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Perspective

Wildfires in Brazilian Biomes: Environmental Impacts, Policy Challenges, and Future Directions

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Abstract: Wildfires play a central role in shaping the landscapes and ecosystems in Brazil by considerably affecting biogeochemical cycles, soil properties, and vegetation dynamics. In this study, the pyrogeography of Brazilian biomes, wildfire occurrences from 1999 to 2024, the primary environmental consequences of fires in each biome, and key challenges related to fire policy in Brazil are elucidated. The analysis of public data from the Brazilian National Institute for Space Research (INPE) has revealed that 80% of fires occur in the Amazon and Cerrado biomes due to the expansion of agricultural frontiers, mainly during dry winter and spring seasons. Their effects of such fires on ecosystems vary with vegetation type, topography, and burn severity, influencing soil properties, hydrological processes, carbon stocks, and erosion. Fire policies in Brazil have structural and institutional limitations such as a limited state presence in remote areas and resource shortages. The implementation of Integrated Fire Management (IFM) in protected areas incorporates prescribed burning and traditional knowledge based on ecological monitoring; however, these efforts remain fragmented and lack national integration. The future of fire management in Brazil focuses on coordinating science, public policy, and local engagement; expanding remote sensing; supporting local brigades; and promoting strategies tailored to the ecological and cultural conditions of different regions. To address the complex dynamics of illegal fires driven by agricultural expansion and apply controlled ecologically oriented burns for conservation, technically informed solutions, social participation, and public action grounded in territorial realities are essential.

Keywords: pyrogeography; tropical landscape; prescribed fire; fire policy; integrated fire management

1. Background

Fire is a fundamental component of the Earth's natural systems and plays a significant role in shaping landscapes and regulating biogeochemical cycles. The evidence of fire, such as fossilized charcoal, dates back to the Silurian period ~420 million years ago [1]. In Brazil, historical records reveal the presence of fires long before European colonization [2]. Over the last century to two and a half centuries, the use and transformation of landscapes in Brazil have intensified [3], with fire as a key tool for land conversion [4]. Fires generally result from a complex interaction of landscape characteristics, climatic and meteorological conditions, and human activities. This interaction can lead to varying fire occurrences within a specific area, which exert diverse impacts on biogeochemical processes and transformations depending on the biome type (Figure 1).

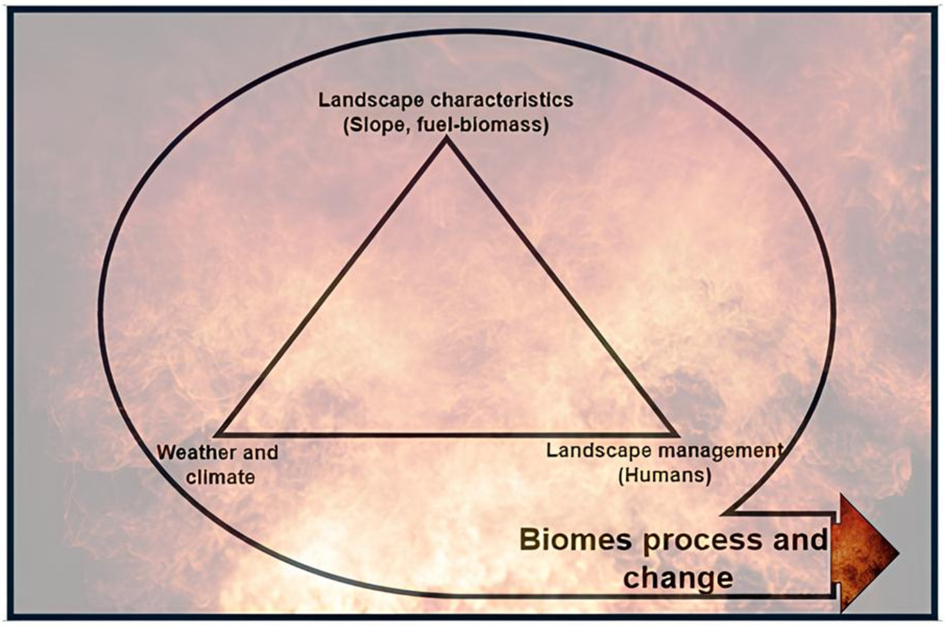

Figure 1. Dynamics of triangle fires: influences on pyrogeography and implications for biome processes and change.

Climate plays a crucial role in shaping fire regimes by influencing the frequency, spatiotemporal patterns, and characteristics of fires (Figure 1), making elements such as seasonality, dry-season length, droughts, and heat waves the key drivers of fire occurrence. Climate change is expected to intensify extreme fire and weather conditions [5]. Moreover, fires in Brazil have been linked to prolonged droughts [6–8] and heat waves [9,10].

Landscape characteristics such as topography; soil type; moisture distribution; and vegetation pattern attributes, including floristic composition, vegetation structure, and flammability, play a decisive role in determining the ignition and maintenance of fire. Thus, grassland and savannah biomes are generally more prone to fires and often lead to low-intensity ground fire events [1,11,12]. Conversely, areas with dense vegetation are more likely to experience crown fires [1,12].

Human activity is the primary driver of fire ignition, and human intervention can modify the fire regime via landscape management [1,13]. For example, fuel-break fire techniques can be employed to reduce fire events; these include selectively removing flammable herbaceous vegetation, shrubs, and exotic species can reduce the fire risk within an ecosystem [14] and prescribed fires can facilitate fuel reduction and ecosystem maintenance [15,16]. In contrast, fire suppression can lead to increased vegetation encroachment, which, depending on its characteristics, can make the ecosystem more prone to fire and increase its severity [1,15,16].

Changes in fire regimes can considerably impact the dynamics of a biome by altering the structure and physiognomy of its vegetation. Consequently, frequent fires can convert a savannah-type ecosystem into a grass-dominated landscape and dense forests into a savannah-type ecosystem. However, fire suppression can also change the structure and physiognomy of vegetation, potentially transforming grasslands into open or even denser savannahs [1,15,17].

Therefore, this study (a) outlines the pyrogeography of Brazilian biomes; (b) identifies the main environmental consequences of fires on Brazilian biomes; and (c) discusses the primary challenges related to the fire policy in Brazil. To this end, public data from the Brazilian National Institute for Space Research (INPE https://terrabrasilis.dpi.inpe.br/queimadas/portal/ (accessed on 25 April 2025), were used [18]. The existing methodology used by INPE for fire detection is complex and involves multiple satellites, posing certain limitations. Specifically, it can only detect fires that are ~30-m long by 1-m wide, and fire fronts smaller than 30 m and fires confined to the forest floor without affecting the tree canopy are undetected by the satellites. Within a burning focus, the exact type of burned vegetation such as secondary growth, pasture, and forest cannot be determined. Existing studies have used various terms interchangeably to describe this phenomenon such as burning focus, heat focus, fire focus, and active focus [18]. In this context, "wildfire" will be used to provide an overview of fire occurrences within the Brazilian territory.

2. Fire on the Brazilian Biomes: An Overview from 1999 to 2024

Brazil is a vast territory (8.51×10^6 km^2) with diverse landscapes and climate types (Figure 2). Based on their areas, the main Brazilian biomes are the Amazon (4.20×10^6 km^2), Cerrado (Savannah; 2.04×10^6 km^2), Atlantic

Forest (1.11 × 10^6 km^2), Caatinga (semiarid scrub forest; 8.44 × 10^5 km^2), Pampa (grassland; 1.76 × 10^5 km^2), and Pantanal (floodplain; 1.50 × 10^5 km^2) [18]. Therefore, a variable fire regime is expected across the country.

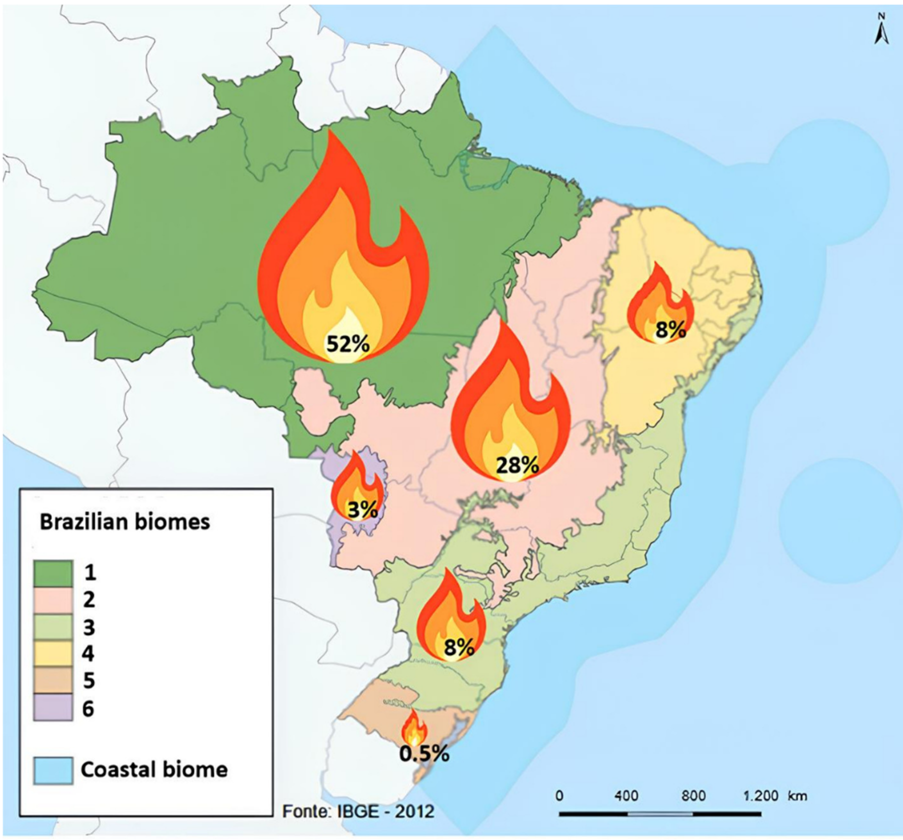

Figure 2. Pyrogeography of wildfires across Brazilian biomes from 1999 to 2024: (1) Amazon; (2) Savannah; (3) Atlantic Forest; (4) Caatinga (semiarid scrub forest); (5) Pampa (grassland); and (6) Pantanal (wetland/floodplain).

However, fires are more frequent in spring (56.6%) and winter (32.0%) across all biomes in the Southern Hemisphere. A total of 47% of all fires in Brazil occur in August, September, and October, whereas fires are less frequent in summer (7.6%) and fall (3.9%). Due to less rainfall in winter, dry vegetation can get ignited. Additionally, fires tend to spread during spring, particularly when the onset of the rainy season is delayed. These dynamics can be further exacerbated due to climate change (Table 1).

Table 1. Projected climate changes up to 2040 and their impact on temperature and precipitation across major biomes in Brazil [19].

Biome	Temperature	Rain Distribution
Amazon	+1 °C–1.5 °C	−10%
Cerrado (savannah)	+1 °C	−10%–20%
Atlantic Forest–Northeast (NE)	+0.5 °C–1 °C	−10%
Atlantic Forest–Southeast (S/SE)	+0.5 °C–1 °C	+5%–10%
Caatinga (semiarid scrub forest)	+0.5 °C–1 °C	−10%–20%
Pantanal (wetland)	+1 °C	−5%–15%
Pampa (grassland)	+1 °C–1.5 °C	+5%–10%

Source: [19].

In the short term, significant climate changes are projected across all Brazilian biomes (Table 1). Despite this, wildfire occurrences in Brazil exhibited a downward trend from 1999 to 2024 ($r = -0.1979$, $p < 0.05$). However, fires tended to increase in late summer (February) and early fall (March), as shown in Table 2. This trend is concerning because it indicates the occurrence of fires that exceed the typical seasonal regimes.

Table 2. Pearson correlation coefficient in relation to the wildfire trends from 1999 to 2024.

January	February	March	April	May	June
−0.0911	0.3729 *	0.4991 **	0.3426	0.2557	−0.1685
July	**August**	**September**	**October**	**November**	**December**
−0.0435	−0.1333	−0.1783	−0.3440	−0.2927	−0.2874

Note: significance level: * ($p < 0.05$); ** ($p < 0.001$).

An average of 220,000 wildfires were documented annually in Brazil, with a recorded minimum of 101,500 in 2000 and a maximum of 394,000 in 2007. A cumulative total of 5.81×10^6 wildfire was recorded between 1999 and 2024; however, the spatial distribution of fires in Brazil is uneven. Currently, 80% of wildfires occur in the Amazon and savannah biomes (Figure 2), which have undergone extensive forest conversion for agricultural purposes.

The dynamics of fire are closely linked to the spatial organization of Brazil's territory, which is divided into three main geo-economic regions: (a) the central–southern region, encompassing savannah, grassland, and Atlantic Forest; (b) the northeastern region, marked by semiarid scrub forest; and (c) the Amazon, which includes both Amazon and savannah biomes. In the central–southern region, agricultural frontiers are firmly established, agricultural practices are advanced, and the population density is relatively high. In contrast, the northeastern Brazil features largely traditional agriculture, with a higher population density along the Atlantic coast and a lower density inland. The Amazon region is characterized by a sparse population, with predominant traditional agricultural practices. In summary, the agricultural frontier that originated in the center–southern region (savannah) is gradually encroaching on the Amazon biome. The transition zone between these regions highlights a contrast between two distinct biomes: the savannah, which is fire-prone and adapted to fire regimes, and the Amazon, a biome that is not adapted to fire [20].

Currently, 80% of fires in Brazil occur within the Amazon and savannah biomes (Figure 2), which represent the developing agricultural frontier, despite their relatively low population densities. In these biomes, fires are associated mostly with (a) deforestation of pristine forest and (b) clearing of secondary forests (capoeira) for pasture and cropland establishment as well as (c) the use of fire for pasture and grassland restoration. Typically, these fires occur far from major urban centers, i.e., the forest–urban interface, particularly in the central–southern regions such as São Paulo.

However, in 2024, Brazil faced a severe drought that affected a substantial portion of its territory and led to widespread fires across the nation. This catastrophic event and other similar events are referred to as "*the fires connecting the country*". Compared with those in 2011–2023, the incidence of fires in 2024 has increased by 50%. The central–southern regions were particularly affected, with fires igniting in forest fragments and agricultural areas, including sugarcane plantations. Furthermore, the visual documentation of dead and injured fauna resulting due to fires in the Pantanal (2020), a prominent wildlife sanctuary in Brazil, considerably impacted public perception, particularly among individuals residing at a considerable distance from the affected region. In the aftermath of these fires, sunlight was partially obscured in several urban locales, with "black rain" in some instances as suspended particulate matter descended during the initial post-fire precipitation.

Fires are a significant natural hazard in Brazil, heavily influenced by human activities such as negligence and intentional ignition, and should therefore be prioritized in the national agenda. Additionally, climate change is expected to increase temperatures and reduce rainfall across most Brazilian biomes (Table 1). High temperatures and prolonged droughts are critical factors that can intensify fire incidents in Brazil in the coming decades.

3. Effect of Fire on the Brazilian Ecosystems: Environmental Impacts

Identifying the primary impacts of fires on Brazilian biomes is a significant challenge due to the unique biophysical characteristics of each biome such as differences in lithology, soil composition, topography, vegetation, and climate. Wildfires in Brazil have had extensive ecological impacts, particularly on forests and the ecosystem services they support. In the Amazon, fire combined with deforestation has affected between 103,079 and 189,755 km^2 of forest since 2001, threatening 77.3%–85.2% of endangered species in the region [21]. These disturbances have compromised forest resilience and reduced its capacity to regulate global climate change processes [22]. In the Cerrado, agricultural expansion and altered fire regimes have transformed the vegetation structure and key ecological processes, undermining biodiversity and ecosystem functioning [23]. In the Pantanal, the unprecedented fires of 2020 caused massive wildlife mortality and triggered cascading effects on the biodiversity and ecosystem services in the region, including tourism, pollination, seed dispersal, and pest control. At the national scale, these events illustrate the substantial social and economic burdens posed by such wildfires, with costs estimated in billions of reais due to biodiversity decline, health impacts, and degradation of ecosystem services [24].

The degradation of ecosystem services caused by wildfires has several dimensions. Climate regulation is strongly affected due to reduced forest biomass and soil organic matter caused by recurrent fires, enhancing greenhouse gas emissions and weakening the carbon sequestration capacity [21,22]. Wildfires also affect provisioning and cultural services, thereby restricting the availability of natural resources and clean water and impacting Indigenous and traditional communities that depend on fire-sensitive landscapes for subsistence and cultural practices [24]. These changes demonstrate that wildfires compromise the resilience of Brazilian ecosystems by eroding the ecological functions and services that underpin environmental stability and human well-being.

Nonetheless, some of the most common effects of fire events on biological, chemical, and physical soil properties are discussed herein. Fires directly impact ecosystems by killing microorganisms, destroying fine roots, increasing soil hydrophobicity, and altering mineralogy. Indirectly, they cause canopy loss, influence soil hydrology via the effect of the ash layer, and promote soil erosion [25]. These effects can be observed immediately as well as in the medium and long term after the fire. The primary effect of fires is linked to their severity, which is measured by the loss of aboveground and belowground soil organic carbon. The severity of a fire directly affects the ecosystem's response, mainly via soil erosion and vegetation recovery [26,27].

Soil has low thermal conductivity and restricts temperature increases to the uppermost layer (≤5 cm), depending on fire intensity [28]. However, temperatures ranging from 50 °C to 200 °C are enough to damage fine roots, eradicate fungi and bacteria, and impact the soil seed bank [29]. Microorganisms are directly impacted by the heat generated by fires, which considerably reduces their population in the short term. These microorganisms are then re-established over medium-to long-term [13]. However, alterations in soil chemistry can lead to changes in microbial communities and their abundance [29]. Such a fire-induced effect is observed consistently across all Brazilian biomes, exemplified by a 65% reduction in the post-fire fungal population particularly in the savannah biome [30], and variations in the characteristics and population of arbuscular mycorrhizal fungi in an Araucaria moist forest subjected to fires [31].

A direct consequence of fire, particularly through soil heating, is the transformation of Fe (oxy)hydroxides into Fe oxides at temperatures beginning around 300 °C. When the temperature exceeds 500 °C, clays undergo fusion and collapse [13]. This general pattern has been confirmed in Ferralsols from the Amazon region, where goethite and gibbsite were not detected in samples heated above 250 °C and kaolinite decomposed after heating at 530 °C [32]. The mineralogy of clay considerably influences various soil properties such as the cation exchange capacity and aggregate stability [33,34]. Depending on the severity and recurrence of fires, changes in mineralogy are expected across all soils within the Brazilian biomes.

Post-fire events considerably alter soil chemistry because nutrients from biomass are partially retained in the ash layer deposited after combustion (e.g., Ca, Mg, K, Na, and P). These nutrients are subsequently leached from the ash by rainfall [29,35]. These basic cations increase the soil pH and enhance nutrient availability. The duration of post-fire fertilization effects can extend for months or even years depending on fire severity, recurrence, and local environmental conditions (e.g., slope) [35,36]. In certain biomes, such as the Savannah, Amazonia, Pantanal, and Pampa, the vertical movement of materials after fires can be more pronounced on the hillslopes. In these biomes, gentle terrain facilitates ash retention on the soil surface and promotes leaching. In contrast, in mountainous regions (e.g., the Atlantic Forest biome), lateral movement of materials after fires predominates on hillslopes, resulting in the transport of ash and organic debris to the valley bottoms and drainage systems.

Ash considerably affects the water quality [30,37]. After a fire, ash can increase the turbidity of water and alter its chemistry by enriching it with nutrients and organic matter. In the Pantanal biome, the effect of ash on aquatic systems, such as rivers and lakes, is crucial for maintaining biota [38,39]. As a floodplain, the burned areas (i.e., ash) and river systems are highly connected. Additionally, shallow subsurface waters are highly vulnerable to leached chemical elements.

The effect of fire on soil aggregates is neither direct nor straightforward [40] and that on aggregates manifests across a wide temperature range (≥50 °C). Large aggregates (≥4.0 mm), which are stabilized by fine roots, fresh organic matter, and fungal hyphae, may exhibit reduced stability [41,42]. Even tropical soils, which typically exhibit high stability due to the presence of aluminum and iron oxides as inorganic cementing agents, can suffer from stability loss due to the depletion of organic cementing agents [43]. Soil aggregate stability is crucial for modulating erosion processes, reducing sealing and crust formation, physically protecting soil carbon, and retaining water and nutrients, thereby facilitating the more rapid recovery of burned ecosystems. Such impacts on soil aggregates stability are expected across all Brazilian biomes.

Soil erosion is one of the most noticeable effects of fire-affected areas, and its extent depends on the severity of fires. Burned areas typically exhibit an irregular mosaic of patches with varying severity levels classified as low, medium, or high. The residual surface cover remaining after fire, comprising leaves, twigs, charcoal, and other materials of distinct colors, indicate the potential severity of fires. For example, dark residues that retain abundant unburned organic matter are characteristic of low-severity areas (from 200 °C to ≤300 °C), whereas white or light-colored ash deposits indicate high-severity fires (>400 °C) [27]. The ash layer, particularly that formed by low-severity fires, can initially function as a protective mulch during the first rainfall event. This layer reduces the impact of raindrops and, consequently, the disruption of soil aggregates and interrill erosion. It can also retain soil moisture, thereby enhancing infiltration and reducing surface runoff [44,45].

Soil erosion becomes progressively severe with increasing fire severity. An experimental study examining the effects of fire severity on soil erosion found that soil loss in an unburned secondary forest area was 0.26 t ha^{-1}. In contrast, areas subjected to low-, moderate-, and high-severity fires experienced soil losses of 1.59, 1.97, and 4.67 t ha^{-1}, respectively [46]. These findings indicate that high-severity fires cause threefold soil losses compared with low-severity fires. Notably, areas impacted by a low-severity fire suffers from soil loss six times greater than an unburned area. In addition, fires considerably influence the hydrological and erosive responses of soil and their effects are linked to the severity of soil heating. Moreover, soil erosion is more pronounced immediately after a fire, particularly within 0.5–1.5 years post-fire [47].

In some cases, the interaction between reduced infiltration and runoff caused by ash can result in dense flows (i.e., mudflow) and promote the development of debris flows and flash floods, particularly in mountainous areas [48]. The recurrence of fires can change the type of vegetation and, consequently, the hydrological dynamics of slopes; these phenomena often lead to a sudden loss of soil stability and slope failure during extreme rainfall events [49]. Therefore, soil erosion, mud debris flow, and mass movement can be expected after a fire, particularly in the Atlantic Forest biome and on steep terrain in the savannah biome.

Fires also interfere with the terrestrial carbon cycle by promoting the combustion of biomass, transformation of soil organic matter, and redistribution of carbon stocks across landscapes [50]. These changes are not exclusive to the ecosystems in Brazil but are particularly significant in tropical environments, where shifting fire regimes impact carbon-rich soils that are essential for ensuring ecosystem stability [51]. In Brazil, fires have been shown to alter carbon pools, primarily in the uppermost soil layers and under the conditions of severe burning and subsequent erosion [52]. Although recent studies have investigated short- and medium-term changes in carbon quality and distribution following prescribed fires, the influence of fire severity, frequency, and seasonality on carbon persistence in different biomes remains understudied [53,54]. These carbon-related dynamics are particularly relevant in a climate change scenario, where increasing atmospheric CO_2 levels result from and intensify wildfire occurrences [55]. This creates a feedback loop that threatens ecosystem resilience and reinforces the strategic importance of fire management practices that balance ecological function and carbon conservation in the long term.

Overall, the consequences and impacts of fires are extensive, affecting both immediate and distant sites across Brazilian biomes. During fires, various volatile chemical elements are released into the atmosphere and subsequently deposited via precipitation [30,56]. Natural mercury (Hg) may also be emitted into the atmosphere or transferred to aquatic systems [35,57,58]. In addition, soil respiration rates increase and greenhouse gases are released from burned soils [59,60], which may also develop hydrophobic properties [61,62]. Furthermore, a correlation exists between an increase in the number of respiratory diseases and a decline in air quality caused by fires [63].

Fire is an ecological process in some Brazilian biomes; however, most of these consequences arise when natural regimes are altered by anthropogenic drivers, leading to higher frequencies, intensities, or seasonality mismatches [64]. In fire-adapted systems, such as the Cerrado, recurrent late dry-season burns exceed the adaptive capacities of vegetation and fauna, thereby intensifying biodiversity loss and ecosystem degradation [65]. Conversely, in fire-sensitive ecosystems, such as the Amazon and Atlantic Forest, even occasional wildfires can trigger long-lasting structural and functional changes because these biomes lack evolutionary adaptations to frequent fires [66,67]. Thus, the impacts observed across Brazil often reflect the disruption of historical fire regimes rather than the ecological role of fire itself.

4. Fire Policy and Future Directions

Wildfire occurrences in Brazil have increased largely due to human activities, many of which are illegal and criminal. The use of fire during dry periods for deforestation; expansion of agricultural frontiers, land grabbing, and mining; and improper use of fire in traditional practices are the key drivers of such wildfires. Extreme climatic conditions such as prolonged drought and elevated temperatures exacerbate this problem.

Brazil's regulatory framework governing the use of fire is mainly structured by the Brazilian Forest Code [68], which regulates its application in agropastoral activities under authorization from environmental agencies and Federal Decree No. 2661/1998 [69], which sets technical and administrative parameters for its controlled use in rural areas.

Although these regulations represent an important legal advancement, their practical effectiveness is hindered by structural limitations such as vast territorial extension, lack of human and financial resources in regulatory agencies, and limited presence of the State in remote regions such as the Amazon and Pantanal.

Among the key public policy instruments is the National Center for Forest Fire Prevention and Combat [70] that is responsible for firefighter training, education, and the development of alert systems. Satellite monitoring, led by the National Institute for Space Research [18], is a strategic tool that enables the near-real-time detection of heat sources and rapid responses.

International experience has demonstrated the effectiveness of Integrated Fire Management (IFM), with an emphasis on prescribed burns, the use of advanced technologies, and community participation [13]. In the context of Brazil, it is imperative to strengthen local brigades, integrate Indigenous traditional knowledge [70], and expand the use of tools such as artificial intelligence and remote sensing. Consolidating a national integrated preventive policy adapted to regional and ecosystemic specificities is crucial for promoting sustainable fire management and addressing contemporary socioenvironmental challenges. As highlighted by Tampekis et al. [71], a holistic framework based on performance-based wildfire engineering can enhance resilience by integrating hazard analysis, socioecological characterization, damage assessment, and loss analysis, offers decision-makers with robust tools for adaptive management.

In line with a performance-based approach for WUI resilience, Brazilian wildfire policy can set explicit performance targets and trigger points linked to the six components of risk assessment (hazard analysis, social-ecological impact characterization, interaction and impact analyses, damage, and loss analyses). These developments will ensure that preparedness, prescribed burning, and suppression are guided by quantitative indicators under climatic uncertainty [71]. Practical targets include seasonal fuel moisture thresholds, early- versus late-dry-season burn ratios, severity distributions (dNBR/RdNBR), and WUI exposure of people and assets to guide adaptive decisions and budget allocation.

Although such systemic changes remain challenging, recent initiatives in Brazil have advanced toward more ecologically grounded and participatory fire strategies [72,73]. The implementation of IFM in federally protected areas has introduced prescribed burns for conservation purposes, supported by ecological monitoring and the inclusion of traditional fire knowledge from Indigenous and local communities [72]. In addition, evidence shows that the Federal Brigades Program has contributed to reducing burned areas in priority regions and fostered environmental heterogeneity. Conservation units with brigades experienced, on average, a 12% reduction in burned areas, with a further 6% reduction in areas where fire prevention activities complemented suppression. However, the program also faces challenges such as increased multiyear fire recurrence and fuel accumulation while operating with a modest mean annual budget of ~US $4.5 million in 2013–2017. This budget is low based on international standards and underscores the need to scale funding and prevention components [74].

However, these efforts often operate in isolation, hindered by a persistent disconnect between research, institutional practice, and local realities [75]. Cultural misconceptions that portray fire as inherently destructive further complicate the adoption of prescribed burning, even in fire-adapted biomes such as the Cerrado [15]. In addition, the exclusion of traditional fire practices in fire-prone ecosystems, such as the Cerrado, has paradoxically increased the risk of catastrophic late-dry-season wildfires, demonstrating the importance of community-based and science-informed IFM [64].

Countries such as Australia and South Africa have more consolidated programs, which combine community fire brigades, performance-based prevention targets, and strong knowledge transfer between researchers and managers. In contrast, initiatives in Brazil continue to suffer from low investment in research and limited communication of scientific results to decision-makers and field practitioners [15]. A deeper articulation between science, public policy, and community engagement is essential to expand the benefits of prescribed fires and develop evidence-based strategies suitable for the ecological diversity in Brazil. The recent catastrophic fire events in the Amazon and Pantanal further highlight how poor governance, combined with climate extremes, accelerates wildfire risk and damages socioecological systems, reinforcing the urgent need for integrated and collaborative policy approaches [76].

To avoid generic guidance and strengthen implementation, wildfire policies should be organized around four governance pillars: (1) actor participation in decision-making; (2) cross-scale collaboration and co-production; (3) attention to local path dependencies and place-based dynamics; and (4) proactive adaptation and anticipation of risks. Combining these pillars with quantitative indicators (e.g., fire weather indices, area burned, and size distributions) will support anticipatory governance and locally tailored decisions across Brazilian biomes [77]. Therefore, the future of wildfire control policies in Brazil depends on profound institutional and cultural reform, guided by technical and scientific advancements based on integration, prevention, participation, education, awareness, and sustainability.

5. Concluding Remarks and Future Directions

Fire activities in Brazil are shaped by seasonal climate patterns, land-use changes, and the ecological characteristics of each biome. Most wildfires are concentrated in the Cerrado and Amazon and occur during the dry spring and winter seasons, respectively. Data from 1999 to 2024 confirm the persistence of these patterns and indicate recent shifts in fire seasonality. The 2024 drought-related fires highlight increasing risks associated with more frequent climate extremes and continued agricultural expansion over natural areas.

These events reinforce the variability of fire regimes across Brazilian landscapes, influenced by both climatic diversity and human pressure. Ecosystem responses to fire depend on vegetation type, topography, and burn intensity, which impact soil properties, hydrological processes, erosion and carbon stock. These impacts determine the resilience of ecosystems to climate change and vary based on regions.

Public fire policies in Brazil continue to face structural and institutional limitations, such as the limited presence of the state in remote areas and shortages of technical and human resources. The implementation of IFM in federally protected areas is a relevant step that incorporates prescribed burning and traditional knowledge based on ecological monitoring. However, these experiences remain fragmented and have not yet been integrated on a national scale.

The future of fire management in Brazil depends on the strong coordination between science, public policy, and local engagement. Expanding the use of remote sensing, supporting local brigades, and promoting fire strategies tailored to the ecological and cultural conditions of different are important. This process must also consider the complexity of fires across Brazil. On one hand, illegal fires and deforestation driven by agricultural expansion persist, reinforced by political and economic constraints. However, scientific and institutional efforts aim to promote the controlled and ecologically oriented use of fire to support conservation. Reconciling these conflicting dynamics requires technically informed solutions, social participation, and public action based on territorial realities.

Author Contributions

E.L.T.: conceptualization, methodology, writing—reviewing and editing. Y.T.C.: writing—original draft preparation, writing—reviewing and editing. P.A.F. writing—original draft preparation, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Data used in this research are from a public repository (INPE https://terrabrasilis.dpi.inpe.br/queimadas/portal/, accessed on 2 November 2025)

Conflicts of Interest

The authors declare no conflict of interest. Given the role as Associate Editor, Edivaldo Lopes Thomaz had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper

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