and Morro do Pilar (10.7%). As can be seen in figure 10.

Figure 10
Percentage distribution of fire hotspots by municipalities in the study area



Source: INPE (2025); ICMBio (2022)

Together, these three municipalities account for more than 80% of the fire hotspots in the EPA, which reinforces the need to prioritize preventive public policies and combat strategies aimed at these localities. It is worth remembering that Santana do Riacho, Jaboticatubas and Morro do Pilar are also the municipalities with the largest territorial extension within the conservation unit.

As outlined in the Integrated Fire Management Plan – PMIF (ICMBio, 2022), the irregular use of fire to renew pastures continues to be one of the main causes of ignition in the region. Even with the removal of cattle and the regularization of land ownership, the intentional introduction of animals by some landowners, who set fires in areas

bordering the conservation unit to encourage the sprouting of vegetation with greater forage value, is still recurrent. In response to enforcement, which involves fines and the removal of these animals, fires are deliberately set as a form of retaliation. This evidence indicates that the fire regime in the area remains strongly conditioned by human activities, especially during the dry season, when the occurrence of lightning, the main natural cause of ignition, is nonexistent.

4. Methodology

4.1. Management areas

As described in the ICMBio (2022), fire management strategies in the Serra do Cipó NP have prioritized the protection of regenerating areas and the adoption of measures to ensure a rapid and efficient response to wildfire, especially during the critical period between August and October. During this period, environmental conditions favor the spread of fire, making it potentially uncontrollable if there is no immediate intervention.

On the other hand, fires that occur before July are considered lower risk and are fought with less urgency. This is due to the fact that, during this period, the humidity of the air and vegetation has not yet reached critical levels, which contributes to the natural slowing down of the flames or their extinction in natural barriers, such as watercourses, forest fragments and rocky outcrops.

The delimitation of areas under fire management, according to the methodology adopted in the ICMBio (2022), is based on an integrated and participatory approach, based on ecological, operational and historical criteria. Accumulated fire data, records of firefighting and prevention actions, as well as the technical and empirical knowledge of the management teams, firefighters and local partners were used. This set of information made it possible to identify areas that are sensitive to fire, such as regenerating forest formations, highly biodiverse rupestrian fields and areas with an accumulation of dry biomass.

The areas were organized into operational sectors, defined by natural boundaries (rivers, elevations), existing infrastructure (roads, trails, operational bases), land use and specific threats. The mapping of the areas was carried out with the support of geoprocessing tools, using satellite images, data from the INPE, thematic maps (slope, dry biomass, Normalized Difference Vegetation Index, outbreak frequency, burning scars and humidity seasonality), as well as field checks. The methodology also incorporated social aspects, such as the presence of traditional populations and local partners, with the aim of strengthening preventive and educational actions.

The Cerrado Monitoring Program provided the technical and operational foundation for enhancing this methodology by providing high-resolution geospatial data, standardized techniques for fire risk assessment, and tools compatible with ICMBio's Geographic Information System (GIS). These resources enabled the generation of georeferenced polygons, facilitating dynamic analyses, real-time monitoring, and strategic planning of annual fire management actions. The most vulnerable sectors are prioritized for interventions, including the construction of firebreaks, implementation of prescribed burns, patrolling, and environmental education activities. This is a continuous and adaptive process, adjusted based on geospatial analyses of changes in fire patterns and land use

alterations. The annual planning is grounded in essential strategic variables, outlined as follows:

- **Dry biomass:** This refers to the accumulated combustible material, which is essential for estimating the intensity and extent of fires. High levels of biomass indicate greater risk and require measures such as controlled burning or preventive firebreaks. This variable is given a weight of 2 in the analysis, given its relevance. Example: an area with dry grasses after prolonged drought has a high potential for severe fires. The data is obtained via Cerrado Monitoring Program, according to the methodology adapted from Franke et al. (2018).
- **Vegetation:** Influences fire behavior and the ecological sensitivity of areas. Environments with dense vegetation or rare ecosystems require special protection, while other areas can be managed with the controlled use of fire. This variable is also given weight 2 in the analysis. Example: riparian forests need strict protection, while dry grasslands can be subjected to prescribed burning. The data is provided internally by ICMBio.
- **Slope:** The slope directly impacts the speed of fire spread. Steeper terrains accelerate this process, as the heat from the flames preheats the vegetation located above the fire front, facilitating combustion. The slope is calculated from Digital Elevation Models.
- **Frequency of fire hotspots:** Indicates the recurrence of fires in a given area, signaling regions with persistent causes and greater risk of ignition. Example: stretches near highways with an annual history of fire hotspots require constant monitoring. The data is obtained from INPE (2025).
- **Burn scars:** Points out areas affected by fires in the previous year, identified through changes in vegetation detected by satellite. The Normalized Burn Ratio (NBR) index is used, which assesses the severity of fires based on a comparison between pre- and post-fire images.
- **Weather conditions:** When prescribed burning is carried out during periods with mild temperatures and higher relative humidity, such as late afternoon, at night or in the early hours of the morning, the tendency is for the fire to spread with less intensity and severity. For this reason, the application of controlled fire is usually planned for the interval between the end of the rainy season and the peak of the dry season. This period, known as the "burning window", is characterized by more favorable atmospheric conditions and the presence of combustible material in a state suitable for the management objectives (Oliveira et al., 2022; Santos et al., 2021).
- **Photolineament:** The predominant direction of fires in the region follows the NW-SE and E-W structural lineaments. These orientations directly influence fire propagation, as they align with prevailing winds and terrain characteristics, facilitating the spread of flames, especially in areas with greater accumulation of dry biomass.
- **Lithology:** The composition of rocks directly influences the characteristics of the soils formed, such as

depth, fertility, and water retention capacity. Depending on the lithology, soils may promote greater accumulation of dry biomass, making them more prone to generating combustible material and, consequently, to fire propagation.

- Wind patterns: Prevailing winds blow from east-northeast (ENE) toward west-southwest (WSW), with a secondary maximum in the east-west (E-W) (Martins et al., 2021). During the dry season, when the combination of low relative humidity and accumulated dry biomass creates favorable conditions for ignition, these winds interact with lineaments oriented E-W and NW-SE, which act as natural corridors that channel and accelerate airflow, creating preferential pathways for fire spread. Lineaments aligned with the wind direction (particularly E-W) are the most critical, as they maximize the channeling effect. The association between wind direction and lineament orientation significantly accelerates fire propagation, particularly in areas with steep slopes where the chimney effect further amplifies flame advancement.

4.2. Management criteria

Although the general methodology follows the guidelines established in the ICMBio (2022), the selection and spatial definition of the sectors prioritized for fire management in 2024 were carried out by the author based on geospatial analysis and updated environmental data. Figure 11 shows the sectors selected for integrated fire management in 2024, each defined based on specific criteria that considered aspects such as dry biomass accumulation, photolineament, fire frequency, vegetation characteristics, topography, anthropogenic pressures and lithology.

Strategic variables for wildfire risk assessment were integrated through geospatial analysis, employing a qualitative overlay of thematic layers to delineate priority management sectors.

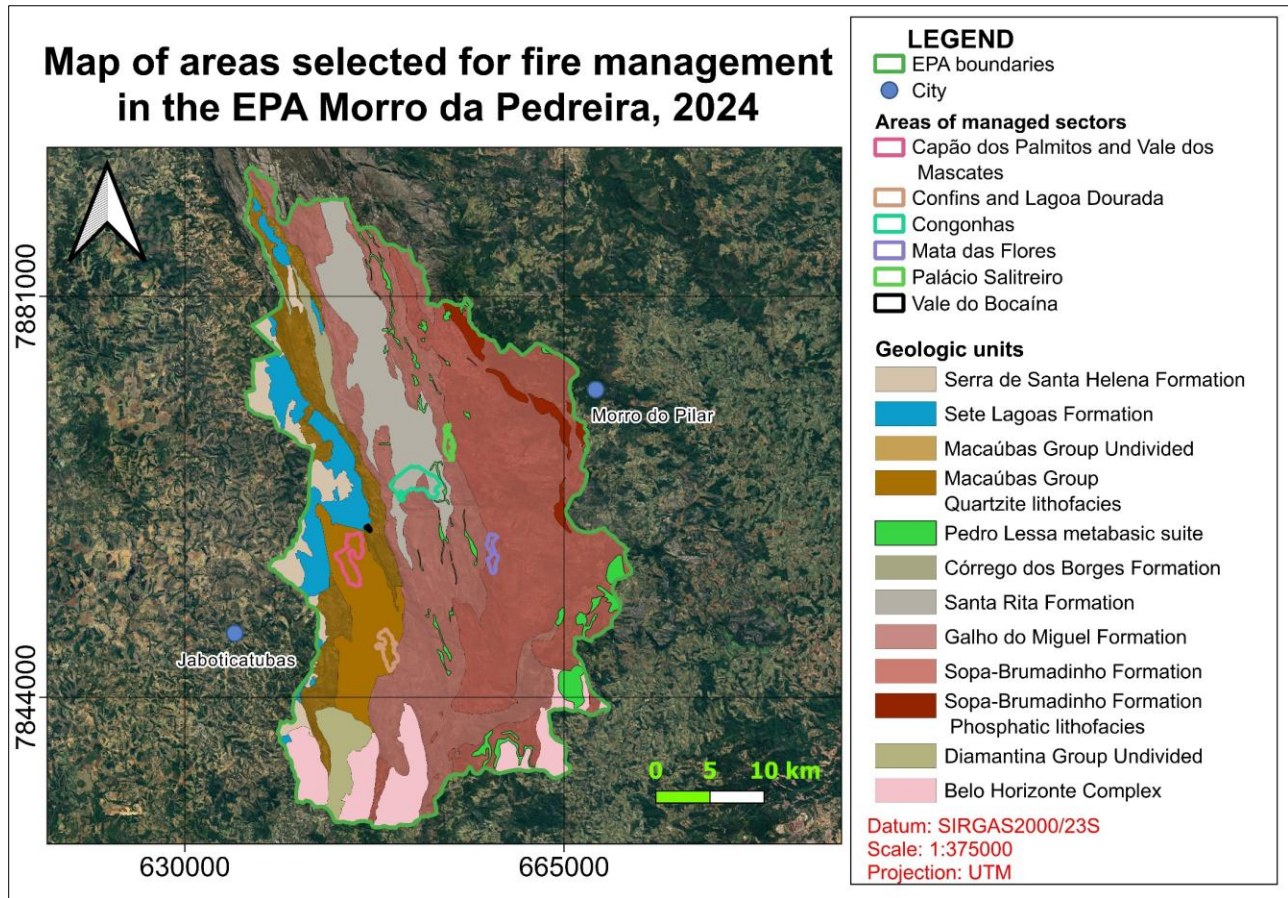
The weighting system drew on the theoretical framework of the fire triangle, which posits that fire occurrence requires the simultaneous presence and interaction of three fundamental elements: fuel, a comburent (typically oxygen), and heat (ignition source) (Stauffer et al., 2008).

This framework informed the assignment of higher weight (2) to dry biomass and vegetation variables. In seasonally dry environments such as the EPA Morro da Pedreira, dry biomass corresponds to the fuel component of the fire triangle. The quantity of available organic material directly determines fire intensity and spread rate, justifying its elevated weighting. Vegetation, in turn, influences both the type and continuity of fuel loads while encompassing sensitive areas warranting priority protection.

The remaining variables received a weight of 1, as they primarily affect fire spread across the landscape rather than initiation. The comburent, typically oxygen, is ubiquitous in the atmosphere and exhibits negligible spatial variation within the study area, thus not warranting differential weighting. To ensure temporal consistency, all datasets were organized and analyzed on an annual basis. This approach enabled hierarchical spatialization of fire risk, thereby supporting prevention and management strategies.

Figure 11

Managed areas in 2024



Modified from: UFMG et al.,(2012); UFMG et al., (2014); Tuller et al., (2010); Padilha et al., (2000)

The Mata das Flores, Palácio Salitreiro, Capão dos Palmitos and Vale dos Mascates, Congonhas do Travessão, Vale do Bocaina, Confins, and Lagoa Dourada sectors were selected based on their ecological significance, fire frequency, and operational needs, as outlined in the ICMBio (2022). These areas encompass diverse landscapes, such as riparian forests and rupestrian fields, each requiring tailored strategies to mitigate fire impacts. The following sections detail the unique characteristics and management priorities of these sectors, emphasizing their role in protecting the region’s ecosystems.

Mata das Flores

Located east of the Serra Cipó NP, the Mata das Flores sector was prioritized due to significant accumulations of dry biomass outside the park’s boundaries, associated with steep terrain and prevailing east-west winds. Photolineaments trend northwest-southeast, situated at the contact zone between the Sopa-Brumadinho Formation (impure quartzites) and the Galho do Miguel Formation (pure quartzites). As one of the NP’s most significant forest fragments, this sector requires urgent preventive measures to safeguard biodiversity and mitigate fire risks.

Palácio Salitreiro

Adjacent to the MG-010 and MG-232 highways, the Palácio Salitreiro sector is a high-risk area due to frequent

fires and steep topography, which complicates access and operational mobility. The landscape comprises sensitive and pyrophytic vegetation, with photolineaments trending east-west, located at the transition between the Sopa-Brumadinho and Galho do Miguel Formations (pure and impure quartzites respectively). The Alto Palácio-Serra dos Alves Traverse trail serves as a strategic access and anchoring point for prescribed burning operations, optimizing fire management efforts.

Capão dos Palmitos and Vale dos Mascates

Situated in the western portion Serra do Cipó NP, these sectors were selected due to substantial dry biomass accumulation and a lower presence of sensitive vegetation. Fire frequency is moderate, but proximity to the Lagoa Dourada sector, outside the park's boundaries, increases anthropogenic pressure and fire risk. Photolineaments trend east-west, and the area lies over quartzitic lithofacies with lateral variation in the degree of impurity of quartzites interbedded with conglomerates. Management of these areas aims to protect ecosystems and mitigate fire impacts.

Congonhas do Travessão

Located in the western EPA, this sector was chosen due to its steep terrain and considerable dry biomass accumulation, exacerbated by proximity to the MG-010 highway, which subjects the area to constant fire pressure intensified by predatory tourism. Photolineaments trend northwest-southeast, situated at the contact between pure quartzites of the Galho do Miguel Formation and metasilites of the Conselheiro Mata Group. With minimal sensitive vegetation, the area was impacted by fires in 2020 and retains significant fuel loads, necessitating management interventions.

Vale do Bocaina

Characterized by predominantly herbaceous vegetation, the Vale do Bocaina is located at the contact between quartzitic lithofacies and argillaceous-carbonatic sequences, with no identified photolineaments. Management of this area is critical to protect sensitive vegetation, water recharge zones, and promote environmental and species diversity, while reducing the risk of fire spread.

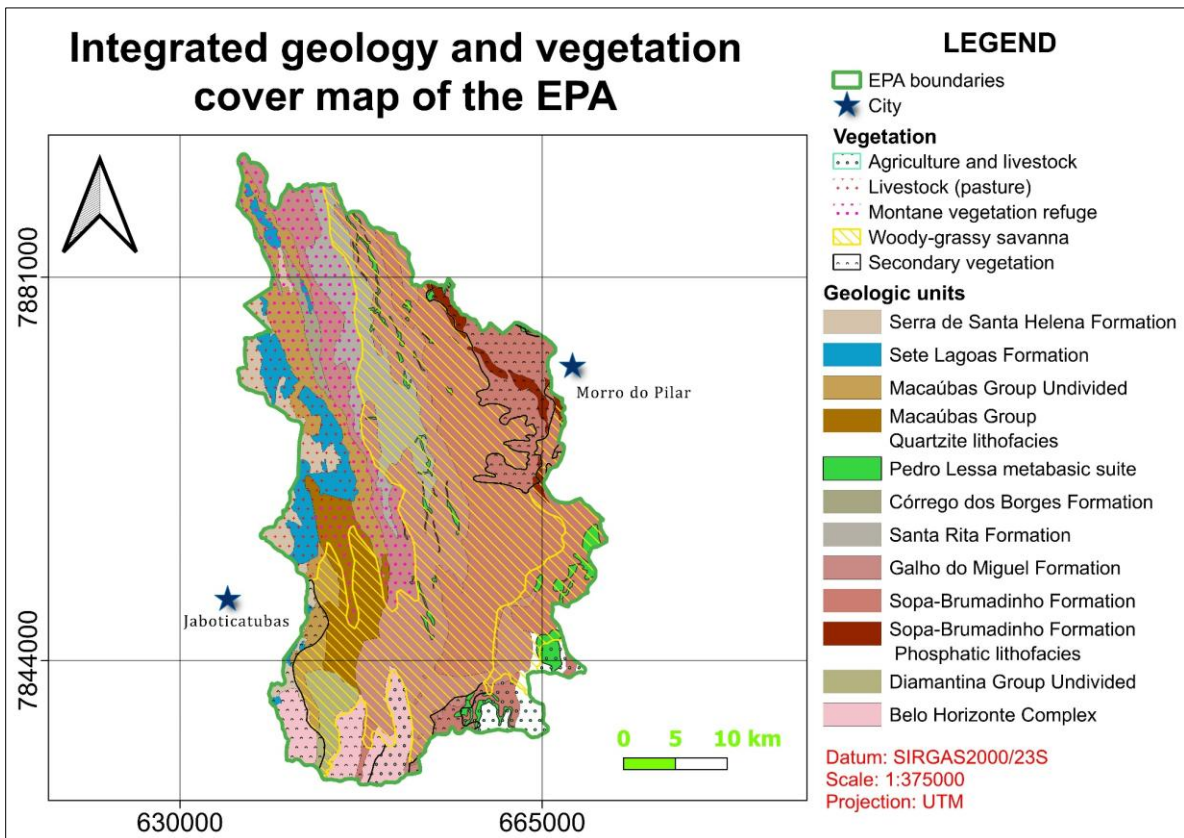
Confins and Lagoa Dourada

Positioned in the southwestern part of the conservation unit, the Confins and Lagoa Dourada sectors experience a high frequency of fires, aggravated by improper livestock farming and predatory tourism. Photolineaments trend northwest-southeast, mapped over quartzitic lithofacies with interbedded metaconglomerates at the contact with pure quartzites of the Galho do Miguel Formation. Interventions in these sectors aim to mitigate anthropogenic impacts and protect local ecosystems, reducing fire risks.

5. Relationship between lithology, vegetation, and biomass in the geological units of the study area

According to the ICMBio (2022) for the EPA Morro da Pedreira, rock outcrops serve as critical biodiversity refuges in fire-prone environments. Non-fire-resistant vegetation tends to concentrate on these surfaces, where fire spread is naturally limited. Figure 12 presents a thematic map correlating lithological characteristics with vegetation types.

Figure 12
Integrated geology and vegetation cover map of the EPA showing spatial distribution of geological formations and land use patterns



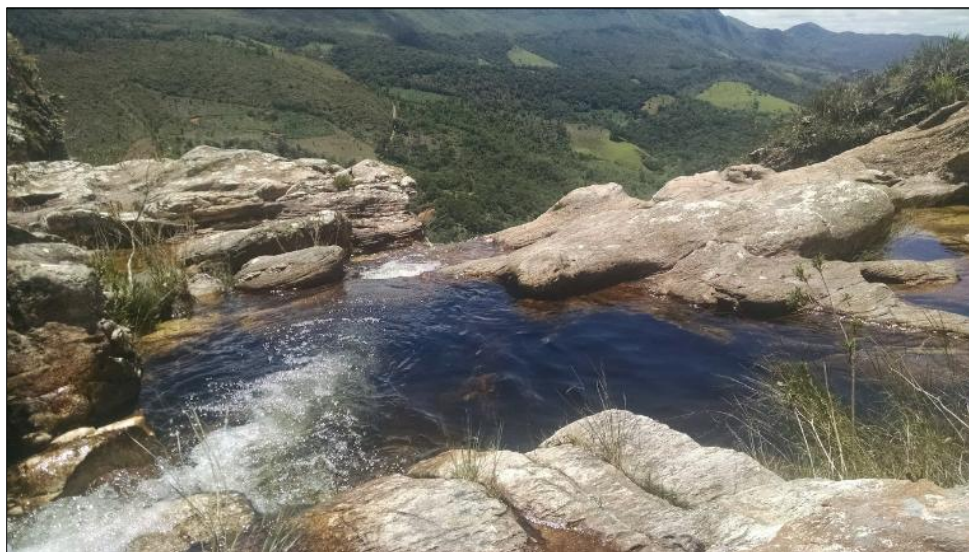
Modified from: UFMG et al., (2012); UFMG et al., (2014); Tuller et al., (2010); Padilha et al.,(2000); IBGE (2025)

In areas associated with the Belo Horizonte Complex, primarily composed of gneisses and migmatites, exposed rock outcrops are uncommon. These lithologies give rise to thick, clay-rich, and structurally complex soils that support the development of continuous vegetation cover. In regions with gentler topography and loamier textures, these rocks produce deep, well-drained soils. Such soil conditions are conducive to both agricultural activities and the establishment of secondary vegetation. The presence of palm trees indicates soils with good subsurface water retention capacity.

In this context, biomass tends to be denser, consisting of woodier and moister plant material, which inhibits flame propagation. Consequently, flammability is reduced, and fires, when they occur, tend to spread more slowly and with lower intensity compared to areas with shallow soils and open vegetation, as illustrated in Figure 13.

Figure 13

Contact between the Galho Miguel Formation and the Belo Horizonte Complex



Source: Google Earth

The Sopa-Brumadinho Formation is primarily composed of impure quartzites, which form relatively shallow soils with limited fertility. These soils are slightly more developed than those formed on pure quartzites, supporting the establishment of low to medium-height vegetation that is sparse, with a high proportion of grasses and shrubs. During the dry season, this type of vegetation accumulates a large amount of fine, dry material, resulting in highly flammable biomass. It is within this formation that the highest number of recorded fires in the study area is observed. The combination of dense grassy vegetation and shallow soil creates an environment highly conducive to ignition and fire spread.

The Galho do Miguel Formation, composed of pure quartzites, in turn, gives rise to shallow, acidic soils with low fertility and limited moisture retention capacity. The associated vegetation is characteristic of rupestrian fields, adapted to nutrient scarcity and water stress, forming specialized montane refugia. These quartzites act as natural fire barriers, impeding fire spread. Due to the shallow soils and sparse vegetation, there is minimal accumulation of combustible material, which limits flame intensity. In these areas, fires tend to slow down or even halt, as the rock itself prevents flame propagation. Additionally, fractures in the quartzites can retain localized moisture, fostering denser vegetation in specific patches. These zones serve as further natural barriers to fire spread. Even during the dry season, when biomass becomes flammable, the lack of continuous combustible material reduces the speed and intensity of fires. Figures 14 and 15 illustrate the contrast between the Sopa-Brumadinho and Galho do Miguel Formations.

Figure 14
Sopa-Brumadinho Formation



Source: Google Earth

Figure 15
Galho do Miguel Formation



Source: Google Earth

The Conselheiro Mata Group, illustrated in Figures 16 and 17, is characterized by rupestrian fields associated with quartzite outcrops and a highly dissected topography of aligned ridges and sierras sculpted in quartzitic rocks. This terrain compartmentalization creates distinct microclimates and ecological niches, fostering a high degree of floral endemism. Vegetation, primarily on ridge tops and slopes over pure quartzites, is highly specialized, with morphophysiological adaptations to severe nutritional and water stress in nutrient-poor soils. In embedded drainages and valley bottoms, where fine quartzose sediments and organic matter accumulate, grassy-woody savannas and gallery forests develop. These microenvironments feature relatively higher water availability, modest nutrient enrichment from organic matter, and less restrictive soil conditions compared to quartzitic ridge tops. Gallery forests, confined to watercourses with consistent water supply, represent the only environments with minimally favorable soil conditions within this geological substrate.

The Santa Rita Formation introduces local heterogeneity through meta-siltstone and ferruginous quartzite layers. Metasilites intercalations support more robust grassy-woody savannas, while ferruginous quartzite layers enhance water retention, favoring the establishment of gallery forests. As depicted in Figure 16, valley bottoms exhibit dark-colored watercourses, typical of organic-rich soils and cerrado vegetation. On slopes and summits, vegetation consists mainly of grasses, shrubs, and small trees adapted to shallow, rocky, nutrient-poor soils, with some rocky surfaces showing an orange hue, possibly indicating micaceous minerals.

Given these conditions, the landscape exhibits high flammability resulting from the interaction of four main factors:

- Quartzitic lithology: shallow, dry soils supporting xeromorphic vegetation and an abundance of fine fuels;
- Rupestrian campo/cerrado vegetation: high production of seasonal dry biomass;
- Irregular topography with exposed slopes: promotes a “chimney effect” that accelerates flame spread;
- High density of photolineaments with a predominant NW-SE orientation: especially in areas of steep slope, influencing fire dynamics.

Even small ignition sources can escalate into large-scale fires, particularly during the transition to the dry season when combustible material accumulates. Fire recurrence in this environment results from a combination of natural and anthropogenic factors, amplified by the region’s lithological, topographic, and ecological configuration.

Figure 16

Conselheiro Mata Group with less dense vegetation



Source: Google Earth

Figure 17

The Conselheiro Mata Group with denser vegetation than figure 16



Source: Google Earth

Yellow dashed lines are used to mark the quartzites of the Espinhaço Supergroup predominate, forming steep, sparsely vegetated slopes. The soils are shallow, sandy, and nutrient-poor, which limits vegetation development, resulting in sparse, low-height cover with minimal biomass accumulation. This type of environment is more susceptible to rapid fire spread, particularly during dry periods.

The Pedro Lessa Suite marked by red dotted lines, is composed of metabasic rocks rich in mafic minerals such as amphibole and pyroxene. The weathering of these minerals produces deeper, clay-rich, and relatively fertile soils with higher contents of magnesium, calcium, and iron. This composition enhances moisture retention and supports the development of denser, taller, and more continuous vegetation. The plant biomass in the Pedro Lessa Suite area is substantial but predominantly consists of moist, woody material, which hinders ignition and slows fire spread. Additionally, the improved soil drainage capacity helps maintain moisture levels, further enhancing the landscape's resistance to fires.

This abrupt transition between the two environments illustrates how lithology directly influences soil structure, vegetation type, and fire dynamics, making it a critical factor for environmental management and fire prevention strategies in the EPA Morro da Pedreira. In Figure 18, the contrast between the Pedro Lessa Suite and the Espinhaço Supergroup is clearly observed, with a notable difference in landscape and vegetation.

Figure 18

Viewpoint of Tombador waterfall highlighting the Pedro Lessa Suite in red and the Espinhaço Supergroup in yellow dashed lines



Modified from: Google Earth

The water flow percolates through the fractures of the pure quartzites of the Galho do Miguel Formation, highlighted in yellow dashed lines in the image. These quartzites are associated with steep slopes and shallow soils, which result in sparser, lower-height vegetation.

In contrast, the areas marked in brown dashed lines correspond to the Macaúbas Group, where less pure quartzites and diamictites predominate. This lithological diversity promotes the formation of more developed soils with greater moisture retention capacity and nutrient availability. As a result, a denser, taller, and more continuous vegetation cover is observed, with significant biomass accumulation.

Although this more robust vegetation represents greater ecological complexity, it also accumulates a large amount of combustible material. During the dry season, this can significantly increase the area's flammability, acting as a natural corridor for fire propagation.

Figure 19 displays a well-defined geological contact in the region of the waterfall Farofa de Baixo.

Figure 19

Contact between the Espinhaço Supergroup (yellow dashed lines) and the Macaúbas Group (brown dashed lines). The inferred geological contact is indicated by a red line



Modified from: Google Earth

In the Espinhaço Supergroup, quartzites predominantly outcrop, with characteristics that favor the development of sparse vegetation, consisting of rupestrian fields with low dry biomass. This results in high flammability in the environment, particularly during the dry season, due to the accumulation of fine material and low moisture availability.

In contrast, areas of the Bambuí Group composed primarily of carbonate and pelitic rocks are more susceptible to weathering, forming deeper, more fertile soils with greater water retention capacity. The weathering of these carbonate-rich rocks releases abundant basic cations (Ca^{2+} , Mg^{2+}), resulting in naturally fertile soils. These conditions support denser and taller vegetation with higher biomass volume, which reduces flammability. The prominent presence of secondary vegetation, including palm trees, indicates not only the natural regenerative potential of these fertile soils but also suggests that palms serve as efficient pioneer species in recolonizing disturbed areas on carbonate substrates. They benefit from the high nutrient availability and water retention capacity.

In Figure 20, a lithological contact is observed between the Espinhaço Supergroup, highlighted in yellow dashed lines, and the Bambuí Group in the Morro da Pedreira, demarcated in blue dashed lines.

Figure 20

Contact between the Espinhaço Supergroup (yellow dashed lines) and the Bambuí Group (blue dashed lines). The inferred geological contact is represented by a red line



Modified from: Geological Survey of Brazil (SBG)

Table 1 presents a summary of the main characteristics observed among the geological units, associated soil types, direction of the photolineament predominant vegetation, and flammability in the study area.

Table 1

Summary of geological units, soil types, vegetation, and flammability

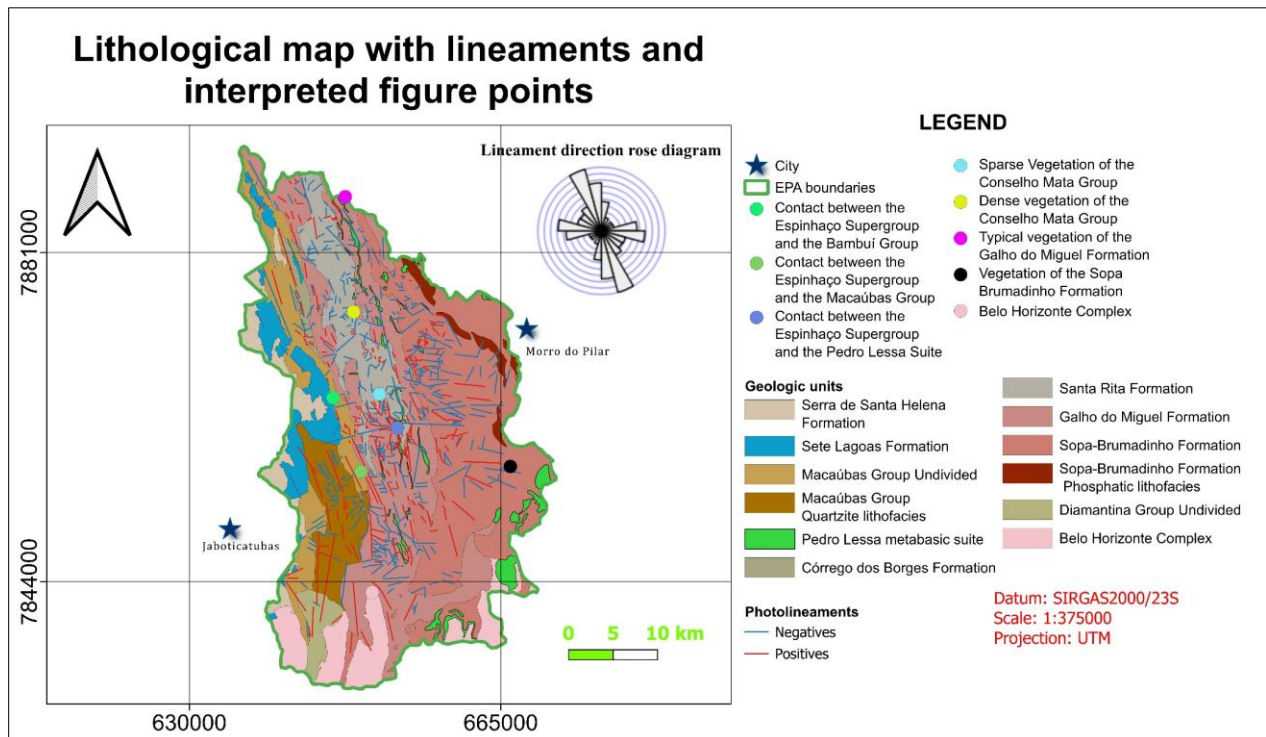
Geological unit	Soil type	Typical vegetation	Flammability	Direction of the photolineament
Bambuí Group	Fertile	Tall and dense vegetation	Very low	Little expressive, with NW-SE alignment in the identified occurrences
Macaúbas Group	Shallow, low water retention	Medium-height vegetation	Moderate to high	NW-SE
Pedro Lessa Suite	Fertile, deep	Dense, tall, and continuous vegetation	Low	Below is the photolineament of the structure it cuts across.
Conselheiro Mata Group	Shallow, low water retention	Low to medium-height vegetation	Moderate to high	NW-SE
Galho do Miguel Formation	Shallow, sandy, acidic, nutrient-poor, slightly rough texture	Sparse grasses and shrubs	Low	NW-SE
Sopa-Brumadinho Formation	Shallow, low water retention	Low to medium-height vegetation	High to very high	E-W
Belo Horizonte Complex	Clay-rich, rough texture	Tall and dense vegetation	Low	Little expressive

Source: Elaborated by the authors

In Figure 21, the map shows the location of points where interpretations of the correlations between vegetation and geology were conducted in the EPA Morro da Pedreira, including photolineaments. These points correspond to observation sites used for the integrated analysis of lithology, soils, vegetation, and fire dynamic.

Figure 21

Lithological map with lineaments and location of analysis points in the EPA Morro da Pedreira



Modified from: UFMG et al.,(2012); UFMG et al.,(2014); Tuller et al., (2010); Padilha et al., (2000)

6. Conclusion

This study demonstrated that wildfire susceptibility in the EPA Morro da Pedreira is determined by the interaction among geological, vegetational, and anthropogenic factors. Lithology plays a fundamental role in this dynamic, conditioning soil type and vegetation density, factors that control dry biomass accumulation and, consequently, the potential for fire ignition and propagation.

The Belo Horizonte Complex, composed of gneisses and migmatites, generates deep and fertile soils that support dense woody vegetation, exhibiting low flammability. The Sopa-Brumadinho Formation, consisting of impure quartzites, proved to be the most susceptible to fires, with high to very high flammability due to shallow soils that support grassy vegetation with substantial accumulation of dry material. In contrast, the Galho do Miguel Formation, composed of pure quartzites, exhibited low flammability, functioning as a natural barrier to fire propagation due to rock outcrops and sparse vegetation of the rupestrian fields. The Conselheiro Mata Group showed moderate to high flammability, with shallow soils over micaceous quartzites that support rupestrian fields and cerrado vegetation, generating significant seasonal accumulation of fuel biomass. The Pedro Lessa Suite, formed by metabasic rocks, develops fertile and deep soils that maintain dense vegetation, resulting in low flammability. The Macaúbas Group, with impure quartzites and diamictites, forms shallow soils with low water retention, which support mostly moderately dense vegetation, resulting in moderate flammability. The Bambuí Group, composed predominantly of carbonate rocks, generates developed soils that maintain dense and moist vegetation, significantly reducing the potential for ignition and propagation.

Beyond lithological control over vegetation and biomass accumulation, geological structures also exert direct influence on fire propagation. Structural lineaments act as fire propagation corridors, especially those oriented east-west, which coincide with the direction of prevailing winds. This combination, when associated with high-slope terrain, intensifies the chimney effect and significantly accelerates the advance of fire fronts, as observed in the Sopa-Brumadinho Formation.

Although geological factors condition fire susceptibility and propagation, heat source density analysis revealed that ignition has a predominantly anthropogenic origin. The data demonstrated strong spatial correlation between fire hotspots and road networks and trails, evidencing human activities as the main ignition vector in the study area. This pattern reinforces the need for prevention strategies focused on areas of greater human circulation.

Field observations indicate that the region encompasses zones of significant operational difficulty regarding wildfire suppression, with varying degrees of accessibility across different sectors. Terrestrial access to specific sub-regions is characterized by a moderate-to-high level of complexity; therefore, firefighting personnel must be strategically prepared for substantial logistical constraints. Future institutional planning should prioritize specialized training protocols, optimized logistics, and the acquisition of heavy-duty equipment tailored for rugged terrain to ensure operational efficacy and safety.

The multicriteria integration, considering lithology, vegetation, structural lineaments, and human use patterns, constitutes an effective methodology for understanding and mitigating wildfire risks. The developed methodology can be replicated in other conservation units, contributing to the improvement of environmental management and protection strategies.

Supplementary Information

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