Fire in highland grasslands in the Atlantic Forest Biome, a burned areas time series analysis and its correlation with the legislation

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Fire has been an intrinsic ecological component of the ecosystems, affecting the public, economic, and socio-cultural policies of human-nature interactions. Using fire over grassland vegetation is a traditional practice for livestock in the highland grasslands and has economic and environmental consequences that have not yet been understood. A better description of the spatio-temporal biomass burning patterns is needed to analyze the effects of creation and application in these areas. This study used remote sensing techniques based on Sentinel-2 data and machine learning algorithms to identify burning scars and compare them with a national fire collection database for the highland grasslands in the Atlantic Forest Biome in Brazil. The aim is to evaluate public management tools and legislation evolution during the 35 years of the time series analyzed. The results indicated that 12,285 ha of grasslands were converted to other uses, losing about 24% of their original formation, with 10% occurring after banned this practice in 2008. The burned areas classification using the Random Forest algorithm obtained an AUC = 0.9983. Divergences in the burned area's extent and frequency were found between the municipality's authorized license and those classified as burned. On average, only 43% of the burned area in the Parque Estadual do Tainhas and its buffer zone had an environmental permit in the last 5 years. This research's results provide subsidies for revising and creating public policies and consequently help territorial management.

KEYWORDS

fire, grasslands, ΔNBR, GEE, MapBiomas, time series

1 Introduction

Fire activity in Brazil is influenced by several factors, the result of complex and dynamic processes generated by interactions between climatic conditions, vegetation attributes, land use and land cover, dynamics between regeneration, productivity and ignition patterns (Fidelis et al., 2021; Pivello et al., 2021). Brazilian biomes have a long history of fire conflicts, as in the Atlantic Forest Biome (AFB), one of the most critical biodiversity hotspots in the world (Myers et al., 2000).

Currently, the AFB remnants are highly fragmented and restricted to highland grassland areas in southern Brazil, where there are mosaics of Araucaria (Brazilian pine) forests and grasslands linked to a fire events history (Pillar et al., 2009; Meireles and Shepherd, 2015).
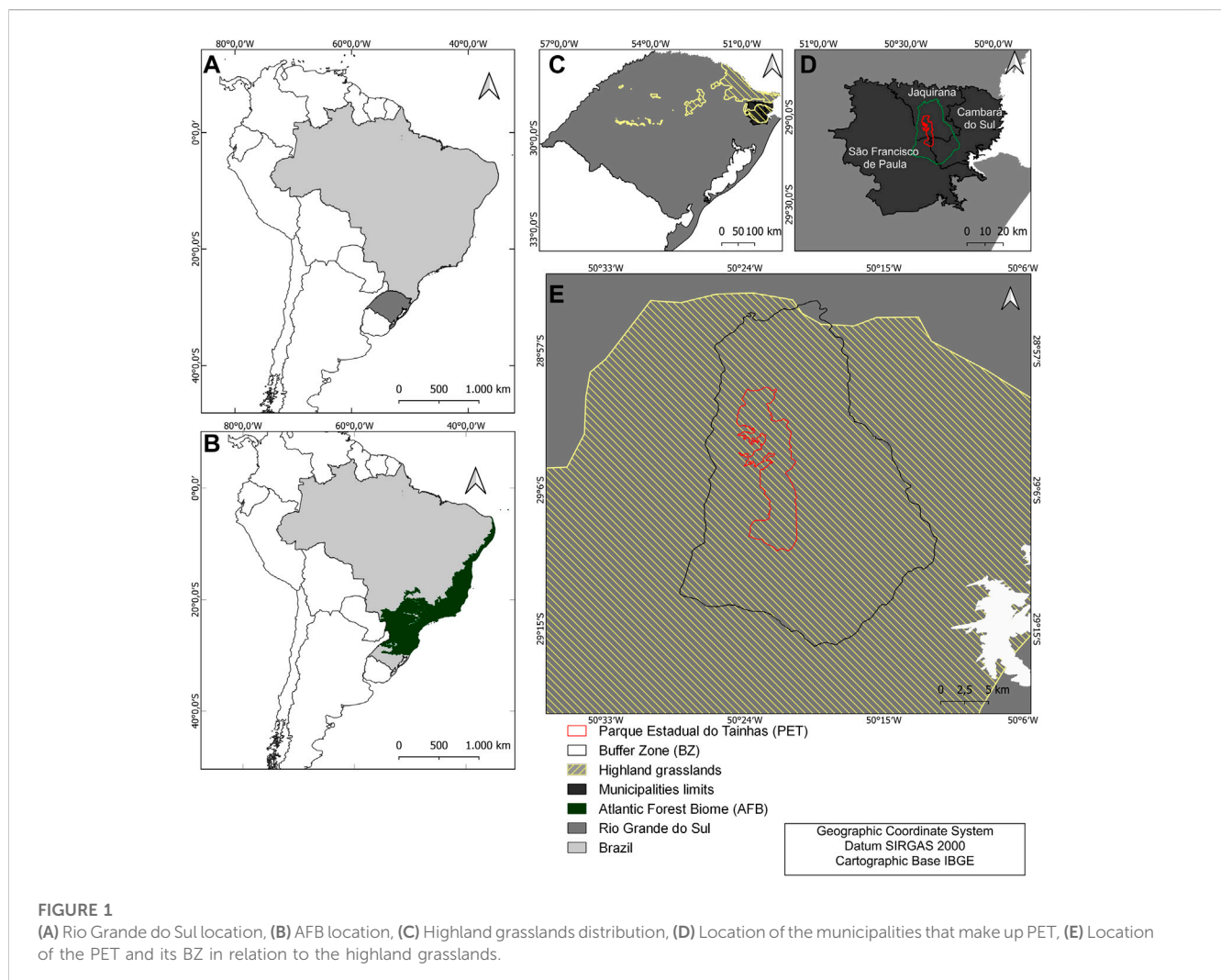
In these areas, fire has been an intrinsic ecological component of the ecosystems, affecting the public, economic, social, and even cultural policies of human interactions with nature (Andrade et al., 2015).

In recent years, conflicts related to fire use have presented economic and environmental consequences that have not yet been clearly understood. The fire use on grassland vegetation in the northeastern Rio Grande do Sul (RS) state is a traditional practice for livestock (Carvalho and Andrades-Filho, 2019). However, it was prohibited by Law 9,519/1992 (Rio Grande do Sul, 1992). This has led to natural grassland area changes to simplified land uses, such as agriculture and forestry, leading to biodiversity loss and difficulties in recuperating degraded areas (Buisson et al., 2019). Subsequently, Law 13,931/2012, which amended Law 9,519/1992 (Rio Grande do Sul, 2012), attributes to the municipal government the power to authorize and supervise the use of fire as a grasslands management practice in areas that cannot be mechanized or as a form of phytosanitary treatment.

Therefore, a better description of biomass burning spatio-temporal pattern is needed to analyze the effects of fire legislation. So, the use of remote sensing derived products such as 1) the Modis product MCD64A1—Collection 6, with 500 m resolution at a global scale (Giglio et al., 2018); 2) the MapBiomas Fire—Collection 1, based on Landsat time series, with 30 m resolution for the Brazil territory (Alencar et al., 2022), and 3) the global forest loss by fire product, also at a spatial resolution of 30 m (Tyukavina et al., 2022) are consolidated as an essential data source by covering vast areas with a multitemporal and multispectral information.

In this study, to minimize these products limitations, such as the spatial resolution, we used Sentinel-2 data developed by the European Space Agency (ESA), which has four bands with 10 m, six with 20 m, and three bands with 60 m (ESA, 2022). Therefore, this study's objective is to improve the spatial resolution of burned areas and compare them with the national MapBiomas Fire product to evaluate the fire use legislation over time in the highland grasslands in Atlantic Forest Biome in Brazil.

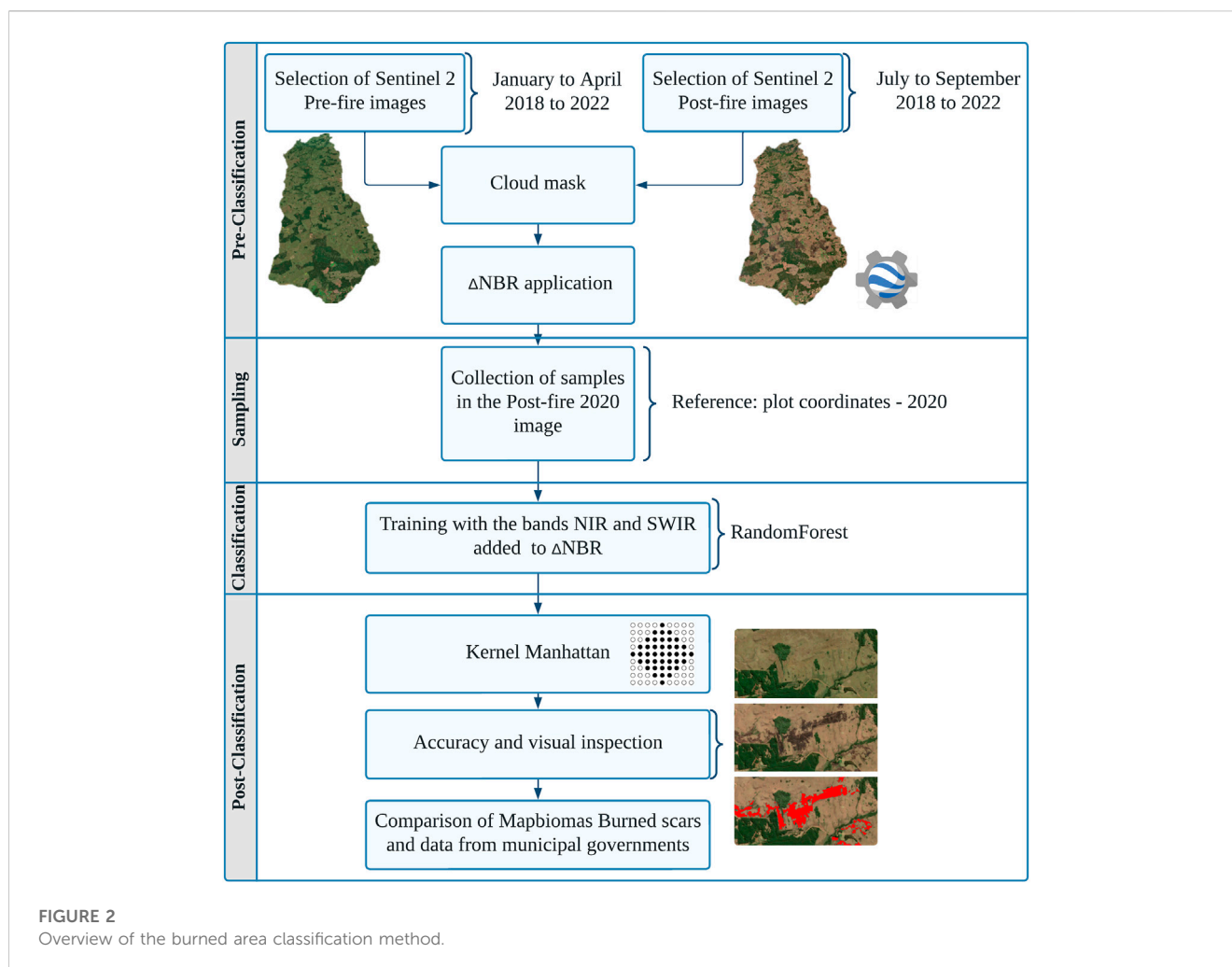**FIGURE 1**
(A) Rio Grande do Sul location, **(B)** AFB location, **(C)** Highland grasslands distribution, **(D)** Location of the municipalities that make up PET, **(E)** Location of the PET and its BZ in relation to the highland grasslands.

FIGURE 2
Overview of the burned area classification method.

2 Materials and methods

2.1 Study area

This study was conducted in the conservation area denominate Parque Estadual do Tainhas (PET) and its buffer zone (BZ) located at latitude 29°5′15″S and longitude 50°22′4″W (Figure 1). The PET was established in 1975 to protect the grasslands and forests in the Tainhas river valley, inserted in the AFB.

The Park is formed by mosaics of forests with Araucaria pine, grasslands, and flooded areas (wetlands) with flatter terrain in the southern portion to valleys in the northern part (SEMA, 2008). It has an area of 6,654 ha with a BZ of approximately 60,000 ha, covering the municipalities of Jaquirana (69.8%), São Francisco de Paula (20.6%), and Cambará do Sul (9.6%) of the Park's area. Around the PET, communities in its BZ depend on agriculture, forestry, and livestock and regularly use fire as a management tool (Bond-Buckup, 2008).

The PET is close to other protected areas, which favors the emergence of the biogeographic conditions that can contribute to the interconnection of these units through ecological corridors, helping preserve fauna and flora populations and maintain the ecosystem services balance in the region.

2.2 Burned areas classification in highland grasslands (BACHG)

The methodological approach for burned area detection used in this study is shown in the flowchart (Figure 2). We use Sentinel-2 MSI Multispectral Instrument, Level-2A data. The Level-2A product provides Bottom Of Atmosphere (BOA) imagery derived from the associated Level-1C products. The imagery used is available from the Google Earth Engine (GEE). This platform combines three tools (code editor, explorer, and client libraries) for users to perform geospatial analysis in the cloud (Adagbasa, Adelabu, and Okello, 2020). We select images from 2018 to 2022, before the start of the fire season, from January 1 to April 1, denominating as "pre-fire" images, while the post-fire images were selected from July 15 to September 15 of each year, when the "burning window" allowed by municipal legislation was established. A cloud mask was applied. First, the function defines two bitmask values for clouds and cirrus (bit 10 and bit 11, respectively) and selects the image's pixel quality band (QA). Then, the function creates a mask that filters out all the pixels where the cloud and cirrus bits are equal to zero, indicating clear conditions.

We used the GEE to collect spectral signatures of the burned and unburned areas, which served as samples for the model
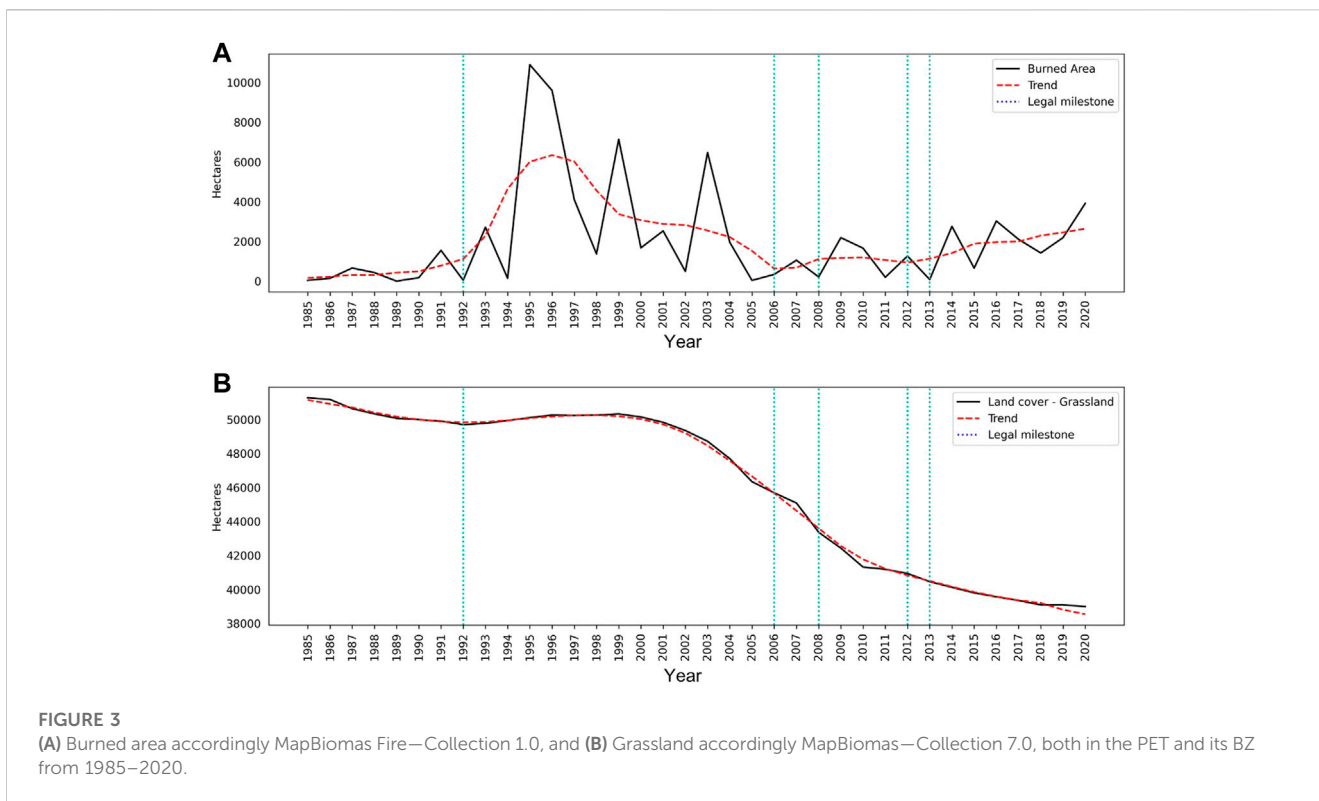
FIGURE 3
(A) Burned area accordingly MapBiomas Fire—Collection 1.0, and **(B)** Grassland accordingly MapBiomas—Collection 7.0, both in the PET and its BZ from 1985–2020.

TABLE 1 Relationship of burnt areas (hectares per year) mapped and permissions of environmental permits.

Legislation	Event	Burned area (ha)	Grasslands (ha)
Law n°9.519/92	Fire use prohibition in the Rio Grande do Sul state	44	49,709
Law n°11.428/2006	Atlantic Forest Biome Law—Prohibits the conversion of grassland to other land uses	339	45,689
Decree n° 6.660/2008	Regulates the provisions of the Atlantic Forest law and defines the legal framework for the conversion of areas	210	43,378
Law n° 13.931/2012	Conditional fire use permission	1,262	40,943
Municipal Law n° 2.954/2013 (Cambará do Sul)	Regulation of fire use licensing by municipal agencies	80	40,464
Municipal Law n° 1.083/2013 (Jaquirana)			
Municipal Law n° 2.924/2013 (São Francisco de Paula)			

classification. In addition, we used data collected from the field in the year 2020 as a reference for sampling in this year's post-fire images. This effort resulted in 7,133 sampled pixels, manually collected as small polygons from burned areas (2,295 sampled pixels) and the unburned regions (4,838 sampled pixels).

For training, we used the shortwave infrared (SWIR) and near-infrared (NIR) bands and the result of the Normalized Burn Ratio spectral index (ΔNBR) calculation.

The NBR is a ratio of the NIR to the SWIR region, developed to identify post-fire burned areas and provide a quantitative measure of burn severity (Key and Benson, 2006). The NBR is calculated by the pre- and post-fire difference (denoted as ΔNBR) using Eqs. 1, 2.

$$NBR = \frac{NIR - SWIR}{NIR + SWIR} \tag{1}$$

$$\Delta NBR = NBR_{pre-fire} - NBR_{pos-fire} \tag{2}$$

The algorithm used for our classification was the Random Forest (RF) (Breiman, 2001; Goehry et al., 2021), which is an ensemble algorithm operated by building multiple decision trees in a training session and assigning the target class by majority vote (PAL, 2005). In this study, we used the RandomForest function in the GEE library. The parameters used were: number0fTrees (20), variablesPerSplit (null), minLeafPopulation (1), bagFraction (0.5), maxNodes (null), and seed (0). After classification, we applied a spatial filter to remove noise and fill

FIGURE 4
ROC curve.
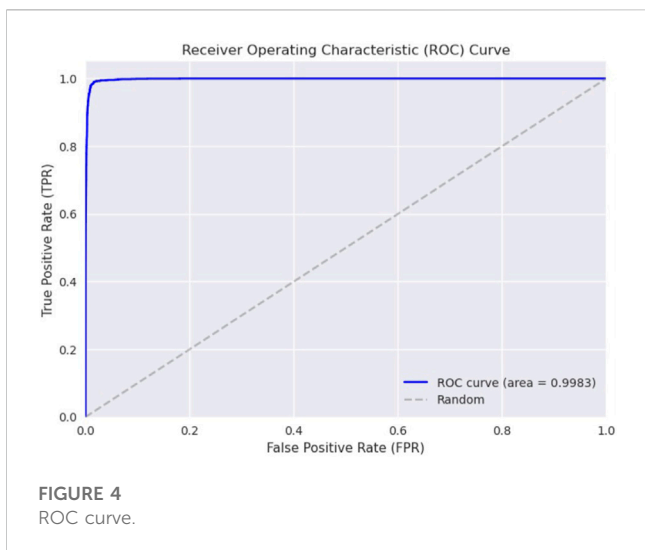
in gaps, where burned areas smaller than or equal to 1 ha (5 × 5 pixels) were removed, and, in the same way, internal spaces were filled as burned. The spatial filter selected was the Manhattan Kernel, which generates a distance kernel based on rectilinear distance (city-block). Reduction is performed by calculating the mode (most common value) of the pixel values in a neighborhood defined by the specified kernel (or window). The filter size was determined considering the difference in the spatial resolution of the Landsat 8 satellite, which was used for the MAPBIOMAS product methodology proposed for exclusion. Finally, the Receiver Operating Characteristic (ROC curve) was calculated to measure and compare the binary classification model's performance.

2.3 Temporal analysis of burned areas

To evaluate the management tools available in conjunction with the classification data generated, we used data on the annual area

FIGURE 5
Examples of burned area classification using RF.

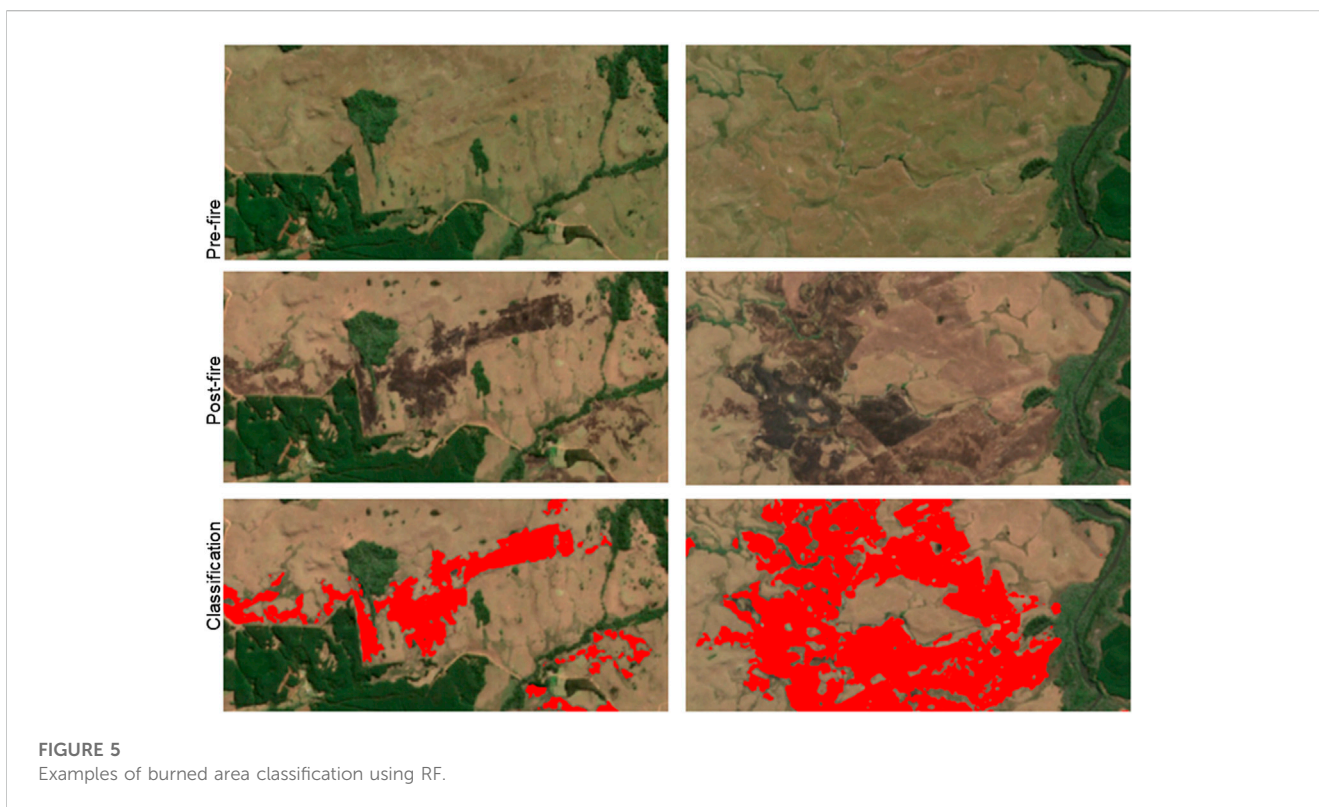**TABLE 2 Comparison of burned areas (ha) authorized by the municipality between mapped by mapbiomas and BACHG.**

	2018	2019	2020	2021	2022
Mapbiomas	1,417	2,189	3,909	-	-
BACHG	5,380	7,373	7,859	2,813	4,681
Match pixels BACHG and Mapbiomas	772	1,132	2,616	-	-
Municipalities	2,587	2,479	1,851	1,953	2,038

FIGURE 6
Representation of the comparison of classified areas in both methods for 2020.
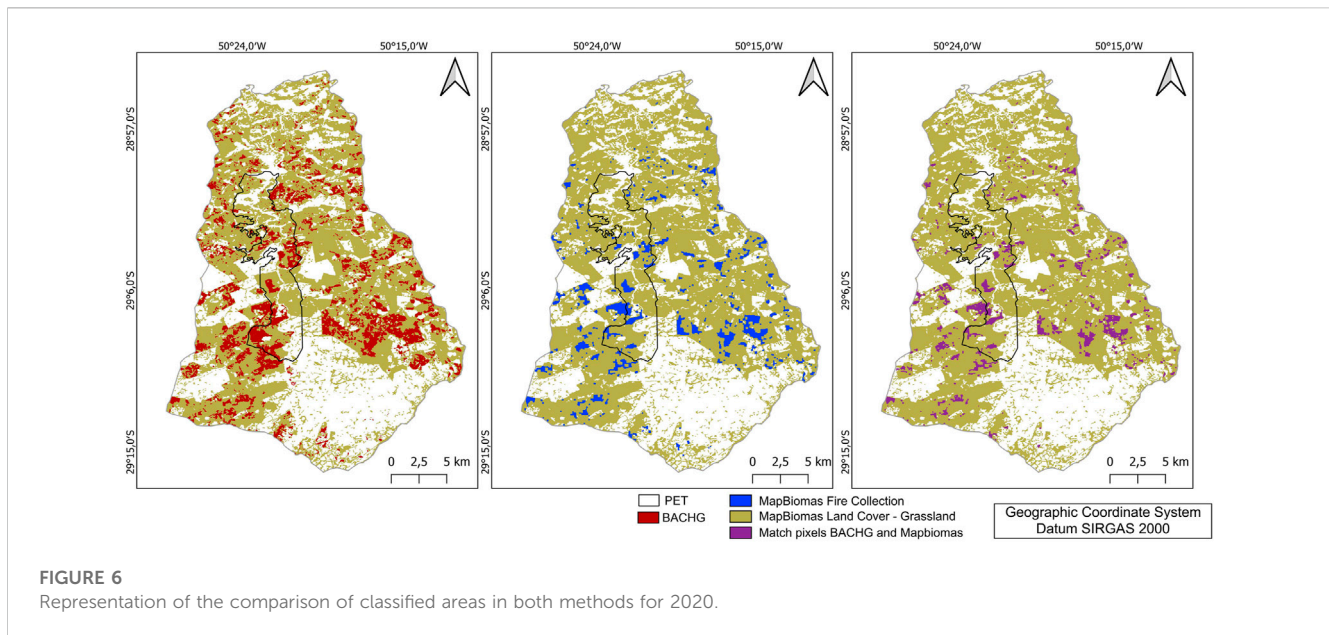
burned by MapBiomas Fire—Collection 1.0 (Alencar et al., 2022) and the land use and land cover areas classified as grassland from 1985 to 2020 available in MapBiomas Collection 7.0 (Souza et al., 2020). In addition, we also used the extent area authorized for burning by Jaquirana, São Francisco de Paula, and Cambará do Sul municipalities located within PET and its BZ.

The annual burned areas stationarity trend covered by grassland was checked using the Augmented Dickey-Fuller (ADF) test. The ADF test is an "augmented" version of the Dicker-Fuller test. The ADF test expands the test equation to include high-order regression processes in the model.

Afterward, the trend was verified through time series decomposition to verify the seasonality and the residuals. Results are obtained by first estimating the trend by applying a convolution filter to the data. Therefore, the trend is removed from the series, and the average of this unbiased series for each period is the seasonal component returned (McKinney, Perktold and Seabold, 2011).

3 Results

3.1 Reconstructing the history of fire use

The burnt areas and the grasslands from 1985 to 2020 in the PET and its BZ are shown in (Figure 3). In this figure is highlighted in vertical dotted lines, the primary legislation, which is also presented in (Table 1) together with the grasslands and the total burned area values. This analysis reveals an increasing trend for the burned area, while there is a decreasing trend for grassland in the PET.

We can observe that the burnt areas remained low after the fire use prohibition in 1992. However, this pattern was not established for a long time, and the highest values for the time series analyzed occurred in 1995 and 1996, with about ten thousand hectares burnt each year.

The most significant burned areas reduction occurred in 2002, reaching the lowest value in 2005, with only 35 ha. By observing the trend curves of burnt area and area occupied by grassland formation, the curve's decline in the same years is noticed.

In 2002, the area corresponding to grassland was 49,359 ha, while in 2005, it was 46,345 ha. Therefore, the PET and its BZ lost more than 3,000 ha in only 3 years. These years precede the AFB Law creation (Brasil, 2006) and its regulation decree (Brasil, 2008), prohibiting new conversions of areas with native vegetation in the biome.

During the 35 years of the analyzed time series, 12.285 ha of grassland areas were converted to other uses, losing about 24% of their original formation, with 10% occurring after the AFB decree banned this practice in 2008 (Brasil, 2008).

Finally, concerning the burned areas only when municipalities begin to legislate about the use of fire, in 2013, a trend definition and a biannual frequency can be observed, as provided by several municipal legislation (Municipio de Cambará do Sul, 2013; Municipio de Jaquirana, 2013; Municipio de São Francisco de Paula, 2013).

3.2 Burned area and frequency of occurrence

The burned areas classification with the RF algorithm obtained an AUC = 0.9983 (Figure 4). With a visual inspection, the scar's demarcation can be identified when comparing the pre-fire and post-fire images (Figure 5).

The results show that larger areas were burned for all years than those allowed by the municipalities' environmental permits. In addition, larger burned areas were found in our classification than those presented by the MapBiomas Fire collection, as can be seen in (Table 2).

The licenses issued correspond to only 48.09% (2018), 33.62% (2019), 23.55% (2020), 69.43% (2021), and 43.54% (2022) of the area identified as burned in our classification. For the three available years of the analyzed period from the MapBiomas collection, they represent only 26.34% (2018), 29.69% (2019), and 49.74% (2020) of the burned areas.

The Mapbiomas burned areas that coincide with our classification represent only 21% of the total classified area on average (Figure 6). The MapBiomas burned omission areas are

FIGURE 7
Fire frequency in the PET and its BZ.
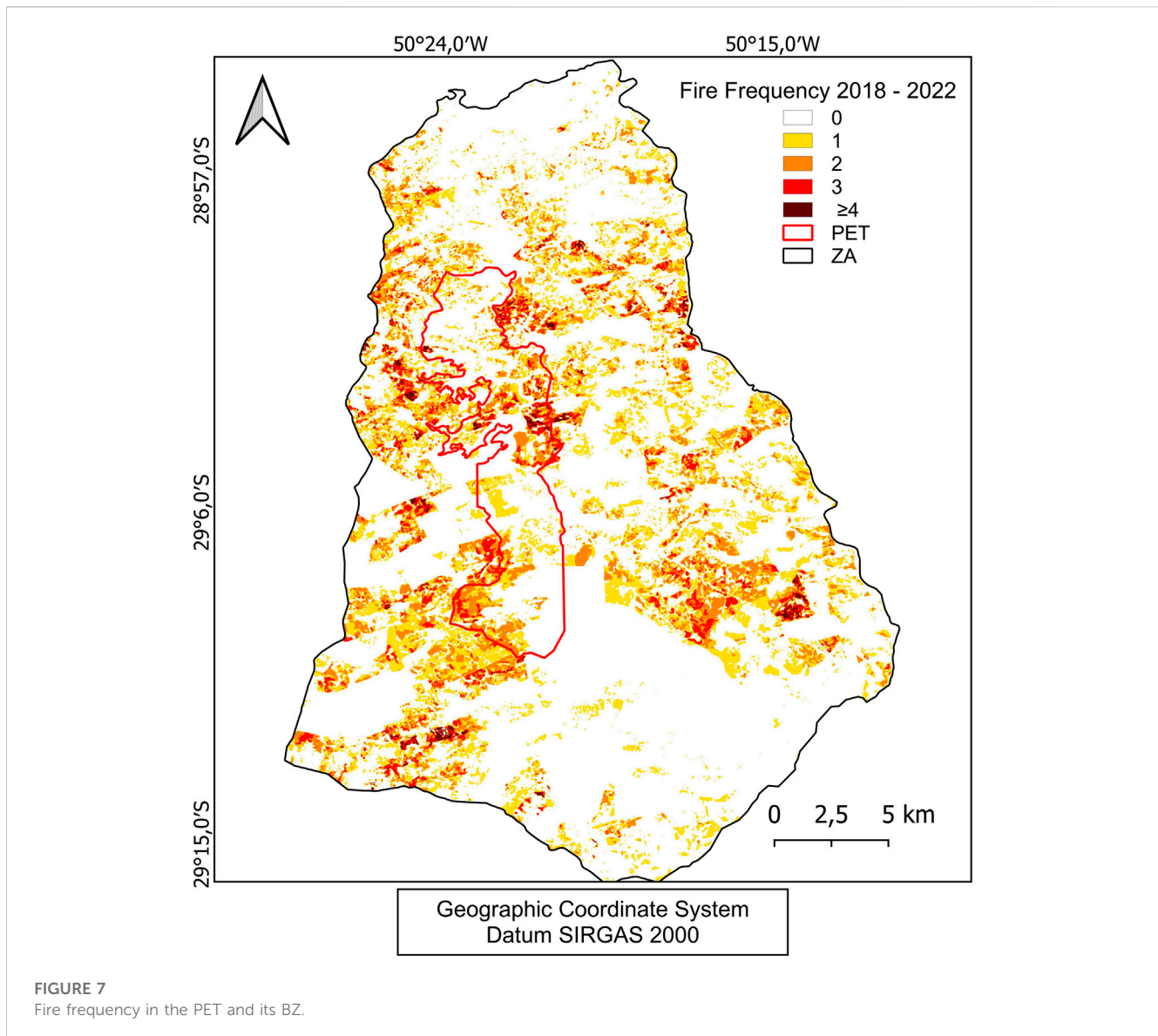
formed by scars smaller than 10 ha or with sites that present a non-continuous formation with gaps of 1 ha.

In addition to the burning extent, the frequency of areas affected by the fire was verified, and about 28% of the PET and its BZ were burned at least once, as shown in (Figure 7). Notably, according to the legislation, the areas could present a burning frequency of 2–3 times for 5 years. However, the results showed that 353 ha were burned 4 to 5 times, exceeding the legal requirements for this period. These areas are within the Jaquirana municipality territory inside the PET or near its boundaries.

4 Discussion

4.1 Legislation analysis and remote sensing

No stationary trends were found in the time series, even though there is a long history of legislation to regulate fire use and vegetation protection practices.

During the 20 years (1992–2012) of fire use practice prohibition, producers changed their economic profile, and extensive native grassland areas conversion to monocultures in the region occurred (Boziki, Beroldt, Printes, 2011; Buffon, Printes, Andrades-Filho, 2018). Grasslands are important for livestock, especially where other agricultural practices are not viable. In this study, we noticed that legislation changes over the time series are related to changes in land use.

Conservation areas (CAs) in Brazil are managed under the National System of Conservation Units (SNUC), which is designed to protect the country's diverse ecosystems (BRASIL, 2000). The SNUC comprises 12 categories of CAs, each with specific objectives regarding protection and use. The PET falls under the Park category, which provides full protection and allows only non-consumptive uses of natural resources. This means that handling fire is not permitted inside the PET. Conservation areas like the PET are essential for preserving Brazil's rich biodiversity and ensuring the long-term sustainability of the country's natural resources.

The fire management practice in the winter period is expected in the region, and it is used to remove dry biomass to provide the vegetation regrowth that will be used to feed the cattle herd in spring and summer (Pillar et al., 2009).

Once forbidden, it can be replaced by other activities much more environmentally damaging than the old fire management grasslands practice, such as forestry and monocultures, which have been advancing into the grasslands (Buffon, Printes and Andrades-Filho, 2018).

It was observed during the study that municipalities lack data and tools to manage and enforce current environmental legislation. So it is necessary to evaluate the effectiveness of existing environmental management tools regulated by municipal laws related to the use of fire (Santos and Andrades-Filho, 2021).

In addition to the environmental laws presented, it was verified the irregularity in the data availability by the municipalities, which do not meet the legal provisions of free access to information in Brazil, especially regarding publicity, accessibility, and transparency, making technological advancement impossible (Brasil, 2011).

4.2 New burned area classification approach

The brief characteristics of the fire marks left on satellite imagery complicate the burned area's detection. There are few fire products available globally, and only one at the national level (Alencar et al., 2022). So, evaluating its applicability to different regions and vegetation formations in Brazil is extremely important.

Our study found significant differences in areas mapped as burned, increasing by more than 50% in our study using a better spatial resolution. The improvement of available products is substantial and progresses with the recent technologies emergence. In previous studies of Russian grassland, the difference in the area mapped between satellites with lower spatial resolutions also increased dramatically from no burning to as much as 19% of the total study area (Dubinin et al., 2010). The strategy of using ΔNBR in conjunction with the NIR and SWIR bands for burned areas classification reduced noise and class confusion, especially with wetlands. The areas with the highest commission error were exposed soil from recently cleared forestry areas.

Due to the rugged relief and mosaics of forest and mountainous grassland vegetation that form the area's landscape, remote sensing data with higher spatial resolution can be explored as they become available. Therefore, Earth observation can significantly support public fire prescription policies and add to other factors that consider CO^2 emissions (Herrmann, Nascimento and Freitas, 2022).

5 Conclusion

This study uses remote sensing techniques to evaluate legislation related to fire use in highland grasslands in Brazil. Long-term time series and exploring new enhancement methodologies are essential to identify the main impacts of human-induced changes.

Divergences in extent and frequency were found between the burned areas authorized by the municipalities and those classified as burned. On average, only 43% of the burned area in the PET and its BZ was licensed in the last 5 years. The municipal databases had recorded only from the year 2018, and it is possible to improve the time series from the continuity of data collection.

Our newly burned area methodological classification developed in this article presented results that provide subsidies for reviewing and creating public policies and territorial management.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PH designed the study, collected the data, performed the analysis, wrote the paper, discussed the results, and contributed to the final manuscript. VN provided critical feedback, supervised the project, verified the analytical methods, discussed the results, and contributed to the final manuscript. MF and JO verified the analytical methods, discussed the results, and contributed to the final manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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