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Analysis of Fire Hotspots in Urban-Rural Landscapes: Case Study in the municipality of Guarulhos

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Análise de Focos de Queimadas em Paisagem Urbano-Rural: Estudo de Caso no Município de Guarulhos

RESUMO

Objetivo - O objetivo principal deste trabalho foi investigar a distribuição espaço-temporal dos focos de queimadas e incêndios (FQI) no município de Guarulhos entre os anos de 2015 e 2024, correlacionando-os com áreas urbanas, tipos de uso e cobertura do solo, e sua ocorrência em Unidades de Conservação (UC).

Metodologia - Os dados de focos de queimadas foram obtidos junto ao Sistema Ambiental Paulista – DataGEO, do Programa Queimadas do INPE, abrangendo detecções de satélites como AQUA_M-T, AQUA_M-M, GOES-16, NOAA-20, NPP-375, NPP-375D, TERRA_M-M e TERRA_M-T. A análise espacial foi conduzida utilizando o software QGIS, com técnicas de geoprocessamento.

Originalidade/relevância - Em paisagens complexas, como o município de Guarulhos (SP) caracterizado por sua alta urbanização e a presença de importantes remanescentes de vegetação nativa essa análise é fundamental para preservar o meio ambiente. Tais informações são vitais, pois subsidiam o conhecimento necessário para o cumprimento de metas ambientais, alinhando-se diretamente aos Objetivos de Desenvolvimento Sustentável (ODS) da Agenda 2030, especialmente os relacionados à proteção da vida terrestre (ODS 15) e as questões referentes as mudanças climáticas (ODS 13). Há possibilidade de contribuir com a educação ambiental afim de minimizar ou prevenir incêndios em áreas urbano-rural.

Resultados - A análise temporal revelou um total de 1255 FQI registrados em Guarulhos no período avaliado, com o ano de 2022 apresentando o maior índice, somando 220 FQI (17,53% do total). Sazonalmente, a maior concentração de FQI (44% da série histórica) foi observada entre julho e setembro, período que coincide com a estação mais seca e o inverno. Em termos de uso do solo, as categorias "Mosaico de Agricultura e Pastagem" e "Formação Florestal" foram as mais afetadas, representando 36% e 35% de FQI, respectivamente. Espacialmente, a Área de Proteção Ambiental Cabuçu-Tanque-Grande destacou-se como a Unidade de Conservação com o maior predomínio de focos, respondendo por 83% FQI.

Contribuições teóricas/metodológicas - Ao mapear e quantificar o problema, este trabalho fornece informações metodológicas e teóricas cruciais para o planejamento territorial e a implementação de estratégias eficazes de prevenção de incêndios e ou manejo do fogo através do diagnóstico ambiental voltado para preparação de políticas públicas municipais e medidas educacionais de preservação do meio ambiente.

Contribuições sociais e ambientais - Os resultados deste estudo, ressaltam a vulnerabilidade significativa de áreas protegidas e de interfaces urbano-rurais, específicas, em Guarulhos contribuindo diretamente para a conservação da biodiversidade e a resiliência urbana frente às mudanças climáticas, em consonância com a Agenda 2030.

PALAVRAS-CHAVE: Focos de Queimadas. Sensoriamento Remoto. Unidades de Conservação.

Analysis of Fire Hotspots in Urban-Rural Landscapes: Case Study in the municipality of Guarulhos

ABSTRACT

Objective – The main objective of this study was to investigate the spatial-temporal distribution of burn and fire hotspots (BFH) in the municipality of Guarulhos between 2015 and 2024, correlating them with urban areas, land use, and land cover types, and their occurrence in Conservation Units (UCs).

Methodology – The data on fire outbreaks were obtained from the São Paulo Environmental System – DataGEO, part of the INPE Fire Program, covering detections from satellites such as AQUA_M-T, AQUA_M-M, GOES-16, NOAA-20, NPP-375, NPP-375D, TERRA_M-M, and TERRA_M-T. Spatial analysis was conducted using QGIS software, employing geoprocessing techniques.

Originality/Relevance – – In complex landscapes, such as the city of Guarulhos, São Paulo state, known for its high level of urbanization and important pockets of native vegetation, this analysis is key to protecting the environment. Such information is vital to support the knowledge needed to meet environmental goals, aligning directly with the Sustainable Development Goals (SDGs) of the 2030 Agenda, especially those related to protecting life on land (SDG

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15) and issues related to climate change (SDG 13). This information can contribute to environmental education aimed at minimizing or preventing fires in urban-rural areas.

Results – The temporal analysis revealed a total of 1,255 BFH recorded in Guarulhos during the period assessed, with 2022 showing the highest index, totaling 220 BFH (17.53% of the total). Seasonally, the highest concentration of BFH (44% of the historical series) was observed between July and September, a period that overlaps with the driest season and winter. In terms of land use, the categories "Mix of Agricultural and Pasture" and "Forest Formation" were the most affected, representing 36% and 35% of BFH, respectively. Spatially, the Cabuçu-Tanque-Grande Environmental Protection Area stood out as the Conservation Unit with the highest prevalence of outbreaks, accounting for 83% of BFH.

Theoretical/Methodological Contributions – By mapping and quantifying the problem, this work provides crucial methodological and theoretical information for territorial planning and the implementation of effective fire prevention and/or fire management strategies through environmental diagnosis aimed at preparing municipal public policies and educational measures for environmental preservation.

Social and Environmental Contributions – The results of this study highlight the significant vulnerability of specific protected areas and urban-rural interfaces in Guarulhos, directly contributing to biodiversity conservation and urban resilience in the face of climate change, in line with the 2030 Agenda.

KEYWORDS: Burning Hotspots. Remote Sensing. Conservation Units.

Análisis de los Focos de Calor en Paisajes Urbano-Rurales: Estudio de Caso en el Municipio de Guarulhos

RESUMEN

Objetivo – El objetivo principal de este estudio fue investigar la distribución espacio-temporal de los focos de quemas e incendios (FQI) en el municipio de Guarulhos entre 2015 y 2024, correlacionándolos con áreas urbanas, tipos de uso y cobertura del suelo, y su ocurrencia en Unidades de Conservación (UC).

Metodología – Los datos de focos de incendios se obtuvieron del Sistema Ambiental Paulista – DataGEO, parte del Programa de Queimadas del INPE, abarcando detecciones de satélites como AQUA_M-T, AQUA_M-M, GOES-16, NOAA-20, NPP-375, NPP-375D, TERRA_M-M y TERRA_M-T. El análisis espacial se realizó mediante el software QGIS, empleando técnicas de geoprocesamiento.

Originalidad/Relevancia – En paisajes complejos, como el municipio de Guarulhos (estado de São Paulo), conocido por su alto nivel de urbanización e importantes remanentes de vegetación nativa, este análisis es fundamental para la protección del medio ambiente. Dicha información es vital para sustentar el conocimiento necesario para cumplir las metas ambientales, alineándose directamente con los Objetivos de Desarrollo Sostenible (ODS) de la Agenda 2030, especialmente los relacionados con la protección de la vida de ecosistemas terrestres (ODS 15) y la acción por el clima (ODS 13). Esta información puede contribuir a la educación ambiental orientada a minimizar o prevenir incendios en áreas urbano-rurales.

Resultados – El análisis temporal reveló un total de 1.255 FQI registrados en Guarulhos durante el período evaluado, siendo 2022 el año con el índice más alto, sumando 220 FQI (17,53% del total). Estacionalmente, la mayor concentración de FQI (44% de la serie histórica) se observó entre julio y septiembre, período que coincide con la estación más seca y el invierno. En cuanto al uso del suelo, las categorías "Mosaico de Agricultura y Pastizal" y "Formación Forestal" fueron las más afectadas, representando el 36% y el 35% de los FQI, respectivamente. Espacialmente, el Área de Protección Ambiental Cabuçu-Tanque-Grande se destacó como la Unidad de Conservación con mayor prevalencia de focos, representando el 83% de los FQI.

Contribuciones Teóricas/Metodológicas – Al mapear y cuantificar la problemática, este trabajo proporciona información metodológica y teórica crucial para la planificación territorial y la implementación de estrategias eficaces de prevención y/o manejo del fuego, a través de un diagnóstico ambiental orientado a la elaboración de políticas públicas municipales y medidas educativas para la preservación ambiental.

Contribuciones Sociales y Ambientales – Los resultados de este estudio resaltan la vulnerabilidad significativa de áreas protegidas específicas y de interfaces urbano-rurales en Guarulhos, contribuyendo directamente a la

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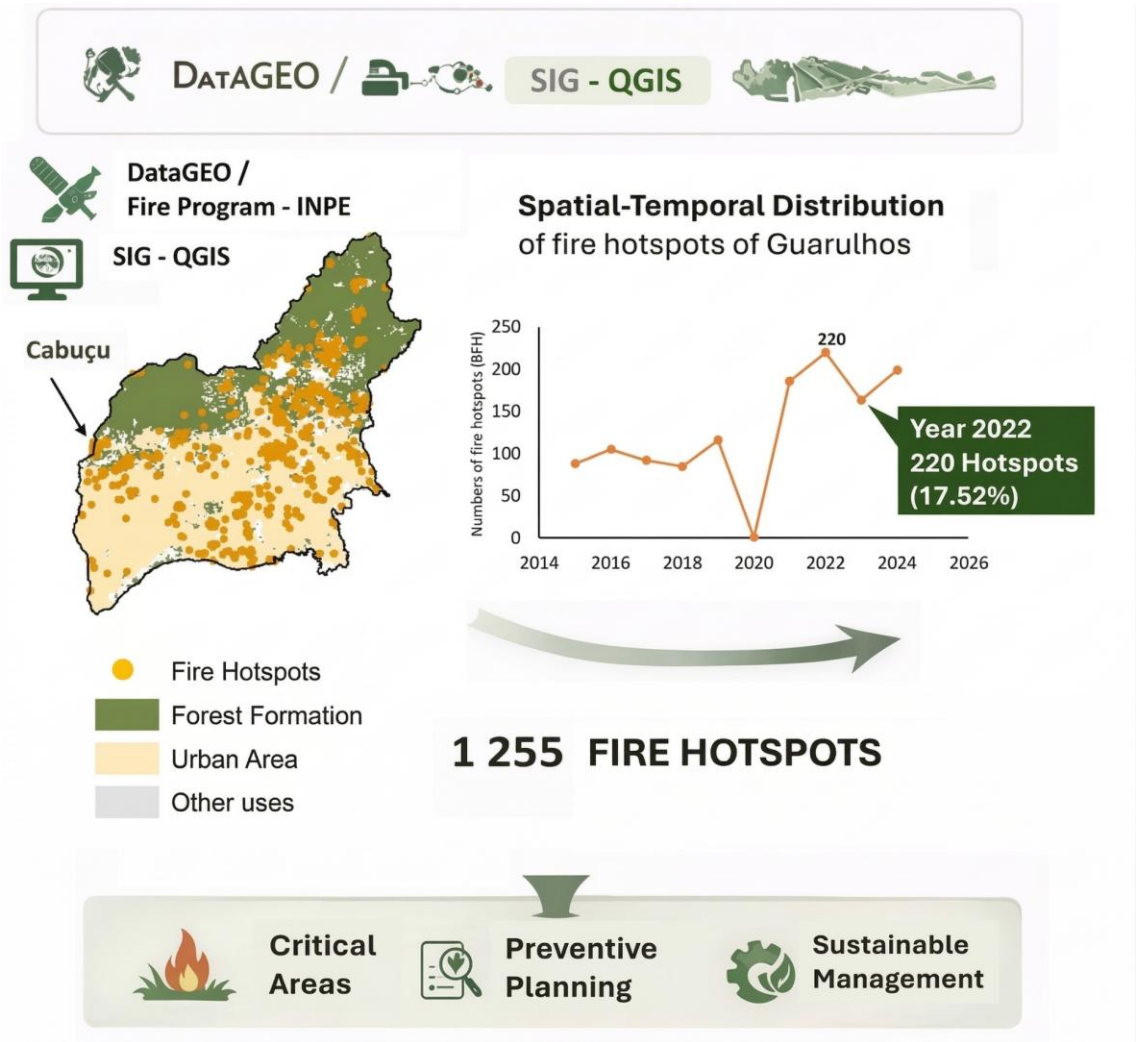
conservación de la biodiversidad y a la resiliencia urbana frente al cambio climático, en consonancia con la Agenda 2030.

PALABRAS CLAVE: Focos de Calor. Sensores Remotos. Unidades de Conservación.

GRAPHIC SUMMARY



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1 INTRODUCTION

Fires represent a persistent global problem that significantly impacts territories. The ongoing global warming has generated fires that add to the increase in climate change. In 2015, the Paris Agreement proposed limiting the Earth's temperature increase to 1.5°C. The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) predicts that global warming of 4°C will increase the global burned area by 50% to 70% and the frequency of fires by about 30% compared to current levels. In 2024, the temperature reached 1.55°C (UNFCCC, 2015; IPCC, 2023; RAF, 2024).

Technological advances have enabled the use of satellite images captured by remote sensors aboard satellites to detect and locate fires in real time (Granemann; Carneiro, 2009). Observing the Earth's surface via satellite is the most effective and economical way to gather the data needed to monitor and model forest fires, especially in countries with large territories, such as Brazil (Batista, 2004).

The recurrence of these events demands constant attention and effective strategies for their containment and prevention (Costa et al., 2025). Between 2023 and 2024, the area burned in Brazil increased from about 16 million hectares to more than 30 million hectares. The year 2024 was considered the second year with the largest burned area since 1985, second only to 2007, which recorded 30.7 million hectares burned (RAF, 2024). Monitoring the number of fire outbreaks or burnings is a key environmental data indicator for measuring the level of burning occurrence (Pirajá *et al.,* 2023).

Burning is more common in smaller areas used for agriculture and livestock farming. However, it also occurs in native vegetation, where it can have either a positive impact on the ecology and evolution of the ecosystem in fields and savannas, or a negative impact, as in forest formations. In forest formations, fire causes huge losses in biodiversity and degradation of the ecosystem (PINTO *et al*., 2024).

Forest fires are disasters that pose a major risk to the safety of our environment, causing billions of dollars in damage every year due to the destruction of infrastructure, disruption of economic activities, and reconstruction efforts (Jones et al., 2024). Most fires are caused by humans, but climatic factors such as drought and wind speed determine their ignition, spread, and behavior, which can also be influenced by other factors such as topography and vegetation (Santos; Soares; Batista, 2006; Antunes; Lopes; Oliveira, 2023). These forest fires also contribute to the increase in atmospheric pollutants, which degrades urban air quality (PASQUETTI *et al.,* 2025).

The Brazilian legislation includes municipal and state laws aimed at preventing fires and urban disasters, integrated with urban policy and land use (Seito et al., 2008). A key example is Federal Law 12.608/2012, which established the National Civil Protection and Defense Policy (PNPDEC), determining technical bodies and requiring the mapping of risk areas, safe urban planning, and environmental licensing control. In 2020, the United Nations (UN) celebrated International Disaster Reduction Day under the topic of governance and national and local strategies for disaster risk reduction, which includes fire risks. This celebration was linked to Sustainable Development Goal (SDG 11) – Sustainable Cities and Communities, which seeks to make cities and communities more inclusive, safe, resilient, and sustainable.

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Analysis of the identification of regions and land uses that are most at risk of wildfires and forest fires reveals that the most vulnerable areas in municipalities are those impacted by reckless human actions. Such actions are linked to land modification for social and economic development and significantly increase the occurrence of these events (Santos *et al.,* 2020).

The high incidence of fires within conservation units poses a direct threat to local biodiversity, native Atlantic Forest vegetation, and vital ecosystem services, such as the protection of water sources (especially in the Cabuçu-Tanque Grande Environmental Protection Area, which supplies part of Guarulhos). Fire can lead to soil degradation, habitat loss, and disruption of the hydrological cycle (Guimarães, 2014; Martinho et al., 2008). As for the protected areas in the city of Guarulhos, the territory analyzed in this study holds an environmentally significant position for being home to the Núcleo Cabuçu, which belongs to the Cantareira State Park Conservation Unit (PE Cantareira). PE Cantareira is federally managed and considered one of the largest urban forests in the world (Santos *et al.*, 2020).

The improvement of combat and prevention techniques depends on protectionist policies tailored to the features of each region. This requires knowledge of the profile, i.e., knowledge of the location, time, cause of forest fires, and their statistics, allowing for the prioritizing of actions in locations with the highest incidence of fires (Oliveira *et al.,* 2004).

Among climatic factors, rainfall is a key factor in controlling hot spots by moistening the soil and vegetation. However, long periods of drought are usually associated with devastating fires (White; Ribeiro, 2011). In urban centers, fires pose a serious risk to the health of the population, as low air humidity favors the dispersion of pollutants, increasing the incidence of respiratory and cardiovascular diseases (Mann, 2023).

Developing regions exert significant pressure on forested areas due to the need for land use and occupation, which results in direct and indirect impacts on habitats (Batista, 2004). Monitoring fires in the city of Guarulhos is critical given its high population density and crucial natural areas. This allows for the protection of public health from smoke and pollutants, the safeguarding of Conservation Units such as the Cabuçu-Tanque-Grande Environmental Protection Area and assists in urban planning and rapid response to these events.

Given this scenario, understanding historical fire patterns, their relationship with climate variations, and the environmental impacts of fire in Brazil is crucial to developing effective strategies for preventing, monitoring, and fighting forest fires.

Over the past ten years, several recent studies have highlighted the relevance of research on heat focus. This topic has received significant attention due to its importance in understanding forest fire patterns and their consequences for ecosystems, biodiversity, and the global climate.

In this context, significant advances have been made in understanding the spatial and temporal patterns of hot spots, as well as their relationship with climatic factors such as temperature, humidity, and rainfall. In addition, the development of remote sensing and computer modeling technologies has provided new opportunities to monitor and analyze these events at different spatial and temporal scales.

The overall objective is to investigate the spatiotemporal distribution of forest fires and burn sites (BFH) in the municipality of Guarulhos (SP), Brazil. Specifically, to assess the

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temporal distribution of fire outbreaks over 10 years (2015-2024) and identify patterns in the spatial distribution of fire outbreaks, land use classes, and their presence in Conservation Units. The aim is to provide input to public authorities and environmental agencies in their decision-making processes.

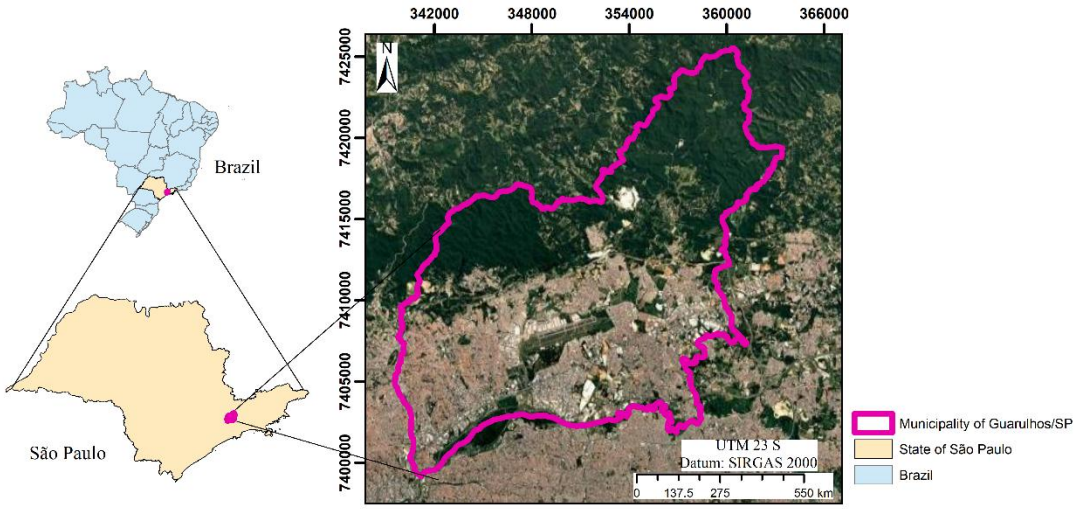
2 MATERIAL AND METHODS

2.1 Study site

The municipality of Guarulhos is strategically located in the northeastern part of the São Paulo Metropolitan Region (RMSP), in southeastern Brazil (Figure 1). Notable for its economic relevance, Guarulhos ranks third in the Gross Domestic Product (GDP) of the State of São Paulo, with its main economic activities concentrated in the industrial, commercial, and service sectors (IBGE, 2021).

Constituting a territory of great urban expansion, the municipality is home to a population of 1,291,771 people, ranking it as the second largest municipality in the state of São Paulo. The municipality is in the Atlantic Forest Biome and has a territorial area of 318.675 km², of which 156.52 km² are classified as urbanized areas (IBGE, 2023; IBGE, 2010).

Figura 1 – Location of the municipality of Guarulhos/SP.



Source: Elaborated by the authors (2024).

Despite its intense urbanization, the municipality of Guarulhos preserves a significant number of Conservation Units (UCs) that are crucial for protecting remnants of the Atlantic Forest, water sources, and local biodiversity. The municipality stands out in the National Environmental Policy (PNMA) for having nine federal, state, and municipal Conservation Units (UCs) within its territory (Table 1).

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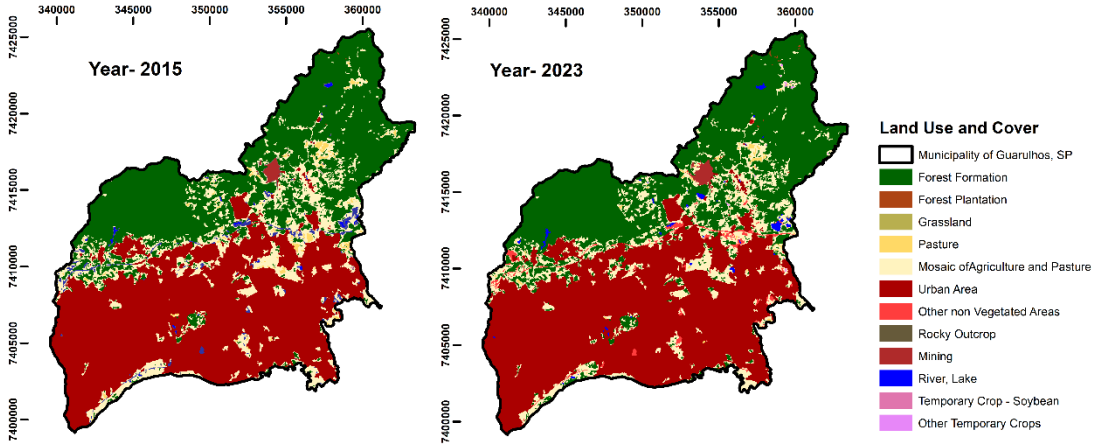
Table 1 – Areas of Conservation Units (UCs) in the city of Guarulhos.

Conservation Units – UCs	ACRONYM	Area (km²)	Area (%)
Itaberaba State Park	PEI	62.23	32%
Paraíba do Sul Environmental Protection Area	APAPS	60.97	32%
Cabuçu Tanque Grande Environmental Protection Area	APACTG	32.23	17%
Cantareira State Park	PEC	26.59	14%
Várzea do Rio Tietê Environmental Protection Area	APAVT	7.63	4%
Parque Natural Municipal da Candinha	PNMCNSC	1.10	1%
Floresta Estadual de Guarulhos	FEG	0.93	0.5%
Tanque Grande Ecological Station	EETG	0.86	0.4%
Burle Marx Biological Reserve	RBBM	0.20	0.1%
Total		**192.74**	**100 %**

Source: Elaborated by the authors (2024).

Among the municipal conservation units, the Burle Marx Biological Reserve (1990), the Tanque Grande Ecological Station (2010), and the Cabuçu-Tanque Grande Environmental Protection Area (2010) stand out (Fonseca; Andrade; Oliveira, 2014). The Cabuçu-Tanque Grande Environmental Protection Area (APACTG), one of the most relevant areas in terms of the incidence of fires, covers approximately 32.23 km², corresponding to 17% of the total conservation units (Silva; Cordeiro, and Arzolla, 2022).

Figure 2 – Mapping of Burn and Fire Hotspots (BFH) by land use and cover in 2015 and 2023 in the municipality of Guarulhos, São Paulo State.



Source: Elaborated by the authors (2024).

Guarulhos shows a dynamic land use pattern, marked by urban expansion and the loss of mixed farming and grazing areas. A comparison of the Land Use and Cover maps for 2015 and 2023 allows us to observe this dynamic of territorial transformation. Although the "forest formation" in the north appears relatively stable in its central area, there is evidence of expansion of "urban areas" in other parts of the municipality. This expansion, particularly over areas of “rural formation” or “mix of agriculture and pasture”, adds to the complexity of the

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urban-wildlife interface (Figure 2). In quantitative terms, the municipality saw a net increase of 3.6 km² in its "urban area" between 2015 and 2023, reflecting a common pattern in large metropolitan centers. Surprisingly, the "forest formation" gained 2.4 km² between 2015 and 2023, which may suggest natural regeneration processes, reforestation, or improvements in classes of land use and cover (Table 2, Figure 2).

Table 2 – Classes of land use and cover in the municipality of Guarulhos/SP.

Land use and cover	Year 2015 Area (Km²)	Year 2023 Area (Km²)	Dif (Km²)
Urban Area	146.0	149.6	3.6
Forest Formation	116.4	118.8	2.4
Mosaic of Agriculture and Pasture	46.8	41.4	-5.4
Other non Vegetated Areas	3.2	3.8	0.5
Pasture	3.1	1.3	-1.8
River, Lake	1.5	1.7	0.2
Mining	1.4	1.6	0.2
Temporary Crop - Soybean	0.09	0.01	-0.08
Forest Plantation	0.08	0.21	0.12
Rock Outcrop	0.02	0.05	0.03
Other Temporary Crops	0.01	0.17	0.15
Grassland	0.006	0.006	0.000

Source: Elaborated by the authors (2024).

The region has humid and rainy summers, in contrast to mild and predominantly dry winters, the latter being the period of greatest risk for fires due to low relative humidity. The average annual temperature in Guarulhos varies between 15.9°C and 22°C, with the lowest temperatures occurring between April and October. Precipitation in Guarulhos is a striking feature of its climate, clearly defining two main seasons: one wet and one drier. The lowest rainfall rates occur during the dry season, with June to August having the fewest number of rainy days, generally less than five days on average (CLIMATE-DATA.ORG., 2024).

2.2 Sources and Characterization of Data on burn and fire hotspots (BFH)

Data from the National Institute for Space Research (INPE), made publicly available by the São Paulo Environmental System, was used to conduct a space-time analysis of the location of burn and fire hotspots (BFH) in the city of Guarulhos between 2015 and 2024 (DataGEO, 2021).

BFH detection was performed using georeferenced points identified by a set of eight optical satellites operating in the thermal band (average of 4µm), whose images are received and processed by INPE. The following reference satellites were used to compile the time series of hotspots: AQUA_M-T, AQUA_M-M, GOES-16, NOAA-20, NPP-375, NPP-375D, TERRA_M-M, and TERRA_M-T (DataGEO, 2021; Rodrigues et al., 2018). These government data are widely used for drafting, evaluating, planning, and developing actions to prevent, monitor, and combat forest fires, and as of 2023, they became part of "Operation SP without Fire." (www.infraestruturameioambiente.sp.gov.br/cortafogo).

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The term "heat spot" refers to points recorded by environmental monitoring that have a temperature equal to or greater than 47°C, captured on the ground surface by remote sensor images and disseminated by INPE's Queimadas Portal (Burns Portal) (Oliveira et al., 2019). For this study, the terminology "Burn and Fire Hotspots – BFH" was adopted, consistent with DataGEO.

It is worth pointing out that hotspots indicate the existence of fire in an image resolution element (pixel), which can vary from 1km x 1km to 5km x 4km; therefore, a single pixel can represent multiple occurrences of distinct fires (Santos, 2011). Remote sensing detection was the method chosen due to the size of Guarulhos and the existence of remote regions, such as conservation units and forests, which lack intensive means of on-site monitoring. To validate the trend of the fires, vector data structures (time/space series by x, y coordinates) and raster data structures (by latitude, longitude coordinate system) were developed to represent the peak of the fires and visualize the digital data from satellite images (Rosa; Brito, 2013).

The annual maps of Land use and cover in Brazil for the period from 1985 to 2023, specifically for the municipality of Guarulhos for the years 2015 and 2023, were sourced from the MapBiomas Project – Collection [1 to 9] of the Annual Series of Land Cover and Land Use Maps of Brazil via the link: [https://plataforma.brasil.mapbiomas.org/]. This collection is the result of nine years of work and is constantly being developed, with information on accuracy (general and by class of use and coverage for each year) provided on the platform's accuracy analysis page. MapBiomas data is public, open, and free. Shapefiles containing the boundaries of Conservation Units (federal, state, and municipal) located wholly or partially in the city of Guarulhos were also used.

2.3 Spatial-Temporal Processing and Analysis

Geographic Information System (GIS) environment, using QGIS software for layer overlay and spatial information extraction through spatial join. In addition, spreadsheets (e.g., Microsoft Excel) were used to organize, tabulate, and perform descriptive statistical calculations on the data, as well as to subsequently generate tables and graphs.

The methodology for analyzing the distribution of Forest Fire Hotspots (BFH) encompassed several integrated approaches. Initially, the total number of fire hotspots was quantified annually and monthly for the period from 2015 to 2024, aiming to detect trends, anomalies, and seasonal patterns.

Regarding spatial distribution by land use type, the BFH events detected annually (2015–2023) were spatially overlaid on Land Use and Land Cover maps. An annual count of outbreaks was performed for each land use class, and the cumulative percentage distribution of outbreaks by land use type was calculated and visualized using a pie chart. The temporal evolution of the contribution of each land use category was illustrated by a stacked bar chart, which showed the number of annual outbreaks per category. Finally, to analyze the spatial distribution in Conservation Units (UCs), the BFH points were superimposed on the vector layer of the Conservation Units in the municipality, and the hotspots that occurred within the boundaries of each UC were counted for the total period (2015-2024).

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This set of integrated analyses provided a comprehensive understanding of the distribution, potential causes, and evolution of the problem of fires in Guarulhos.

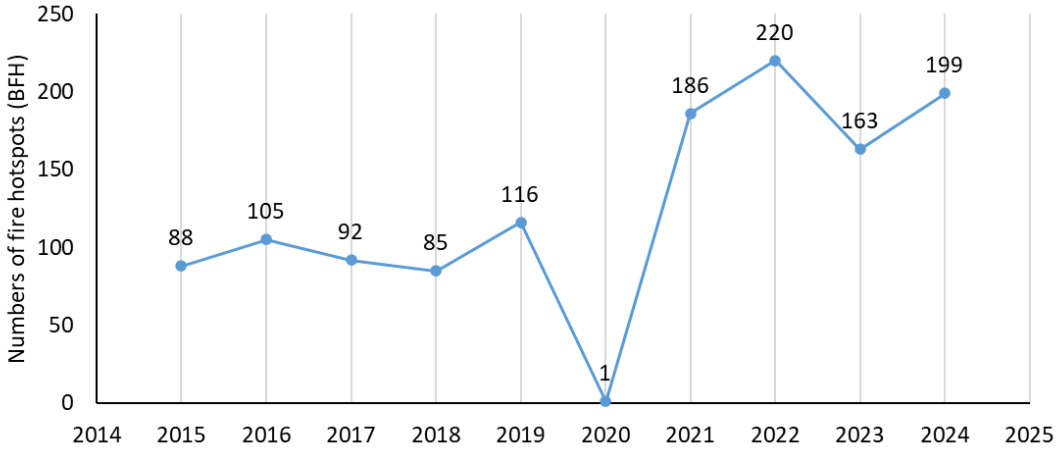
3 RESULTS AND DISCUSSION

3.1 Spatial-Temporal Distribution of burn and fire hotspots (BFH)

Research into the spatial and temporal distribution of burn and fire hotspots (BFH) in the city of Guarulhos reveals a significant increase in recent years (2021-2024). The high incidence recorded in 2022 and 2024 reinforces the urgency of implementing effective prevention and firefighting strategies in the city.

Figure 3 shows the annual variation in the number of fire outbreaks, revealing significant trends and peaks over the decade evaluated. The analysis of burn and fire hotspots (BFH) recorded a total of 1,255 BFH between 2015 and 2024. The years with the highest rates were 2022, with 220 BFH (17.53%), and 2024, with 199 BFH (15.86%). From 2015 to 2019, the number of BFH remained relatively stable, ranging from 85 (2018) to 116 (2019), with an average of approximately 97 BFH annually. This suggests a baseline of occurrences before 2020.

Figure 3 – Distribution of cumulative numbers of burning and fire hotspots (BFH) by year in the municipality of Guarulhos/SP.



Source: Elaborated by the authors (2025).

The year 2020 shows an abrupt and atypical drop, registering only one BFH (Figure 4). This is a significant anomaly that deviates from the entire historical series. Further investigation is needed to understand the causes of this drastic reduction, which may be related to factors such as (i) changes in the detection methodology or availability of INPE data in that specific year for the municipality of Guarulhos; (ii) extremely atypical climatic conditions favorable to the non-occurrence of outbreaks or immediate combat; (iii) possible gaps in monitoring data for the municipality; and/or (iv) a drastic reduction in anthropogenic activities or increased enforcement/prevention during the COVID-19 pandemic (Costa et al., 2022).

Research conducted in Amazon found an increase in weaknesses in the environmental monitoring system. In this period, political and economic factors are believed to have affected the occurrence of fires (Costa et al., 2025).

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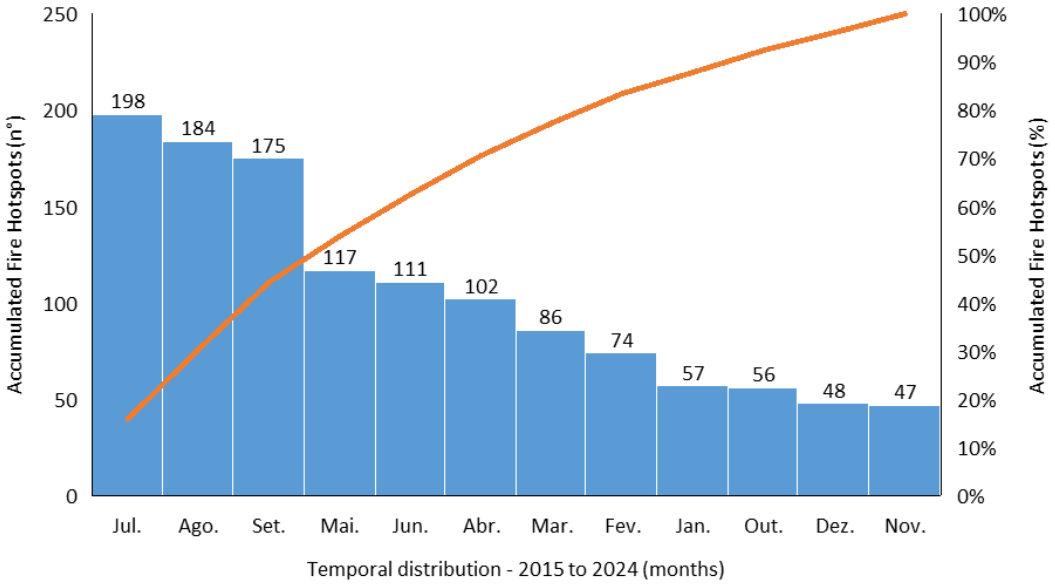
After the anomaly in 2020, there is a sharp recovery in the number of outbreaks in 2021 (186 BFH), surpassing the figures for any previous year in the series. In 2023, there was a slight drop to 163 BFH. In 2024, the number of outbreaks rose again, reaching 199 BFH, making it the second year with the highest number of occurrences (15.86%), approaching the 2022 peak of 220 BFH (17.53%) (Figure 4).

Analysis of the temporal distribution of fire outbreaks in Guarulhos based on the Pareto principle (Figure 4) revealed a disproportionate concentration of occurrences. The months of July, August, and September, which coincide with the driest season, were found to be the most critical, accounting for approximately 44% of the BFH recorded between 2015 and 2024.

Figure 4 – Burn and Fire Hotspots (BFH) by Month and Cumulative Percentage (2015-2024), municipality of Guarulhos, São Paulo state.



Source: Elaborated by the authors (2025).

The order of the months from July to September at the top of the bars reinforces the direct correlation between the dry season (winter and early spring) and the occurrence of fires in Guarulhos. The months preceding the peak (April, May, and June) show a gradual increase in BFH: 102 (Apr), 117 (May), and 111 (Jun). This indicates the beginning of increased fire risks as the rainy season ends, and the dry season sets in (Figure 4).

The descending order of the months confirms the marked seasonality in the occurrence of fires in Guarulhos. Drier vegetation and lower air humidity create ideal conditions for ignition and spread of fire. Studies show that the period from August to November is the "normal season" for fires, reaching their peak intensity in September and October (Pinto et al., 2021).

Table 3 provides further insight into the spatial-temporal distribution, allowing us to correlate the outbreaks with climate variables at the annual and monthly levels of detail. The concentration of fire outbreaks in Guarulhos persists notably in the winter and early spring months (July to September), with a substantial contribution from these months in the years with

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the highest incidence, such as July 2021 (46 BFH) and September 2024 (42 BFH), which drove the annual totals.

For example, although the total is high in 2022, July and September were the peak months, while in 2024, September stood out even more. The analysis by month and year may guide the discussion on specific climatic and anthropogenic factors that might have contributed to the peaks in certain months of certain years. For example, a more prolonged drought or El Niño events could be correlated with the July/September peaks (Table 3).

The period between 2015 and 2016 was marked by one of the most intense El Niño events ever recorded, a phenomenon known to impact global and regional climate patterns, including rainfall and temperature regimes. In the city of Guarulhos, data reveal 88 BFH of fires in 2015 and 105 BFH in 2016. Despite the climate changes caused by El Niño, these figures, although reflecting a continuing occurrence, do not stand out as the highest peaks in the historical series analyzed, which would be observed in later years such as 2021, 2022, and 2024 (Table 3).

Table 3 – Temporal distribution of the number of burn and fire outbreaks (BFH) accumulated by year/month in the municipality of Guarulhos, São Paulo state.

Month/Year	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Total
January	8	3	1	0	8	0	9	15	10	3	57
February	4	7	7	5	6	0	9	28	8	0	74
March	7	10	1	8	7	0	19	8	19	7	86
April	6	21	3	8	6	0	13	10	18	17	102
May	6	10	4	10	10	1	16	22	16	22	117
June	7	5	8	4	12	0	9	15	23	28	111
July	6	14	11	22	14	0	46	44	21	20	198
August	26	13	9	4	18	0	34	15	27	38	184
September	9	10	36	7	15	0	10	26	20	42	175
October	4	3	3	4	15	0	4	11	1	11	56
November	3	2	4	6	3	0	10	11	0	8	47
December	2	7	5	7	2	0	7	15	0	3	48
Total	**88**	**105**	**92**	**85**	**116**	**1**	**186**	**220**	**163**	**199**	**1255**

Source: Elaborated by the authors (2025).

The occurrence of a prolonged La Niña event between 2020 and early 2023, which typically induces conditions of lower rainfall and higher temperatures in parts of southeastern Brazil, such as Guarulhos, coincides with the periods of highest incidence of fires observed. Table 3 shows that 2021 (186 BFH) and, especially, 2022 (220 BFH) recorded the highest peaks of fire outbreaks in the historical series, suggesting a correlation between La Niña climate anomalies and the increased vulnerability of the municipality to fires.

Throughout the entire historical series (2015-2024), the northern and northeastern portions of Guarulhos emerge as the main area of concentration of fire outbreaks (Figures 5a and 5b). This region is known for important conservation areas (like the Cabuçu-Tanque-Grande Environmental Protection Area and parts of the Cantareira and Itaberaba State Parks), remnants of the Atlantic Forest, and/or patches of Cerrado (Durigan; Siqueira; Franco, 2007). Even in years with a lower total number of outbreaks (2015-2019), the presence of points in these areas was

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already noticeable, pointing to an intrinsic vulnerability of this interface between natural areas and human occupation.

Although the main concentration remains in the north/northeast, the maps for 2021-2024 also indicate a greater dispersion of hotspots to other areas of the municipality, including more central, western, and even southern portions (Figures 5a and 5b). This suggests that the problem of fires is not limited to large areas of forest, but is becoming more widespread, affecting the urban-rural mosaic and areas of peri-urban development.

This expansion may result from growing pressure for land use and occupation, manifested in the expansion of irregular settlements, waste disposal, and burning to clear land for social and economic development, coupled with other direct human interference, such as vandalism or fire accidents in areas with dry vegetation near buildings (Figures 5a and 5b).

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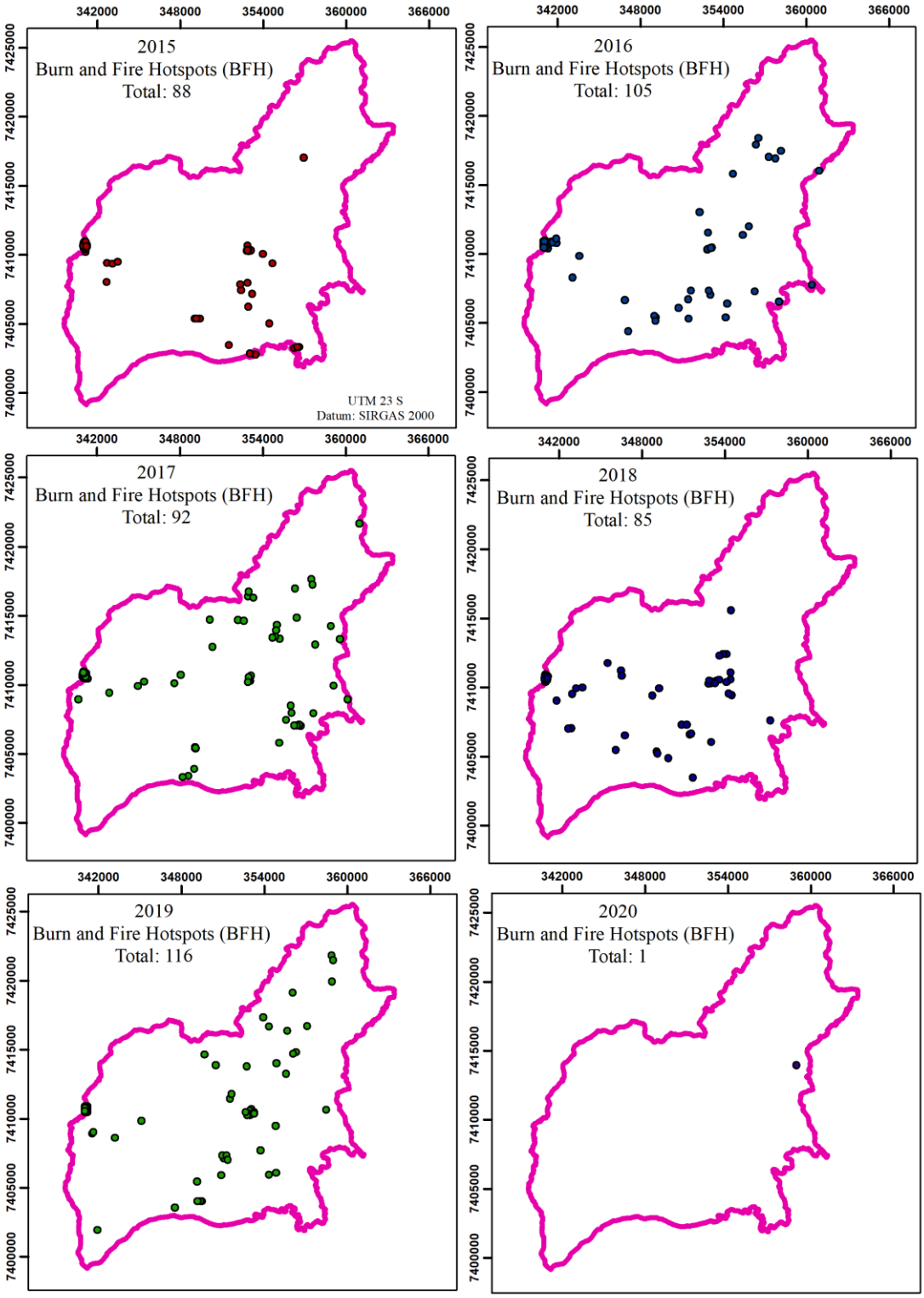
Figure 5a – Spatial-temporal distribution of accumulated burn and fire hotspots (BFH) by year in the municipality of Guarulhos, São Paulo State (2015-2020).



Source: Elaborated by the authors (2025).

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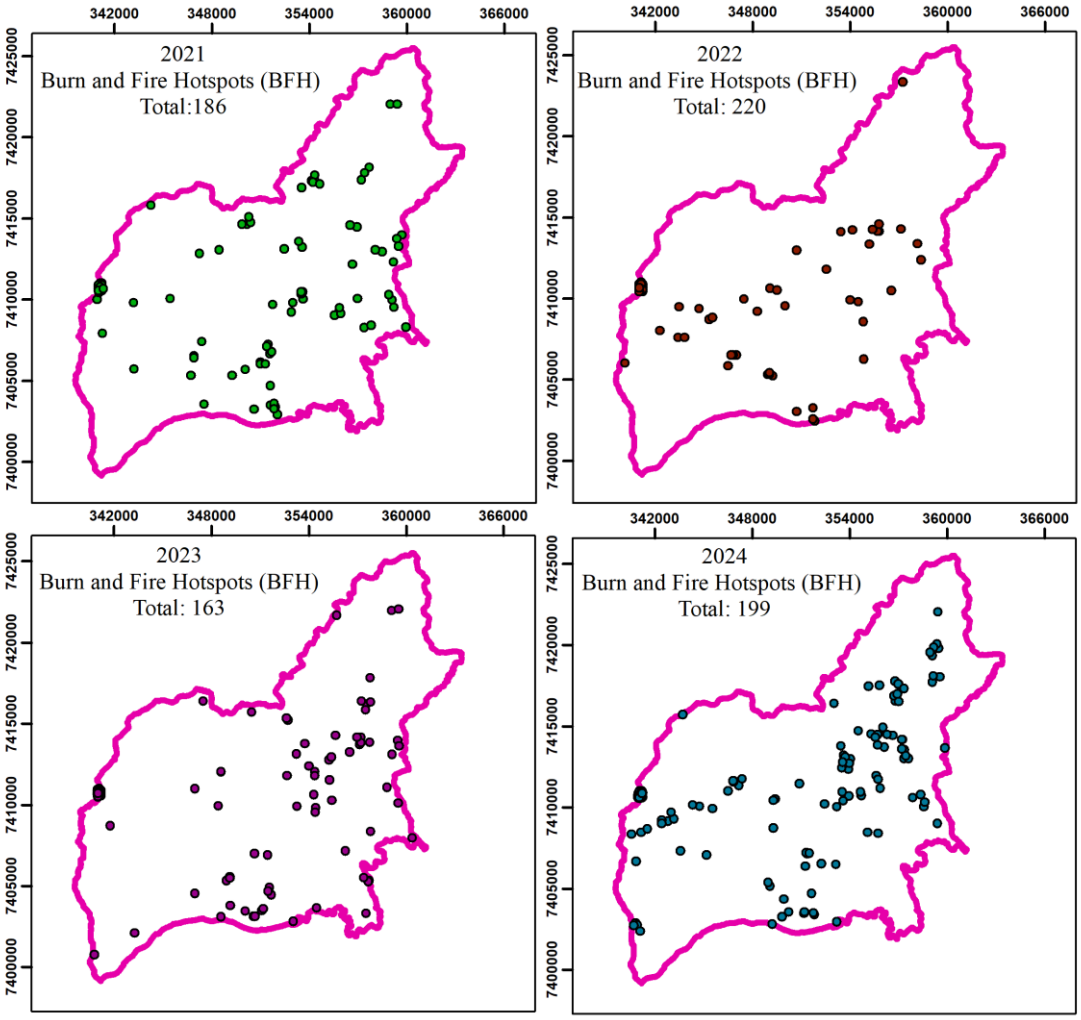
Figure 5b – Spatial-temporal distribution of accumulated burn and fire hotspots (BFH) by year in the municipality of Guarulhos, São Paulo State (2021-2024).



Source: Elaborated by the authors (2025).

In Brazil, the expansion of the road network is likely to increase, reaching several regions that are rich in biodiversity and provide essential ecosystem services. An emblematic example is the route of the Mário Covas Ring Road, under construction in the state of São Paulo, whose implementation has led to habitat fragmentation, an increase in forest fires, and other forms of environmental degradation (Reis, 2014; Saavedra; Costa, 2025). Particularly in the last year (2024), there has been an increase in the incidence of BFH in the areas adjacent to the northern section of the ring road (still under construction), highlighting the environmental impacts associated with this type of occupation.

3.2 Distribution of Fire Hotspots in Conservation Units

The map shown in Figure 6 is key to contextualizing the fire outbreaks in relation to the Conservation Units (UCs) in the city of Guarulhos. It overlays all outbreaks recorded between 2015 and 2024 on the UCs areas, allowing for a crucial analysis of the environmental vulnerability of the city. Visually, it confirms the extremely high vulnerability of the Cabuçu-

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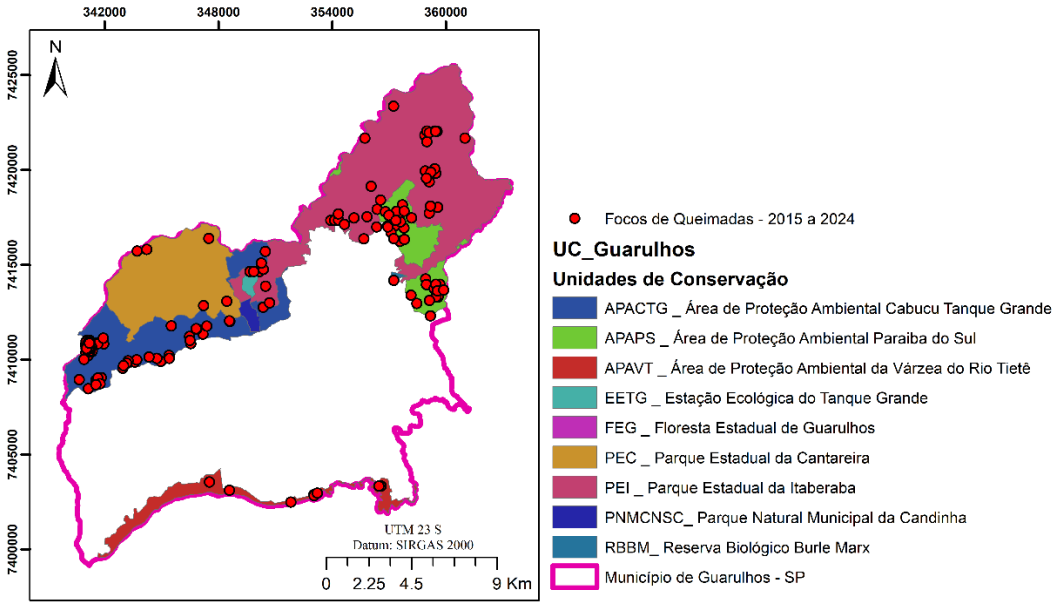
Tanque Grande Environmental Protection Area (APAFCTG), which is an epicenter of fire outbreaks and fires (BFH). A very high density of red dots is located within the boundaries of this APA.

The concentration of outbreaks in conservation units, especially in areas bordering urban areas or settlements, suggests that many fires may originate from human activities in the surrounding areas or within these areas. This includes littering, inappropriate recreational use of fire, or burning for illegal expansion.

The analysis of BFH in Protected Areas reveals an alarming situation for the municipality, given that 52% (652 BFH) of all fire outbreaks in the city of Guarulhos (1,255 BFH) occurred within Conservation Units (Figure 6, Table 4). This high proportion is extremely significant, as it shows that more than half of the fire events directly affect legally protected areas designated for the conservation of biodiversity, water resources, and ecosystem services.

Figure 6 – Spatial distribution of burn and fire hotspots (BFH) by conservation units in the city of Guarulhos, São Paulo state.



Source: elaborated by the authors (2025).

Table 4 provides a quantitative representation of this finding, revealing that APACTG recorded 543 BFH (83%) between 2015 and 2024, representing most occurrences in conservation units. This high concentration in APACTG explains the correspondence with the Cabuçu neighborhood being identified as the area with the highest occurrence of BFH in the municipality (Table 4).

In addition to the Cabuçu-Tanque Grande APA, other conservation units in the northern section also feature a significant number of BFHs, such as the Itaberaba State Park (PEI) with 37 BFHs and the Cantareira State Park (PEC) with 5 BFHs. This numerical and visual correspondence validates the distribution of risk among the various conservation units.

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Table 4 – Burn and fire hotspots (BFH) by conservation units in the city of Guarulhos, São Paulo state.

Conservation Unit – UC	Acronym	BFH	BFH (%)
Cabuçu Tanque Grande Environmental Protection Area	APACTG	543	83%
Paraíba do Sul Environmental Protection Area	APAPS	55	8%
Itaberaba State Park	PEI	37	6%
Várzea do Rio Tietê Environmental Protection Area	APAVT	10	2%
Cantareira State Park	PEC	5	1%
Tanque Grande Ecological Station	EETG	1	0%
Burle Marx Biological Reserve	RBBM	1	0%
Parque Natural Municipal da Candinha	PNMCNSC	0	0%
Floresta Estadual de Guarulhos	FEG	0	0%
Total Geral		**652**	**100%**

Source: Elaborated by the authors (2025).

The phenomenon of anthropogenic pressure (notably urban expansion) on conservation areas and the resulting increase in the incidence of forest fires is not unique to Brazil. Similarly, China has seen a significant increase in incidents over the last decade, with urban expansion in proximity to nature reserves cited as a direct contributing factor (ZHANG et al., 2019). Added to this is the fact that suburban regions marked by housing and infrastructure shortages present higher climate vulnerability, potentially elevating the probability of fire hotspot (GODOY, BENINI, SILVA, 2025). This correlation underscores the need to investigate the relationship between rapid urbanization and the risk of fires in interface areas.

In this perspective, analyzing urban expansion in the buffer zones of protected areas in the city of Guarulhos and pinpointing the risks of fires that come with it is key. This study aims to test the hypothesis that the fire incidents seen in the city are caused (or made worse) by the urban frontier pushing into these areas of ecological and legal transition.

3.3 Distribution of Burning Hotspots in Land Use

The analysis of the stacked bar chart (Figure 7) shows the annual distribution of the number of fire outbreaks by land use and occupation category between 2015 and 2023, revealing an overall increase in the number of annual outbreaks starting in 2021. The categories “forest formation” (35%) and “mix of agriculture and pasture” (36%) are the largest contributors to this rise. The graph shows a dramatic jump in contribution from 2021 to 2022, with significant bars in those years, indicating that areas of native vegetation were particularly affected during periods of greater drought and overall incidence of fires.

The graph (Figure 7) allows us to infer the main areas of vulnerability to fire and reveals a strong concentration of fires in a limited number of land use categories. The four main categories — mix of agricultural and pasture mosaic, forest formation, urbanized area, and pasture — account for an impressive 98% of total occurrences, pointing to where prevention and firefighting efforts should be prioritized. This land use class is mainly located in transition zones, where agricultural and grazing activities are mixed, often marked by the advance of the urban frontier. Such peripheral regions are particularly susceptible to the expansion of informal settlements due to less enforcement and more affordable land costs.

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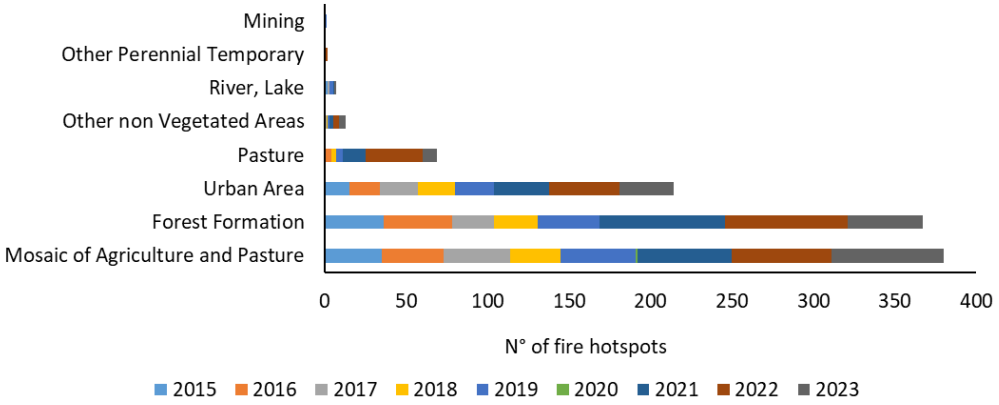
Figure 7 – Spatial distribution of accumulated burn and fire hotspots (BFH) by land use (2015 to 2023) in the city of Guarulhos, São Paulo State.



Source: Elaborated by the authors (2024).

The influence of illegal occupation on the increase in the number of fires can be understood by several interrelated factors. First, the use of fire for the quick and economical clearing of dense vegetation for the construction of new homes or small crops is a common practice in informal settlements, often leading to the uncontrolled spread of fires. Second, the lack of basic infrastructure services, such as regular waste collection in irregular settlements, leads to the burning of garbage in the open, a practice that, especially in periods of drought and wind, can easily cause fires to spread to adjacent vegetation.

In addition, the expansion of urbanized areas and the creation of informal settlements in regions of "mosaic of agricultural and pasture" lead to an enlargement of the urban-wildland interface (UWIS); the increased human presence in direct contact with combustible biomass raises the probability of accidental or intentional ignitions. Finally, the unplanned nature of irregular occupation hinders the implementation of preventive measures, such as firebreaks or fuel management, and environmental enforcement becomes more complex, perpetuating risky practices.

Considering that the "mosaic of agriculture and pasture" category accounts for the largest percentage of fire outbreaks (36%) and that the "urban area" category also showed significant expansion, the correlation between illegal occupation in these transition areas and the rise in fire outbreaks is highly plausible, posing a substantial challenge for fire management in the city of Guarulhos.

4 CONCLUSION

The research showed that the occurrence of fires in the city of Guarulhos between 2015 and 2024 is not random, but rather strongly determined by well-defined spatial-temporal patterns. The temporal analysis revealed that the risk of fire is intrinsically linked to climatic seasonality, with a critical concentration of approximately 44% of events occurring between July and September, which coincides with the driest period and winter. This finding, coupled with the trend of a significant increase in incidence in recent years (2021–2024), highlights the urgent

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need to focus prevention and firefighting efforts on the strategic window from May to September.

In terms of spatial analysis, clear distribution patterns emerged that highlight the vulnerability of urban-rural interfaces and the critical nature of protected areas in the north/northeast of the municipality. The Cabuçu-Tanque-Grande Environmental Protection Area (APA) stands out as a perennial hotspot, reinforcing the strong correlation between outbreaks and the presence of Conservation Units and transitional land use categories.

In conclusion, this study provides vital environmental diagnostics that enable the optimal allocation of resources by accurately pinpointing where (critical conservation units) and when (in the months of highest risk) fires are most likely to occur. The results provide crucial input for the formulation of proactive public policies and the implementation of effective and targeted fire management strategies in Guarulhos, directly contributing to biodiversity protection and urban resilience.

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STATEMENTS

CONTRIBUTION OF EACH AUTHOR

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Marisa Vianna Mesquita: Research, Methodology, Writing - Critical Review

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DECLARATION OF CONFLICTS OF INTEREST

We, Luciana de Meneses Castro, Fabricio Bau Dalmas, Marisa Vianna Mesquita, Renata Cristina Araújo Costa, declare that the manuscript entitled "Analysis of Fire Outbreaks in an Urban-Rural Landscape: Case Study in the Municipality of Guarulhos":

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