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Essays and Perspectives

Understanding Brazil's catastrophic fires: Causes, consequences and policy needed to prevent future tragedies

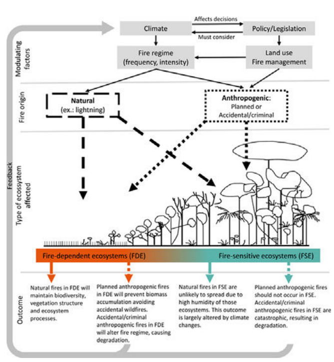
Vânia R. Pivello[a,*], Ima Vieira[b], Alexander V. Christianini[c], Danilo Bandini Ribeiro[d], Luciana da Silva Menezes[e], Christian Niel Berlinck[f], Felipe P.L. Melo[g], José Antonio Marengo[h], Carlos Gustavo Tornquist[i], Walfrido Moraes Tomas[j], Gerhard E. Overbeck[e]

[a] *Departamento de Ecologia, Instituto de Biociências, Universidade de São Paulo (USP), Rua do Matão Travessa 14, 05508-090, São Paulo, SP, Brazil*
[b] *Museu Paraense Emílio Goeldi, Av. Governador Magalhães Barata, 376, 66040-170, Belém, PA, Brazil*
[c] *Departamento de Ciências Ambientais, Universidade Federal de São Carlos (UFSCar), Rodovia João Leme dos Santos Km 110, 18052-780, Sorocaba, SP, Brazil*
[d] *Instituto de Biociências, Universidade Federal de Mato Grosso do Sul (UFMS), Av. Costa e Silva s/nº - Pioneiros, 79070-900, Campo Grande, MS, Brazil*
[e] *Departamento de Botânica, Instituto de Biociências, Universidade Federal do Rio Grande do Sul (UFRGS), Av. Bento Gonçalves 9500, 91501-970, Porto Alegre, RS, Brazil*
[f] *Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), Centro Nacional de Pesquisa e Conservação de Mamíferos Carnívoros, Estrada Municipal Hisaichi Takebayashi, 8600, 12.952-011, Atibaia, SP, Brazil*
[g] *Centro de Biociências, Universidade Federal de Pernambuco (UFPE), Av. Professor Moraes Rego s/nº 50670-901, Recife, PE, Brazil*
[h] *Centro Nacional de Monitoramento e Alertas de Desastres Naturais, CEMADEN, Rodovia Presidente Dutra Km 40, 12630-000, Cachoeira Paulista, SP, Brazil*
[i] *Departamento de Solos, Faculdade de Agronomia, Universidade Federal do Rio Grande do Sul (UFRGS), Av. Bento Gonçalves 7712, 91540-000, Porto Alegre, RS, Brazil*
[j] *Laboratório de Vida Selvagem, EMBRAPA/Pantanal, Rua 21 de Setembro 1880, 79320-900 Corumbá, MS, Brazil*

HIGHLIGHTS

- Fire incidence in Brazil increased in 2019–2020, with unprecedented magnitude in the Pantanal.
- Fire effects vary according to the evolutionary history of the affected ecosystem.
- A drier climate and land use changes increase the risk of wildfires throughout Brazil.
- Poor governance further exacerbates the risk and damage of wildfires.
- Fire policies must be improved by collaboration among different sectors of the society.

GRAPHICAL ABSTRACT



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ABSTRACT

Brazil has experienced unprecedented wildfires in the last decade. Images of immense burnt areas or dead animals that failed to escape the 2020 wildfires have shocked the world. To prevent or minimize further similar disasters we must understand the factors that have led to these catastrophic events. The causes and consequences of wildfires entail complex interactions between the biophysical and sociocultural spheres, and suitable management decisions require a sound scientific base. We present the recent panorama of increasing fire outbreaks in the Brazilian biomes, and discuss the causes that have contributed to such fires, their impacts on the environment and overall consequences for human well-being, based on reviewing the extensive specialist literature, on authors' expert knowledge and information provided by environmental managers, researchers and politicians during a workshop organized to debate the

* Corresponding author.
E-mail address: vrpivel@usp.br (V.R. Pivello).

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wildfire issue in Brazil. Our up-to-date review is aimed at the academic public, environmental managers and decision- and policy-makers. First, we present evidence on the contrasting effects of fire on different ecosystems. Second, we outline the historic perceptions and policies related to fire use and management in Brazil since its colonization to the present date. Third, we propose means to advance fire prevention and develop successful management strategies. Finally, we answer frequently asked questions to clarify and/or demystify some fire-related issues not always properly addressed in the media.

EXECUTIVE SUMMARY

Introduction

In 2019 and 2020, fires in different Brazilian biomes[1] received much attention in the media and in the public debate, also internationally. Fires in the Amazon sadly symbolize the immense problem of deforestation. In the Pantanal, the wildfires in 2020 marked a sad record of burning the largest area registered over the past 20 years: almost 30% of the biome's area was on fire. The other biomes had seen years with more fires in the past, but the last two fire seasons were also indicative of the immense challenges Brazil is facing regarding conservation of its natural ecosystems. However, the topic of 'wildfires' is extremely complex and often discussed without a proper scientific basis, which can lead to unsuitable management decisions and inefficient policy. The objective of this White Paper is to stimulate the development of effective fire management approaches across Brazil's biomes and ecosystems based on scientific evidence.

The relationship of fire with the evolutionary history of vegetation in Brazil

Brazil's biomes and ecosystems differ in their response and vulnerability to fire. Ecosystems characterized by the dominance of grasses - grasslands and savannas - coevolved with fire, and their plants and animals show several adaptations and synergies with fire; therefore, they are considered as fire-dependent from an ecological perspective. The opposite is true for the country's tropical forests that are not fire-adapted and do not easily burn, unless when suffering extreme drought or degradation that can make them more vulnerable to fire. When these forests do burn, fire can cause severe negative effects on their biodiversity, and thus they are considered as fire-sensitive. Overall, fire-dependent ecosystems benefit from fires for maintenance of their biodiversity and ecological processes, while the opposite occurs in the case of fire-sensitive ecosystems. Fire impacts in a given ecosystem - whether it is fire-dependent or fire-sensitive - is determined by the fire regime, i.e. the pattern of fire type, frequency, seasonality, intensity and extent. Natural fire regimes have been modified by human activities – usually related to land use practices or due to climate extremes linked to global warming and to climate change – and often towards higher frequency and extent, as well as altered seasons. Such altered fire regimes usually bring negative effects, not only on biodiversity but also on ecosystem processes and services for human populations. However, in the case of most protected areas, fire has been banished even though the ecosystem is fire-dependent, what will also lead to important ecological changes and often to a rather rapid loss of their natural characteristics. The trade-offs among the distinct effects of fire on the environment, from biodiversity to ecosystem services, must be considered in all discussions about the fire issue.

[1] We here use the term, following the classification of Brazilian biomes according to IBGE (2004), which in fact represent morphoclimatic domains according to Ab'Saber's definition (1977).

Fire management, policy, and legislation in Brazil

Since colonial times a 'Zero Fire' policy prevailed in Brazil, even in fire-dependent ecosystems. Only from the 1970's on, other perspectives on fire have slowly developed, as fire became a subject of scientific studies. By then, negative effects of fire exclusion in fire-dependent ecosystems, such as loss of biodiversity and fuel buildup that would lead to catastrophic fires, have been documented. From 2008 on, an Integrated Fire Management Strategy (IFM) was developed and has been increasingly applied in federal protected areas. Besides controlling fuel and decreasing the risk of wildfire, this strategy allows for the integration of traditional fire management practices of local people or at least sets a framework to find joint solutions in the case of conflicts. Despite successes, IFM is yet not widely implemented across the country, and remains restricted to a relatively small number of protected areas, mainly in the fire-dependent Cerrado. For private land, no general fire management strategy exists. Fires are used for different purposes: in the context of land clearing for future agricultural use (deforestation fires), to manage agricultural or grazing systems, or as part of slash-and-burn systems (swidden cultivation) often practiced by subsistence farmers. While fire may be legally used for agricultural purposes (requiring authorization), a great part of the current fires is illegal, especially when associated with deforestation and suppression of native vegetation, e.g., in the Amazon and in parts of the Cerrado. In some cases, policy has been able to reduce the use of fire when alternatives exist, e.g., in sugarcane plantations in the southeastern region. In other types of land management, however, fire remains a cheap and, at the moment, often the only feasible alternative for smallholders who depend on subsistence activities: alternative technologies exist, but support is needed for their implementation and to allow market access to local producers who change their land management. A clear general strategy to deal with fire on private land – allowing its controlled use when it is overall beneficial, and avoiding it where negative effects overwhelm – still needs to be developed.

Towards effective fire management in Brazil

The risk of severe fire events will likely increase in the future, as climate change effects become stronger and cause more extreme climatic events. This means that it is important to increase the overall resilience of our socio-ecological systems to fire. Despite the recent adoption of the IFM approach in protected areas, both in fire-dependent and fire-sensitive ecosystems, the actions taken in response to wildfires in Brazil by governmental agencies overall have been more reactive than preventive, and a huge policy gap to face the fire problem exists. To advance we must, first of all, recognize that fires occur within complex ecological and socio-economic settings. Fire management thus must be developed in an integrated way with other policy fields, especially those related to land tenure and land management, and in accordance with the climate change agenda. Command-and-control approaches are important and illegal fires need to be prosecuted, but it is also important to actively incentivize land users to adopt alternative techniques to fires (e.g., agroforestry, crop-livestock-forest integration, rotation between crop and pasture, no-tillage cultivation, shredding of cut

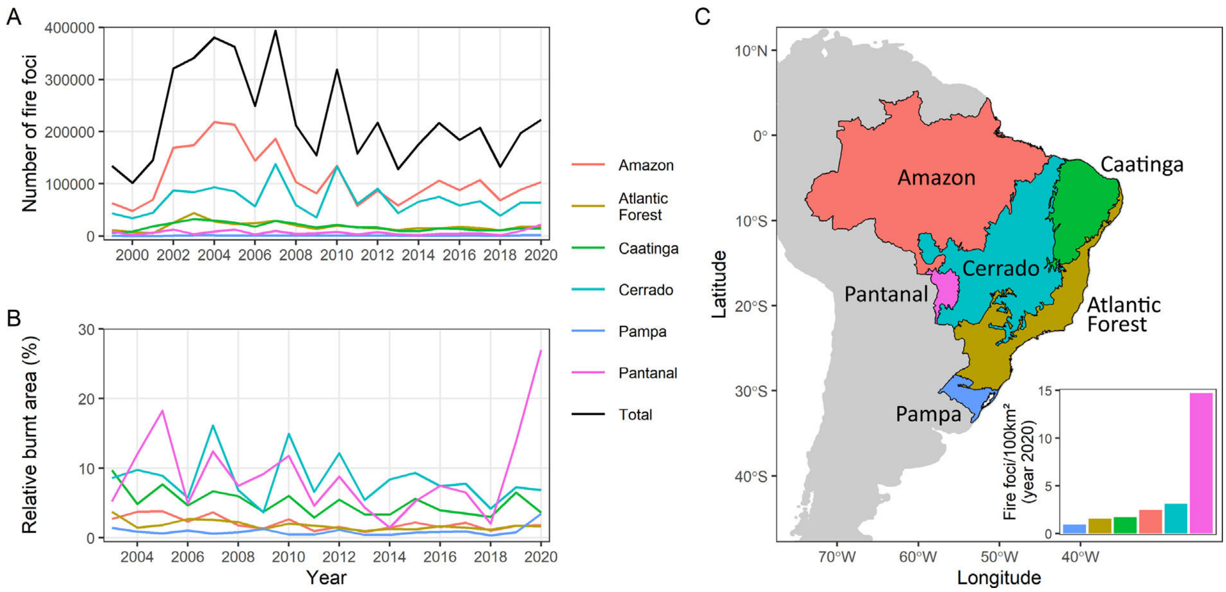

Fig. 1. Fire in the Brazilian biomes: (A) historical time series of number of fire foci, 1999–2020; (B) Area burnt (%) annually per biome; (C) Brazilian biomes, and the density of fire foci in each (bar graph) – the Pantanal (seasonally flooded savanna) has been by far most affected by fire in 2020. Fire data from INPE (2020); map based on IBGE (2004a).

vegetation), and thus allow for a transition to more sustainable and fire-free types of land use. Second, fire management as such can only be efficient if agencies are properly equipped, supplied and trained; capacity building on the ground and also development of monitoring systems are thus important tasks. Third, research on fire should integrate different knowledge areas from biological to human science in a national research agenda that will create a better basis for developing landscapes that are more resilient to fire. In addition to this, education and outreach are necessary to introduce a deeper understanding on the role of fire to all professionals dealing with natural resources conservation and fire management.

Conclusions

The recent mega-fires in different parts of the country have evidenced unpreparedness in institutional capacities and policies, and the lack of appropriate policies to deal with the issue of fires, which also results from the recent emptying of environmental bodies and of political initiatives not committed to the objectives of sustainable development. To effectively reduce fires and their negative effects, Brazil needs a long-term commitment with conservation and sustainable development that considers the distinct ecological, socio-economic and cultural realities across the country.

Introduction

Brazil's vital and irreplaceable biomes[1] (Fig. 1, SM) are burning (Fig. 1). Every year, during the dry season, scenes of fires, destroyed ecosystems, animals dying from burning or starvation, and drying streams and springs are shown in Brazil, and in mega-fire years the global media reports "thousands of burned football fields" destroyed. Fires in the Amazon, mostly associated with deforestation, had reached an absolute record in 2004 (Silva-Junior et al., 2021). Following this peak, government initiatives led to major efforts to control deforestation and the use of fire (Escobar, 2019a; Silva-Junior et al., 2021), resulting in a sharp drop in deforestation rates – and consequently in the number of fire foci – by 2013 (Fig. 1A). However, deforestation and the number of fire foci began to rise again from 2014, reaching in 2020 the greatest number for the period 2011–2020, with 222,798 fire foci registered (INPE, 2020). On the afternoon of August 19th, 2019, smoke from the Amazon fires plunged the city of São Paulo – 2000 km apart from the fire sources – into darkness (Bencherif et al., 2020). In the following year, 2020, wildfires in the Pantanal (hyper-seasonal savanna, affected by annual flooding) shocked the entire country (Marengo et al., 2021): a total area of 40,606 km^2 burned (almost 30% of the biome), leading to the death of a great amount of wildlife that failed to escape fire flames. Over 312,140 km^2 of the country burned in 2020 (INPE, 2020), with most of the fire foci concentrated in the Amazon basin (46.3%) and the Cerrado, the Brazilian savanna (28.6%). Meanwhile, 13% of the fires at the country level were registered in the Pantanal, an unprecedentedly high value since data recording began in 1998 (Fig. 1B and C). These extensive burns have impacted biodiversity, ecosystems structure and function, ecosystem services, human health and overall human well-being.

Fire activity in Brazil is influenced by a myriad of factors, mainly land use change and climatic conditions, and once started, fires can rapidly become widespread and uncontrollable, then considered wildfires (Box 1). Wildfires can have natural causes (e.g., lightning) but have shifted dramatically from a natural phenomenon to a man-made hazard (Dube, 2009; Pivello, 2011; Balch et al., 2017; Brando et al., 2020), either as a direct consequence of land management (Pivello, 2011) or indirectly, due to climate change (Field et al., 2007). An increase in the number of fire outbreaks and the extent of burned areas is not a problem that only afflicts Brazil: in the Anthropocene and around the world, fire has become more frequent (e.g., Chergui et al., 2018), more intense (e.g., Singleton et al., 2019) and/or more extended (e.g., Collins et al., 2021), often with serious consequences on the sustainability of socio-ecological systems (*sensu* Collins et al., 2011).

Based on a synthesis of current scientific knowledge and a discussion of legal, institutional and political issues related to fire management, we present a panorama of the fire problem across Brazil's regions (biomes) and propose key strategies for effective and science-based fire management or control. We also discuss some common misconceptions on fire and its effects on Brazil's ecosystems and society. In this paper we (1) outline the underlying causes of rising fire incidence in Brazil in recent years; (2) provide evidence on the impacts of these fires on ecosystems and people (health and overall well-being); (3) analyze how such events could have been avoided; and (4) present evidence-based actions for deci-

Box 1: Glossary of fire terms.

Wildfire – Unplanned and uncontrolled fire, usually caused by lightning or humans. As a wildfire is not expected in a given place, it may develop to a destructive fire, damaging natural resources, properties, and threatening lives.
Prescribed fire – A controlled burn, contained in a defined and conducted based on clear management goals. A prescribed fire involves careful planning on a landscape perspective and considering season, weather conditions, vegetation type, amount and characteristics of fuel, animal life cycles, human settlements.
Mega-fire – This is a wildfire that affects huge extensions of land (> 100, 500 or 1000 ha, depending on the classification), causes great impacts on the environment and human costs, and is very difficult to fight. It usually results from a combination of extreme climatic conditions (hot, dry, windy) and high amounts of available fuel (Fidelis et al., 2018).
Integrated fire management (IFM) – The IFM approach involves ecological, cultural, socioeconomic and technical aspects of a fire in order to minimize damage and maximize benefits to the natural environment and local people (Rego et al., 2010). It includes the planning and management of prescribed fires, as well as suppression of undesired fires. See main text for details.
Fire behavior – The way a fire starts, develops and spreads.
Fire regime – General pattern of a fire, considering its main parameters: fire type (according to the main fuel layer: groundfire, surface fire, crown fire; see this box, below), intensity, frequency, seasonality and extent (details in Cochrane and Ryan, 2009). A natural fire regime is the one occurring in the absence of human intervention, in opposition to anthropic or human-altered fire regime.
Fire season – Period of the year when fires are most likely to occur, and when the defense agencies organize operations for fire combat and fire control.
Fire severity – Ecological negative impacts that fire causes on ecosystems, and positively related to fire intensity and duration. It is usually measured by the loss or decomposition of soil and vegetation organic matter, including mortality (Keeley, 2009; Cochrane and Ryan, 2009).
Fire intensity – Most commonly defined as the energy released in the fire front. In a broader definition, fire intensity represents the energy output from fire (Keeley, 2009).
Crown fire – Forest fire where the flames jump from one tree crown to another. Crown fires can be very harmful to the environment, reaching very high intensity, with flames that can be twice as high as the tree tops.
Ground fire – Occurs in soils with accumulation of organic matter, and slowly consumes the fuel (for days, weeks, or even months) without producing flames (smoldering). This kind of fire is very difficult to extinguish.
Surface fire – Typically consumes the fuel deposited on the top of soil (litter) and the vegetation herb layer (e.g., grasses, low plants). This is the typical fire in grasslands and savannas, although it may also occur in forests.

sion makers on how the occurrence of such extreme fire years may be prevented from happening in the future.

The relationship of fire with the evolutionary history of vegetation in Brazil

The consequences that fire today has on natural ecosystems depend, to a large extent, on the coevolution of the ecosystem with fires, that is, how natural fires have shaped speciation, species composition, and vegetation structure, as well as animal populations over time. The adaptations of different organisms that have resulted from coevolution with natural fire thus should be important in determining the responses of plant and animal communities to anthropogenic fires. Hardesty et al. (2005) have classified the world's biomes as fire-sensitive, fire-dependent/influenced and fire-independent. This classification considers natural ecosystems and natural *fire regimes* (characterized by the type, intensity, frequency, seasonality and extent of fire; Box 1; see Cochrane and Ryan, 2009), and it does not consider human impacts. Fire-sensitive biomes/ecosystems, such as evergreen tropical forests, are composed of plant and animal species that have no adaptations to tolerate fire events, which cause them serious harm (Laurance, 2003). In contrast, in seasonally dry environments where sufficiently large amounts of combustible dry plant material accumulate, recurring fires, often started by lightning strikes, have long affected the so-called fire-dependent/influenced ecosystems (from now on simply "fire-dependent"). The evolution of their biota has been shaped by various forms of adaptations to survive fire events, for example, in plants, the development of thick bark and of protected buds, and burrowing behavior in animals (Pausas and Parr, 2018). From an evolutionary perspective, the flammability of plants is considered to be a characteristic that promotes periodical fires, and thus favors the selection of fire-adapted plants in a feedback scheme (Bond and Keeley, 2005). Thus, the structure and functioning of fire-dependent ecosystems is the result of a long history where fire has a pivotal role in selecting species and influencing ecological processes (e.g., Pilon et al., 2021). In the so-called fire-independent ecosystems, fire rarely occurs either because of unfavorable climatic conditions (very humid, very dry, or very cold) or for the lack of fuel (plant biomass) to carry a fire.

Applying the classification of Hardesty et al. (2005) to the Brazilian biomes, the Cerrado, Pantanal and Pampa are fire-dependent; the rainforests of the Amazon basin and Atlantic Forest are fire-sensitive, and the Caatinga is fire-independent (Fig. 2). This type of classification of ecosystems in relation to fire sensitivity on the biogeographic region level is necessarily made based on the predominant vegetation type that defines the biome. However, all biomes contain vegetation types with different sensitivities to fire (see small patches of different colors within each biome in Fig. 2, and examples in Fig. 3). For example, embedded in fire-sensitive tropical Atlantic rainforests there are patches of flammable open shrubby grasslands (Fig. 3D), mainly in its southern part. Similarly, there are sporadic patches of savanna in the Amazon basin's lowland rain forests (Fig. 3C). Likewise, patches of fire-sensitive vegetation can be found in fire-dependent biomes, such as the patches of semideciduous forest associated with more fertile soils and along water courses in the Cerrado, Pampa and Pantanal (Fig. 3B). Under natural conditions (without human interference), mosaics of fire-dependent and fire-sensitive ecosystems would likely be rather stable and driven by climatic fluctuations over long periods of time (e.g., Müller et al., 2013).

Fire regimes (Box 1) are determined by multiple factors that interact with the type of vegetation – shaped by the coevolutionary history with the fire – and refer to the fire behavior (Box 1) in each type of environment. For example, fires in savannas and grasslands are usually rapid events with relatively low intensity, while very intense fires may occur in forests, sometimes affecting tree crowns. Vegetation structure and composition, fuel characteristics such as amount, type, moisture content, and continuity on the ground, as well as climate and weather conditions, seasonal water deficit, and topography affect fire characteristics and fire regimes (Fig. 4). However, anthropogenic conditions such as land use, land management, agricultural techniques, religious traditions, or recreation practices, among others, are also important drivers of vegetation fires or modifying agents of the natural fire regimes (Fig. 4). Fire severity – the ecological impacts caused by fire on the environment (which some authors include as part of the fire regime, e.g., Liu and Wimberly, 2015) – is determined by the fire regime.

Fire-dependent ecosystems

In Brazil, fire-dependent ecosystems are formed by grasslands and savannas of the Cerrado, Pampa and Pantanal. Grasslands are also within the Atlantic Forest – often associated with specific topographic and edaphic conditions (Vasconcelos, 2011) – as well as in its southernmost part (Fig. 2; Overbeck et al., 2007). About 5% of the Amazon biome comprises patches of savanna and *campinarana*,

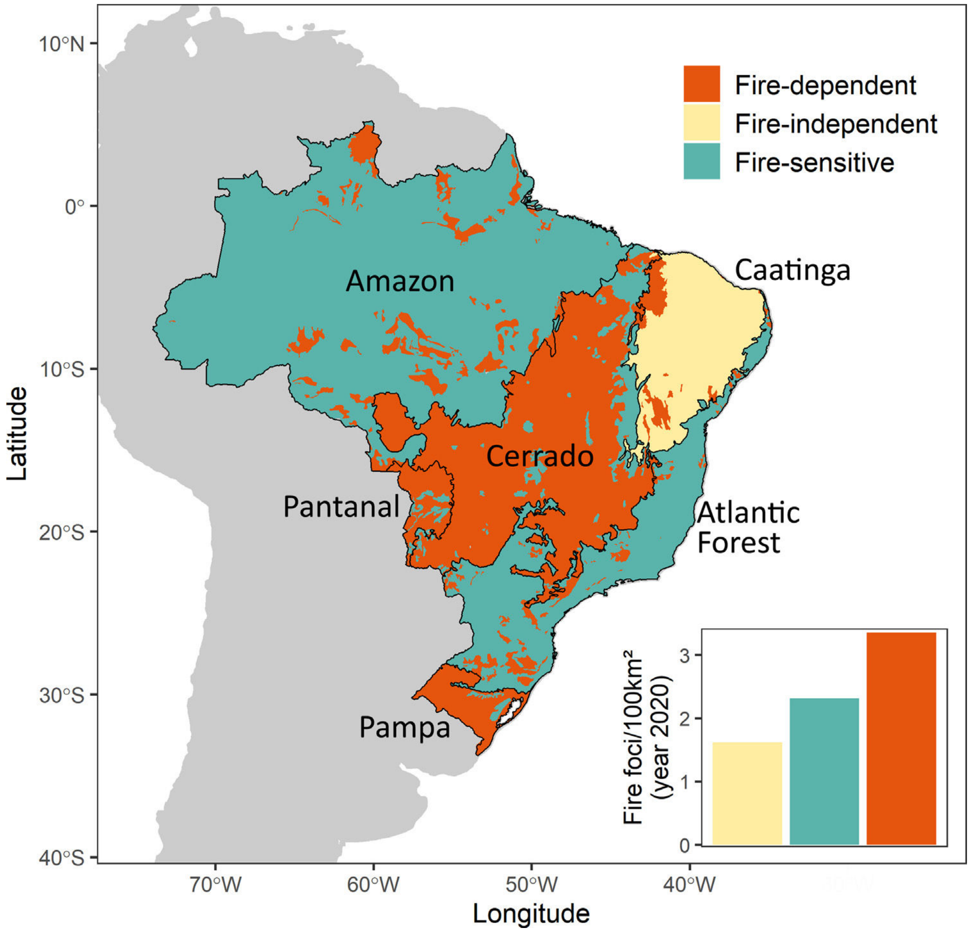

Fig. 2. Brazilian vegetation types (based on IBGE, 2004b) classified as fire-dependent, fire-sensitive and fire-independent, following Hardesty et al. (2005). Open vegetation types (grasslands, open savannas) are classified as fire-dependent; forests (rainforests, seasonal forests, woodland savanna) are classified as fire-sensitive, and xerophytic vegetation is classified as fire-independent. The inlay graphs indicate density of fire foci in 2020 for each fire sensitivity class (calculated using QGis 3.12.3 software, geographic coordinates of fire foci occurrences in 2020 retrieved from INPE).

defined by edaphic conditions and influenced by fire (Adeney et al., 2016; Flores and Holmgren, 2021). Fires in these savannas and grasslands are typically surface fires (Box 1): they pass rapidly, affecting mostly the ground layer, are usually of low intensity (mild) and return relatively frequently (3–6 years, according to Ramos-Neto and Pivello, 2000 and Pereira-Junior et al., 2014) (Fig. 5K to P). In the seasonally dry climate of the Cerrado and Pantanal, natural fires usually occur in the transitional months between seasons (more often at the beginning or occasionally at end of wet season), caused by lightning strikes that ignite the accumulated dry vegetation mass. Under these conditions, fire usually does not spread over large areas because it is extinguished by the coming rain (Ramos-Neto and Pivello, 2000; Medeiros and Fiedler, 2004).

The ecological impacts of surface fires in the open savannas and grasslands – which consume the fine and flammable tissues of grasses rapidly enough to not kill the plants and most vertebrates – are generally mild. Heat generated by these fires does not penetrate below the topsoil layer, as soil provides insulation (Coutinho, 1982; Castro-Neves and Miranda, 1996), allowing buried seeds and perenniating plant parts to survive by 'escaping' fire. As a result, after such rapid and low-intensity fires plants resprout, and shortly after fire a burned Cerrado or Pampa may turn into a green flowery landscape (Coutinho, 1982; Overbeck et al., 2005; Gottsberger and Silberbauer-Gottsberger, 2006; Overbeck and Pfadenhauer, 2007; Fidelis et al., 2019) (Fig. 5K to P). Other subterranean adaptations include root-suckering, that is, regrowth from perennial buds belowground (where they are protected from fire) usually associated with storage organs (Pausas et al., 2018), or extensive woody stem system belowground (Bond, 2019). However, seedlings and saplings of many of these tree species are fire-sensitive and may be severely damaged by very frequent (1–2 years) fires (Medeiros and Miranda, 2008). Many woody species in fire-dependent ecosystems also have adaptations to resist fire, the most conspicuous being a thick bark that protects buds, allowing fast recovery of the canopy after a fire (Coutinho, 1990). High fire frequency tends to favor herb species (fire-adapted and more resilient) at the expense of trees. Overall, recurring fires maintain the characteristic structure of fire-dependent ecosystems – open savannas and grasslands – and fire exclusion leads to the development of closed vegetation dominated by woody species (Rosan et al., 2019).

Surface fires in fire-dependent ecosystems are generally thought not to harm fauna, which, like plants, also shows fire adaptations (e.g., smoke detection, fossorial habit) and can be benefitted by post-fire conditions when regrowth of biomass offers abundant food for herbivores (Pausas and Parr, 2018). The synchronous flowering and fruiting promoted by fire attract several animal species that may exploit these transient resources, such as some bees (Peralta et al., 2017), deer (Rodrigues and Monteiro-Filho, 2000), flower-head insect herbivores (Prada et al., 1995), raptors, insectivorous bats (Santos et al., 2021) and seed-eating birds (Reis et al., 2016). Durigan et al. (2020) have shown that prescribed burnings in a Cerrado in south-eastern Brazil did not affect the richness of several vertebrate taxa; some of these animals protected themselves by entering burrows or moving to areas protected from fire,

Fig. 3. Enclaves of fire-sensitive vegetation can occur within fire-dependent biomes, such as *veredas* (linear wetlands; A; Jalapão Environmental Protection Area, Tocantins) and riparian forests (B; Serra da Canastra National Park, Minas Gerais) in the Cerrado. Patches of fire-dependent vegetation may occur in fire-sensitive biomes, such as savannas in the Amazon (C; Cerrado de Joanes, Pará) and grasslands in the Atlantic Forest, in mosaic with Araucaria Forest (D; São José dos Ausentes, Rio Grande do Sul). (Photos: Vânia R. Pivello [A], José Carlos Motta Jr. [B], Dário Amaral [C], Gerhard Overbeck [D]).

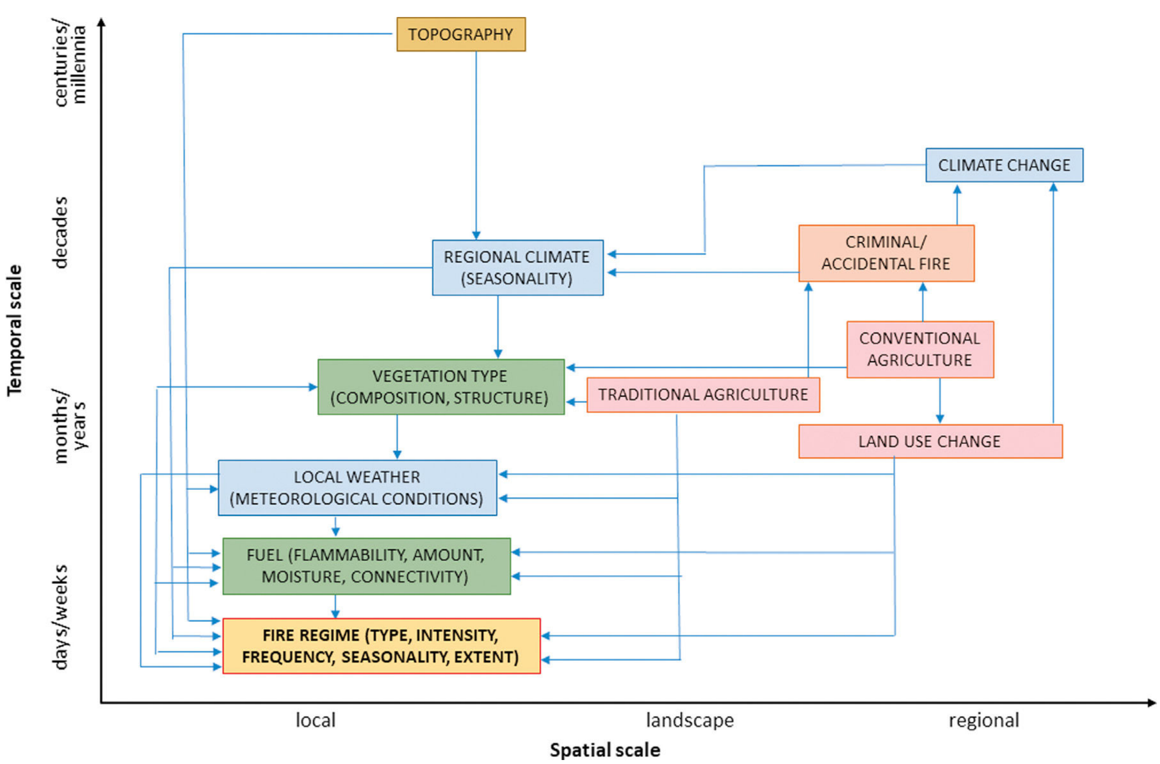

Fig. 4. Main conditions influencing fire regimes according to different spatial and temporal scales (adapted from Liu and Wimberly, 2015).

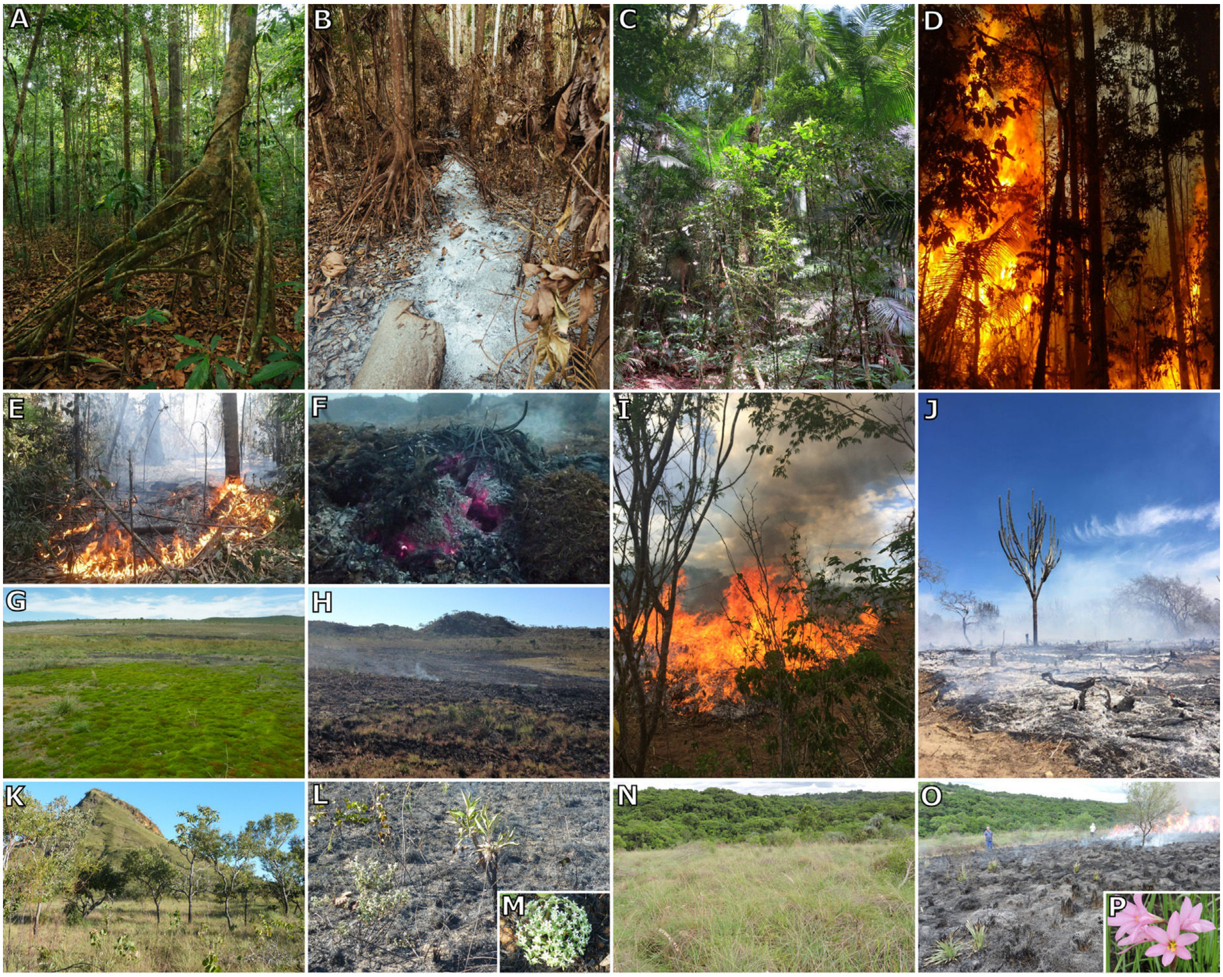

Fig. 5. Different Brazilian ecosystems before and after fire: Rainforest (A–F): fires in this type of fire-sensitive ecosystem usually occur as (D) crown fires, (E) surface fires or (F) smoldering ground fires (see Box 1 for fire types definition), in all cases most trees are killed; (A–B: Amazon rainforest at Santarém, Pará; C: Atlantic forest at Carlos Botelho State Park, São Paulo; D: Atlantic forest at Sooretama Biological Reserve, Espírito Santo; E: Amazon rainforest at Tapajós-Arapiuns Extractive Reserve, Pará and F: Amazon rainforest at Lagoa Piratuba Biological Reserve, Amapá); Wet grassland (G–H): showing the persistence of ground fire (Cerrado at Sempre Vivas National Park, Minas Gerais); Dry forest (I–J): experimental surface fire, little is known about fire behavior in this type of vegetation (Caatinga at Catimbau National Park, Pernambuco); Grasslands (K–P): surface fires in (K–M) Cerrado (campo sujo) and (N–P) Pampa grasslands, in detail (M) *Euphorbia* sp. and (P) *Zephyranthes gracilifolia* flowering a few days after fire (K–M: Serra do Tombador Natural Reserve, Goiás; N–P: Saint'Hilaire Municipal Natural Park, Rio Grande do Sul). (Photos: Adam Ronan/ECOFOR [A–B], Alexander V. Christianini [C], acervo ICMBio [D], Fredson F. M. Batista [E], Christian N. Berlinck [F], Simone N. Fonseca [G], Felipe P. L. Melo [I–J], Vânia R. Pivello [H, K–M], Juliana Schaefer [N–P]). (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

such as gallery forests (but see Vieira and Marinho-Filho, 1998), or recolonize from populations on neighboring unburned sites (Marini-Filho, 2000). Animals may play important roles in dispersing plant propagules: this relates to a fire-escape strategy, helps to maintain healthy metapopulations of plants not adapted to fire-prone ecosystems (Mariano et al., 2019), and favors the recovery of fire-sensitive sites damaged by fire (Martini and Santos, 2007). However, extensive high-temperature wildfires, or very frequent fires even in fire-dependent ecosystems can negatively impact invertebrates in trees, such as bees, wasps and arboreal ants (Peralta et al., 2017; Vasconcelos et al., 2017) and less mobile vertebrates, such as some reptiles and amphibians (Sousa et al., 2015; Abom and Schwarzkopf, 2016), and large mammals (Silveira et al., 1999).

Evidence for the coevolution of the Cerrado biota with fire include a study by Simon et al. (2009) who have used time-calibrated phylogenies of Cerrado plant groups to establish the co-occurrence of probable increase in fire frequency and its coincidence with the diversification of Cerrado plants, around 4–5 million years ago, when C_4 grasses became widespread in the tropical and subtropical world. It has been proposed that in a warm and seasonal tropical climate, with productive wet seasons, the spread of C_4 grasses provided plentiful fuel for wildfires (Gottsberger and Silberbauer-Gottsberger, 2006; Simon et al., 2009) in the dry season, or during extensive periods of drought. This, in turn, helped to establish a regime of recurrent fires and thereby favored grasses and herbs over woody plants (Keeley and Rundel, 2005; Pivello, 2011). Maintained by frequent fires, the Cerrado became the world's richest savanna. Today, it holds over 12,000 plant species (Forzza et al., 2012), 40% of them endemic (Klink and Machado, 2005), and adaptations to fire can be found in most families, especially in the more open physiognomies. Paleo-pollen and charcoal records from different sites in the Cerrado evidence the presence of fire in the past 32,000 years, with fluctuations over time that indicate shifts in the dominant vegetation types (Ledru, 2002; Pessenda et al., 2004, 2005). Fires appear to have increased in the Holocene (Cassino et al., 2020), possibly linked both to a highly seasonal climates and the presence of human populations – who likely have used fire (Behling, 2003).

A similar fire history has been deduced for the Pampa grasslands of southern Brazil (Behling et al., 2004), as well as the grasslands in the highlands of the southern Atlantic Forest. Charcoal records date back to the beginning of the Holocene, possibly linked to the presence and impact of human populations (Behling et al., 2004, 2005; 2009). Herbaceous plant species in the Pampa show similar adaptations to fire than those in the Cerrado: regrowth and flowering after fire, underground structures that protect the buds, tussock grasses with their protected buds being the dominant species (Overbeck et al., 2005; Overbeck and Pfadenhauer, 2007). In the highlands of the Atlantic Forest, where grasslands had been the dominant vegetation type over the past millennia (Silva and Anand, 2011), the vegetation history is similar to that in the Pampa. Here, charcoal records have become less frequent from about 1.100 YPB on, linked to the expansion of *Araucaria* Forest over the grasslands, i.e., local substitution of a fire-dependent by a fire-sensitive vegetation type, as climate became more humid (Behling et al., 2004). Little is actually known about natural fire regimes in the Pampa and in the grasslands of the southern part of the Atlantic Forest, as remnant natural grasslands have been for a long time, and currently are, under grazing management (which may include fire, usually lit at the end of the austral winter): current land management – lack of accumulated fuel that could be set alight by lightning – impedes the occurrence of natural fires that we would expect based on the ecological characteristics of the ecosystems (see also Overbeck et al., 2018). Under high grazing levels vegetation structure and composition change considerably, with prostate rhizomatous species becoming dominant (Overbeck et al., 2007).

The presence of fire in past millennia has also been verified for the Pantanal, where the peak of fire activity appears to have been about 12,000 BP, while the oldest human settlements date to 8000 BP (Power et al., 2016). Paleo-pollen analyses thus indicate that fires affected the Pantanal before human occupation and concur with the hypothesis that fire-driven ecosystems in tropical regions dominated by C_4 grasses have naturally existed (Bond, 2019). The Pantanal, however, has very peculiar dynamics. The mosaic of savannas, seasonal forests and grasslands which composes its vegetation is influenced by a natural flooding regime that developed in the late Pleistocene and established with the reorganization of the drainage system in the Holocene (Assine and Soares, 2004). Rainfall causes in the Pantanal a seasonal flood pulse whose peak slowly moves from north (rainy season) to south (peak of the dry season) (Arruda et al., 2016). This flood regime regulates the temporal dynamics of biotic communities, primary productivity, nutrient cycling, and the fire regime (Arruda et al., 2016). There is an intimate interaction between floods and fire that shapes communities (Pott et al., 2011; Oliveira et al., 2014; Arruda et al., 2016; Tomas et al., 2019). Fire promotes germination of some species (Pott and Pott, 2004), and together with the flood pulse it is related to the existence of several monodominant vegetation types. This is the case of the 'Paratudal', where the landscape is dominated by *Tabebuia aurea*, the 'Piuval', dominated by *T. heptaphylla*, and the 'Cambarazal', dominated by *Vochysia divergens* (Pott and Pott, 2004; Pott et al., 2011; Gris et al., 2020; Manrique-Pineda et al., 2021). Drought years may diverge from the annual rhythm, when the low river levels prevent flooding, exposing on the floodplains a large amount of fuel that originates from dry vegetation and peat (Penha et al., 1999). In such periods the risk of large wildfires increases, and the absence of waterlogged areas facilitates fire spread. In wetland soils, ground fires may develop as a consequence of the burning of the organic material in the soil (Watts and Kobziar, 2013; Box 1). In these fires, there are no flames and soil organic matter may smolder for several weeks; fire severity is high, as roots and soil biota may be highly damaged by the long-lasting fires. This is what happened in 2020, an exceptionally dry year in the Pantanal, when river levels reached extremely low values and did not flood the wetlands. As a consequence of the drought, fires spread and severely affected the native species, as well as agricultural crops, cattle husbandry and tourism.

Fire-sensitive environments

Humid tropical forests, dominant in the Amazon basin and in the Atlantic Forest, present no indication of evolutionary history influenced by fire, and their species do not have adaptations that favor their resistance to and resilience after fire events. Outside extreme climate events, rainforests are rarely affected by naturally lit fire, as high humidity levels and lack of fuel prevent fire from starting and propagating. The natural fire return intervals in these forests are estimated to be of hundreds or even thousands of years (Kauffmann and Uhl, 1990). However, extreme droughts increase the probability of forest fires. An initial fire in a rainforest usually occurs as a low-intensity surface fire (Fig. 5E) that travels along the forest floor consuming dry litter and may result in a considerable heat load reaching the bark of the trees (Cochrane, 2003). Such fires may evolve into crown fires (Box 1, Fig. 5D), or to ground fires (Box 1, Fig. 5F) in peat swamp forests (Cochrane, 2003; Watts and Kobziar, 2013).

The impacts of fires in humid and semideciduous tropical forests, in general, are very detrimental. The immediate impacts of fire include consuming the litter layer that protects the soil from erosion and recycles nutrients, killing most small trees and seedlings. Severe fires can kill most thin-barked large trees (Uhl and Kauffmann, 1990; Barlow et al., 2002; Staver et al., 2020); fire damage to roots may also lead to tree death (Flores et al., 2014) (Fig. 5F). Tree death leads to opening up the canopy which, in turn, leads to drying the forest and favors pioneer trees with their large amounts of litter occupying the gaps along with an herb layer proliferation, thus making the forest susceptible to further fire events (Sansevero et al., 2020). The above feedback process may facilitate new and increasingly large fire events, changing ecosystem dynamics and functions (Flores et al., 2016; Sansevero et al., 2020). A more and more open and degraded forest offers less suitable habitat and resources for humid forest-dependent animal species. For example, changes in forest structure and composition affect fruit production for large vertebrates (Barlow and Peres, 2006), as well as patterns of bird and dung beetle diversity (Hidasi-Neto et al., 2012; de Andrade et al., 2014). Large canopy frugivores and understory insectivorous birds have been shown to be severely affected during the first three years after fires (Barlow et al., 2003; Barlow and Peres, 2004), and long-term effects on vertebrate fauna have been predicted as long as environmental conditions remain altered (Sales et al., 2020). Recurrent fires cause a decline in the abundance of specialist ant species and of fruit-feeding butterfly species (de Andrade et al., 2017; Paolucci et al., 2017) and seriously harm local biodiversity and habitat integrity on a regional scale in the long term (Pires et al., 2005; de Andrade et al., 2017; Paolucci et al., 2017; Sales et al., 2020).

Riparian and gallery forests along water bodies in the grasslands and savannas are also considered fire-sensitive ecosystems. Fire mostly affects them at their edges, in contact with the fire-prone ecosystem in which they are embedded, and recurrent fires can gradually reduce these forests (Hebert-Dufresne et al., 2018). Another type of fire-sensitive vegetation within the fire-dependent Cerrado are the *veredas* (Fig. 3A), a specific type savanna that occurs on hydromorphic and flooded soils conditioned by a permeable surface soil layer over an impermeable subsoil, on flat terrain and with a superficial groundwater table (Drummond et al., 2005). *Veredas* are characterized by dense populations of *Mauritia flexuosa*, a palm species, and an herbaceous layer dominated by Poaceae and Cyperaceae species, as well as patches of small shrubs. Wildfires in the *veredas* can be very harmful, with flames reaching up to 20 m high and burning completely the highest crowns of palms (Maillard et al., 2009); they may also evolve to ground fire (Fig. 5G and H), then burning plant roots, seedlings and the soil seed bank, thus severely impacting regeneration (Maillard et al., 2009).

The fire-independent Caatinga

Natural fire events in the Caatinga are rare (Althoff et al., 2016), both because its vegetation does not provide continuous and easily flammable fuel (de Queiroz et al., 2017) and because there is a low incidence of lightning events in the region (Pinto, 2008). In consequence, flora and fauna of the Caatinga lack adaptations to frequent fires. The Caatinga is thus classified as fire-independent under the natural fire regime and conditions (Pivello, 2011). However, due to recent human activities, the Caatinga has been increasingly affected by fires that subject it to degradation (Althoff et al., 2016) and can turn it into a fire-sensitive system.

Human-altered fire regimes and consequences

By using fire to manage the environment for food production, hunting, housing and rituals humans have changed radically the natural fire regimes (definitions in Box 1) across the world (Hardesty et al., 2005), often entailing an increased fire frequency. Humans can affect the fire regime in many ways including ignition, suppression, and alteration of fuel type and amount (Bowman et al., 2011), with consequences for many aspects of the ecosystems. In Brazil, indigenous peoples have been using fire in most ecosystems for thousands of years (Peixoto et al., 1999; Pivello, 2006; Power et al., 2016; Maezumi et al., 2018), including the fire-sensitive Amazon rainforests. Pre-Columbian inhabitants appear to have used frequent low-severity fires in their agricultural practices and forest enrichment with edible species since about 4500 BP (intensified around 2500 BP) (Maezumi et al., 2018) and in the Atlantic Forest, probably much earlier, since between 7000 to 12000 BP (Dean, 1996; Leonel, 2000). Their practices included opening gaps in the pristine forest canopy and thinning the vegetation to select useful species (Levis et al., 2018), changing forest structure, composition and flammability. Therefore, natural fires that were almost absent in the humid forests (or occurred at intervals of centuries or millennia) became much more frequent by human action (Fig. 6).

Differently from the traditional burning practices of indigenous peoples in the rainforest, large-scale fires have been used for land clearing following the European colonization of Brazil. Early use of fire by colonists was made for land clearing for agriculture in the Atlantic Forest (Fonseca, 1985) and in warfare against indigenous groups by gold explorers to secure access inland (Dean, 1996). The use of fire for deforestation and land management in the Atlantic Forest has continued over centuries, and such fires are still frequently registered today (Scarano and Ceotto, 2015; Santana et al., 2020). In the Amazon basin, the process of deforestation and land conversion started much later. The use of fire was low in post-columbian times, largely associated with rubber tapping; traditional pre-Columbian fire management practices were abandoned (Maezumi et al., 2018). Over the last 20 years anthropic fires have reached record levels, mostly to expand areas for agricultural use and owing to logging and mining, activities that lead to forest degradation and increased risk of wildfires.

The use of fire in the Amazon today occurs in a complex socio-economic setting (Barlow et al., 2020); it is one of the elements that underlie agricultural expansion in the region. Intentional fires are associated with land speculation, cattle husbandry, small farmers who practice rotational agriculture. For small farmers, burning practices increase soil fertility in the short term and reduce pests, thus facilitating cultivation of subsistence crops in small patches of forest (Alencar et al., 2015; Barlow et al., 2020). According to Alencar et al. (2020), 33% of the Amazon fire outbreaks in 2019 were associated with intentional fires lit on private lands with CAR (*Cadastro Ambiental Rural*) and 18% in rural settlements. Many accidental wildfires that affect forest areas are the result of uncontrolled land management fires lit intentionally (Nepstad et al., 2001). Moreover, the spread of selective logging has increased forest flammability (Uhl and Kauffman, 1990) which increases the probability of fires affecting extensive areas, especially in dry years. The combination of deforestation and drought in extreme El Nino years can cause high fire years, such as 2015/2016, as has been shown by Aragão et al. (2018) and Marengo et al. (2018). The underlying issues related to forest fires in the Amazon include a combination of changes in the socio-ecological system, increasing pressures (e.g., climate change; global markets) and the cascading impacts of pulse disturbance, initiated by logging, land conversion and fires, leading to local changes in climate, ecosystem structure and function, and resulting in self-accelerating feedback loop. Wildfires, drought and logging increase the susceptibility to further burnings through fragmentation, flammability and ignition, while deforestation and smoke can inhibit rainfall and exacerbate fire risk (Marengo et al., 2018). Drought-induced forest fires in the Amazon have contributed largely to carbon emissions at the national level in Brazil (Aragão et al., 2018; Assis et al., 2020).

Recently, recurrent anthropogenic fires have also affected the Caatinga. Natural fires are rare in that biome (Althoff et al., 2016), and the increasing use of fire by locals has been contributing to the degradation of the ecosystems of the Caatinga, sometimes leading to desertification (Althoff et al., 2016; Melo, 2017; Tabarelli et al., 2018). Simulations have estimated that natural regeneration after anthropogenic fires requires at least 50 years (Althoff et al., 2016).

In fire-dependent ecosystems, where natural recurrent fires are expected and maintain species and structural diversity, as well as ecological processes, fire regimes have also been changed by humans, resulting most commonly in increased frequency and altered timing of burning (Pivello, 2011). In the Cerrado and Pantanal, indigenous semi-nomadic populations established in the transition Pleistocene-Holocene (about 8000 BP), who actively used fire (Prous, 1992; Fiedel, 1992; Bespalez, 2015). The concentration of paleo-carbon in the south Brazilian grassland region shows increased frequency of fire in the same period, from 7400 BP, possibly caused by indigenous populations (Behling et al., 2009). A contributing factor to increased fire frequency was the introduction of cattle husbandry to Brazil by Europeans in the 16th century. The Cerrado, Pantanal and the south Brazilian grasslands, dominated by grasses, soon started to be used for extensive livestock husbandry. Fire in the austral winter (coincident with the dry season in the Cerrado and Pantanal, and the cold season in southern Brazil) in these grazing systems has traditionally been used to remove dead plant parts and kill pests, control shrubs and stimulate the regrowth of palatable grasses for cattle. In the Pantanal farmers can also burn during a relatively dry spell in the wet season (locally called 'veranico'). Therefore, in such grazing systems where natural fires used to occur every 3–6 years, anthropogenic burnings increased fire frequency 2–3-fold (Fig. 6). The timing of anthropogenic fires also changed in relation to natural fires. In the Cerrado, for example, natural fires caused by lightning occur at the beginning of the rainy season, when thunderstorms are frequent (Ramos-Neto and Pivello, 2000). Such fires lit by lightning are extinguished by the rain that follows. Conversely, anthropogenic fires for cattle ranching are set in the middle or towards the end of the dry season and are more intense than natural fires, spreading over much greater extensions, as there is no rain to extinguish them. This way they can be especially harmful for slow-moving animals (Ramos-Neto and Pivello, 2000; Pivello, 2011). Thus, besides increasing the fire season and frequency, ranchers have also changed their spatial pattern and intensity.

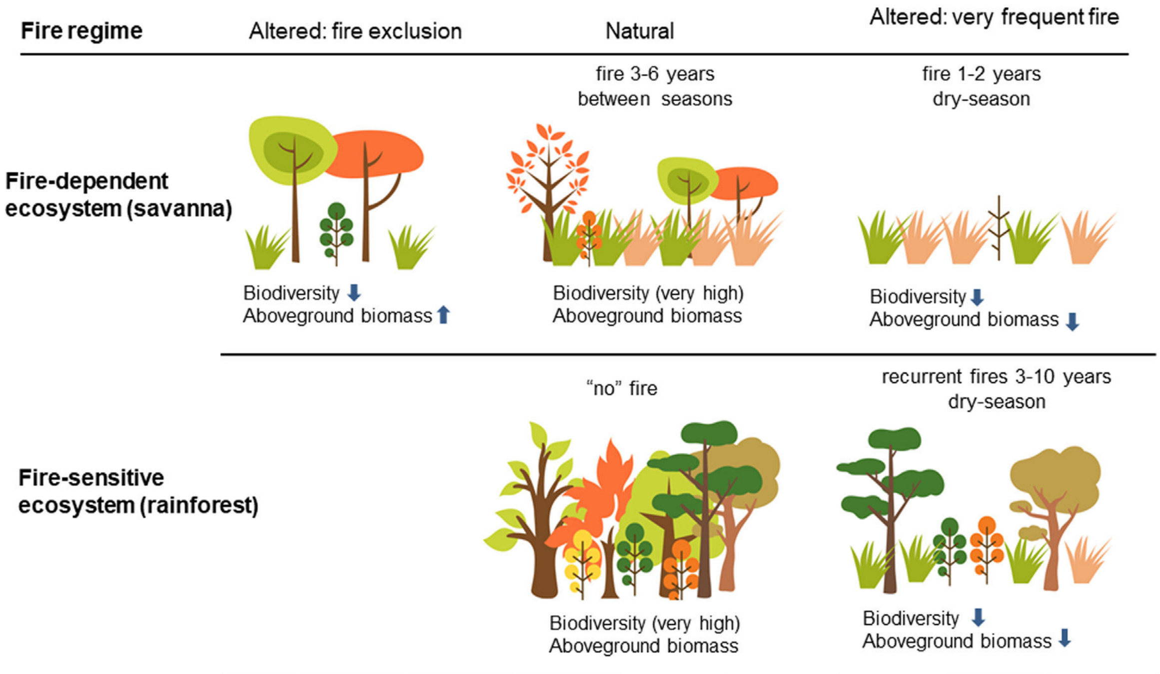

Fig. 6. Comparison of fire regimes under natural (lightning) and anthropogenic drivers in both fire-dependent (e.g., savanna) and fire-sensitive (e.g., rainforest) Brazilian ecosystems. In the savannas, periodical mild lightning fires every 3–6 years maintain biodiversity and ecological processes; anthropogenic burnings increase fire frequency and change the fire season. Very frequent or intense fires kill young trees and reduce aboveground biomass; fire exclusion instead may lead to tree encroachment, and in both cases biodiversity is reduced and ecosystem processes are altered. In the rainforests, natural fires are almost absent, but recurrent fires resultant from human activities (accidental or criminal fires) open up and degrade the forest. Great amounts of gases are emitted to the atmosphere, vegetation is impoverished and the forest becomes vulnerable to recurrent wildfires. (Data from: Pivello and Coutinho, 1992; 1996; Ramos-Neto and Pivello, 2000; Alencar et al., 2004; Barlow and Peres, 2008; Pivello, 2011; Pereira-Junior et al., 2014).

On the other hand, in many protected areas of the Cerrado and grasslands of southern Brazil – fire-dependent systems – humans have altered fire natural regimes by decreasing the burning frequency. As part of an inherited view of the European colonizers, who valued forests far more than open ecosystems (see item below: *Changing historic perceptions on the use of fire in Brazil*) and were not aware of the important ecological role of disturbance regimes in such environments (Overbeck et al., 2016; Pausas and Bond, 2019; Silveira et al., 2020a) fires have been seen mostly as undesirable and harmful: they were to be prevented and extinguished even if natural (lit by lightning). For a long time, this view influenced ecologists and conservationists worldwide and also in Brazil. As a consequence, fire-dependent ecosystems in protected areas have been under a fire exclusion policy for many decades (Ramos-Neto and Pivello, 2000; Pivello, 2006; Durigan and Ratter, 2016; Durigan, 2020), which culminated either in periodic wildfires due to fuel buildup or woody encroachment, in both cases resulting in loss of biodiversity and of ecosystems services (Fig. 6) (Abreu et al., 2017; Rosan et al., 2019). At the end of the last century, scientific advances began to show the need to maintain a regime of frequent burns in fire-dependent ecosystems (detailed below: *Changing historic perceptions on the use of fire in Brazil*).

Beyond vegetation: impacts of fire on ecosystem services, infrastructure and human populations

It has been widely recognized that water, energy and food security for a growing human population rely on ecosystem integrity: natural ecosystems provide a broad range of ecosystem services and promote human well-being (Metzger et al., 2019; Melo et al., 2021). By changing the structure and function of ecosystems, fire can affect many of these ecosystem services. Intense fires can severely impact the biota, with cascading effects on trophic interactions, and, therefore, ecosystem functions and the benefits that humans derive from ecosystems. Fire can directly affect humans, e.g., health, such as was the case in the southeast of Brazil in 2019 when smoke and aerosol plumes from the Amazon region reached São Paulo, causing nightly darkness during the day. This illustrates how much effects of burnings can go far beyond a local scale (Prist et al., 2019), negatively affecting air quality of cities far away (Freitas et al., 2005).

Emissions from biomass burning are particularly harmful to human health and motivate thousands of premature deaths each year (Nawaz and Henze, 2020), crop yield losses, and ecosystem damage (UNEP/CCAC, 2016; UNEP, 2016). These emissions are a variable mixture of trace gases, aerosols and particulate matter (PM) that affect atmospheric composition in complex ways (Sokolik et al., 2019). Vegetation fires are among the most important sources of PM and trace gases to the atmosphere, and one of the main threats to public health. Fine PM (<2.5 μm or PM2.5; Cohen et al., 2017) has been associated with respiratory and cardiovascular diseases, in addition to premature deaths, especially in the more vulnerable groups (Sant'Anna and Rocha, 2020). During the burning season, high concentrations of PM have been registered in the so-called "deforestation arch" in southeastern Amazonia, and have been related with respiratory diseases (Ignotti et al., 2010). Increasing risks of damage to DNA, gene mutations, inflammation, and cancer in the Amazon region have also been attributed to smoke (Alves et al., 2017; Galvão et al., 2018). In 2019, for example, when deforestation indices in the Amazon rose sharply, 2195 cases of hospitalization due to respiratory diseases were attributable to smoke from forest fires, with almost 50% being elderly people. Patients spent a total of 6698 days in the hospital, at a cost of R$ 2.6 million (USD 660,000) to the public healthcare system (SUS) (Sant'Anna and Rocha, 2020). Obviously, health risk owing to exposure to smoke is not only associated with deforestation fires. For instance, pre-harvesting burning of sugarcane is also associated with the occurrence of respiratory diseases, especially of children under five and the elderly, contributing to the exacerbation of episodes of asthma and rhinitis (Paraiso and Gouveia, 2015; Ribeiro, 2008; Riguera et al., 2011).

Fires can have indirect negative effects on human populations beyond health problems caused by smoke. Water quality and quantity can be affected by wildfires if forests that protect watersheds (Bixby et al., 2015) by increasing nutrient and soil particle transport, and peak flow of streams. Catastrophic fires can also affect shrubland and dry forests of the Caatinga where people rely on biomass as a primary source of energy (Althoff et al., 2016), thus affecting energy security of vulnerable rural populations. Fires are among the main causes of damage to power transmission lines and can pose important threats to both wind and solar power stations (Sathaye, 2011). Food security can be affected by uncontrolled fires, in the short term, if crops are directly affected. Long-term effects on food production can be expected if soil fertility and water for irrigation are affected by fires. Finally, fires linked to large-scale deforestation lead to carbon emissions, and thus increase climate warming (Assis et al., 2020), cloud formation and rainfall patterns (UNEP, 2016), which also can cause a number of indirect impacts in agriculture and food security, water provision, spread of pests and diseases, among others (Hoegh-Guldberg et al., 2018), with severe economic consequences and negative impacts on overall human well-being. Silva et al. (2020) show that in 2019 the Amazon – where deforestation has been increasing since 2012, after almost a decade of clear reduction – was responsible for 295 million tons of net CO_2 emissions, corresponding to 16.4% of the combined CO_2 and CH_4 emissions for that year in Brazil. Importantly, emissions from forest fire do not occur only from the fire event as such: after a burn, forests can remain a carbon source for as long as 30 years, and net annual emissions peak 4 years after the fire (Silva et al., 2021). Silva et al. (2020) also indicate that CO_2 emissions in the Brazilian Amazon due to deforestation exceed those from the transport, electricity, manufacturing, industry, building sectors, which underlines the need to curb deforestation, and thus reduce the occurrence of fire in the region for climate change mitigation.

On the other hand, in fire-dependent ecosystems, fires can be considered as an important process that supports biodiversity of grasslands and savannas (e.g., by maintaining processes of nutrient cycling, synchronicity of phenological events, diversification of ecological niches, among others, as discussed above), and thus also contribute to many of the ecosystem services provided, including supporting, regulating, provisioning and cultural services (Pausas and Keeley, 2019). However, as any other fire event they will lead to greenhouse gases emissions. As mentioned before, appropriate analyses of fire effects need to consider the fire regime, and not just single fire events. Taking into account the yearly carbon balance, Santos et al. (2003) analyzed carbon fluxes in a burnt open savanna (*campo sujo*) in Central Brazil and verified that all carbon emitted in a burning were neutralized in approximately one year thanks to higher net ecosystem productivity stimulated by fire, a response of fire-adapted systems.

However, even where specific fire regimes are desirable for biodiversity conservation in savannas or grasslands, there may be negative effects on other components of the ecosystem or on society (for example, human health). Managing fire always means to consider trade-offs and balances among different management goals, and decisions need always be made for the specific situation and the context in question; this includes the local and regional demand for specific ecosystem services (Wolff et al., 2015).

Fire management, policy and legislation in Brazil

Changing historic perceptions on the use of fire in Brazil

Fire had been widely used by indigenous peoples as a management tool for millennia before the European colonization. For the Portuguese colonists, fire was mostly negative and its use had to be avoided (Mateus and Fernandes, 2014; see e.g.: Ordenações Afonsinas, 1466; Ordenações Manuelinas, 1521; Ordenações Filipinas, 1603[2]) (Fig. 7). The "Zero Fire" policy was established in colonial times partly to guarantee hardwood exploitation for shipbuilding, dyeing (including with brazilwood) and other demands in the Atlantic Forest (Regimento do Pau Brasil 1605, see Mendonça, 1972; Regimento da Relação do Rio de Janeiro 1751, see Paranhos, 1995.; Ordens para Preservação de Madeiras Navais 1795, see Prestes, 2000). The ban on fire has prevailed over five centuries, as evidenced by several legal instruments (e.g., Royal Law form 1799 [*Carta Régia*], Law nº 601/1850 [*Lei das Terras*], Law nº 3.311/1886, first Brazilian Forest Code [Decree nº 23.793/1934], Penal Code [Decree nº 2.848/1940], second Brazilian Forest Code [Law nº 4771/1965], Regulation IBDF 231P/1988, Law nº 11.428/2006 [*Atlantic Forest Law*], Decree nº 6.686/2008). In 1998, Decree 2.661/1998 regulated the use of fire in agricultural and forestry practices, but not for other purposes; it also established the basis for the National System for the Prevention and Fighting of Forest Fires (PrevFogo). Catastrophic wildfires with an international repercussion have reinforced the 'Zero Fire' policy: in 1963, 2 million ha of native vegetation and agricultural lands burned in Paraná State (Atlantic Forest), killing more than 110 people (Berlinck and Batista, 2020), and in 1998, 1.2 million ha of Roraima State (5% of the state, in the Amazon), burned, destroying settlements and the Yanomami Indigenous Reserve (Xaud et al., 2013).

The discussion on fire management started to change from the 2000's on, based on research initiated by Leopoldo Magno Coutinho in the 1970's and on data from the *Projeto Fogo* (Fire Project) that was initiated in 1981 in the Cerrado (Miranda, 2010) (Fig. 7). It became clear that the "Zero Fire" strategy was inefficient in terms of conservation of fire-dependent environments: keeping fire-dependent ecosystems free from fire is usually an unsuccessful task due to biomass (that is, fuel) accumulation over time, and thus increased risk of severe wildfires in the dry season (Fidelis et al., 2018; Durigan, 2020). If fire avoidance succeeds for several years in fire-dependent ecosystems, it will lead to encroachment of woody species, changing habitats and greatly decreasing the richness and abundance of typical taxa from the open environments. This means that fire suppression is undesirable from a biodiversity conservation perspective (Abreu et al., 2017; Costa et al., 2020). Furthermore, fires that occur after long fire-free periods tend to be much more severe than frequent fires, due to the high fuel buildup. Overall, fire exclusion is thus not adequate to achieve conservation goals in fire-dependent ecosystems; the question is much rather if fires should be allowed to occur naturally or if active fire management (through prescribed burnings, Box 1) should be adopted to reduce negative effects of fire and increase benefits; in the last case proper decision making frameworks that consider fire within the overall landscape context must exist (see Pivello and Norton, 1996).

[2] Ordenações Afonsinas. 1466. Available at: http://www.ci.uc.pt/ihti/proj/afonsinas/ accessed 05 March 2021. Ordenações Manuelinas. 1521. Available at: http://www.ci.uc.pt/ihti/proj/manuelinas/ accessed 05 March 2021. Ordenações Filipinas. 1603. Available at: http://www1.ci.uc.pt/ihti/proj/filipinas/ accessed 05 March 2021.

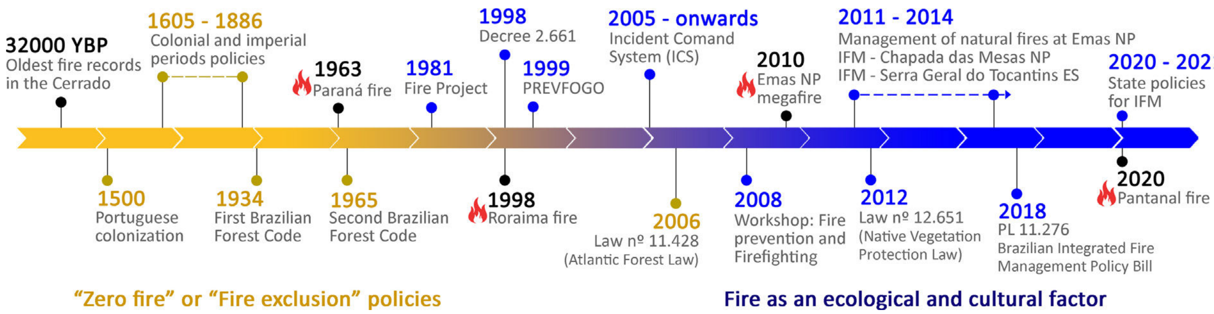

Fig. 7. Main landmarks related to use and fire throughout the history of Brazil, from European colonization until today. The change from yellow to blue color indicates the increasing understanding of the use of fire for ecosystem management in Brazil. (For interpretation of the references to colour in the figure legend, the reader is referred to the web version of this article.)

Fire management in protected areas

This new understanding regarding the role of fire in fire-dependent ecosystems led to the inclusion of regulations for using fire for ecological and cultural purposes in the Law for Protection of Native Vegetation (Law 12.651/2012, often referred to as the *New Forest Code*). Also, it stimulated a new approach for federal protected areas: Integrated Fire Management (IFM; Box 1) (Fig. 7). The IFM strategy integrates local practices and cultures into fire management (Fidelis et al., 2018; Schmidt et al., 2018); it is based on the goals of protected areas and vegetation types, treating forests as fire-sensitive (i.e., where fire should be avoided and suppressed) and grasslands and savannas as fire-dependent (i.e., where fire may be allowed to burn or are managed). Therefore, decisions about fire management are made based on the ecological context, including also the demands of local populations and according to their cultural traditions and socioeconomic conditions (Eloy et al., 2019a).

By 2011, the IFM approach began to evolve from the decision to accept and manage natural fires (lightning fires) in Emas National Park, Goiás state, after the last mega-fire of 2010 that burned almost 90% of the park. The first IFM prescribed burns occurred in 2014 in Chapada das Mesas National Park and Serra Geral do Tocantins Ecological Station (Berlinck and Lima, 2021) (Fig. 7). Since then, other protected areas – especially in the Cerrado – have adopted IFM. In the IFM approach, decisions about allowing natural fires to burn or not, and the application of prescribed fire and fuel management are always made in agreement with local managers and under specific management and conservation goals, under consultation with experts from IBAMA and ICMBio. In the Cerrado protected areas, the IFM strategy anticipates fuel burning in the early dry season, when damage to vegetation is less severe (Pivello and Norton, 1996; Sato et al., 2010). Also, this reduces the occurrence of anthropogenic late season wildfires (Ramos-Neto and Pivello, 2000) – of higher severity to biota and dangerous to humans – such as observed in Estação Ecológica Serra Geral do Tocantins (Fidelis et al., 2018).

The number of prescribed burnings in protected areas in the Cerrado has since then increased considerably; at the same time, the number of late-season wildfires has decreased, reducing considerably firefighting efforts and costs (Schmidt et al., 2018; Berlinck and Batista, 2020; Berlinck and Lima, 2021). In 2019, as a result of IFM actions, the reduction of the total area affected by wildfires reached approximately 40% in the Cerrado, indicating that IFM is an important strategy in fire-dependent environments (Berlinck and Lima, 2021). Despite these successes, the use of prescribed fires for conservation management is not yet widely understood and accepted in the general conservation debate in Brazil (Pivello, 2006; Durigan and Ratter, 2016; Overbeck et al., 2016). Part of the resistance to adopt a national IFM policy may be owing to the marked differences in response to fire by fire-dependent and fire-sensitive ecosystems that in many regions may occur side by side, the potential impact on iconic fauna (which can be overestimated, see Durigan et al., 2020) and the way fire is treated in forest-oriented policies.

IFM has been developed and implemented at the federal level, and to date only Minas Gerais and Roraima states have specific state level legislation regarding IFM; it is under consideration in some other states. IFM policies so far target only public lands such as conservation areas, indigenous reserves and traditional communities (*quilombos*). For privately owned land no such policy exists, yet 44.2 % of land in Brazil has private ownership (Sparovek et al., 2019). The recognition of the socio-ecological importance of controlled fires in the fire-dependent ecosystems led to proposing the Brazilian Integrated Fire Management Policy Bill in 2018,[3] with the objective of regulating the use of fire and promote inter-institutional partnership for wildfire prevention and firefighting, as well as encouraging the implementation of IFM on public and private land. The policy intends to reduce the damage associated with wildfires and illegal fires, and to restore the ecological and cultural role of fire, and it should be implemented by federal, state and municipal authorities, the civil society and private entities in a regime of joint effort. However, the policy proposal is yet to be discussed by the lawmakers in the lower house (chamber of deputies) of the Brazilian parliament.

However, results from the IFM may take time, and strategies need to be constantly reevaluated. For instance, in Serra da Canastra National Park, Minas Gerais, the use of fire by residents was authorized in 2002, after which some increase in wildfires were observed. Wildfire reduction was observed only in 2016 after implementation of awareness campaigns associated with firebreaks and prescribed fire strategies, and after the involvement of residents and surrounding landowners. In Campos Amazônicos National Park – a park that protects savanna and grasslands enclaves within the Amazon rainforest – prescribed burns have been used to reduce flammable fuel in the savanna and grassland patches; however, management has been focused on fire control and exclusion because these patches are surrounded by fire-sensitive vegetation. Controlled burnings in the savanna and grassland patches contribute to protect the fire-sensitive forest around them (Berlinck and Batista, 2020). Similarly, a fire management policy is being proposed for the Tapajós National Forest. It includes guidance to farmers for reducing the use of fire together with extra-careful fire management to reduce combustible material and the risk of mega-fires (Maezumi et al., 2018). IFM may be adjusted to long-term conservation goals in protected areas. For instance, experimental prescribed burns are being used in the open shrubby grassland in Itatiaia National Park and in grasslands in Aparados da Serra National Park to maintain typical landscapes and biodiversity that would be at risk under successional processes after the exclusion of grazing and fire (Overbeck et al., 2016, 2018).

[3] www.planalto.gov.br/CCIVIL_03/Projetos/PL/2018/msg774-dezembro2018.htm.

IFM still has challenges, as can be expected when different objectives need to be balanced. The more consistent scientific basis that has been established with regard to the multiple roles of fire has led scientists and several managers of protected areas to change from the Zero Fire policy in all ecosystems to the management based on prescribed fires in the fire-dependent ecosystems, while keeping Zero Fire in fire-sensitive vegetation. However, proposals for the use of controlled fires to reduce accumulated fuel and, therefore, lessen the risk of wildfires, exist even for fire-sensitive rainforests (Maezumi et al., 2018) and deserve more research. The current challenges to improve IFM strategies in protected areas involve better understanding of the relationships among fire, vegetation and man, including both fire-dependent and fire-sensitive ecosystems, and also considering climate change scenarios. Normative instruments to govern the application of IFM are lacking. It seems important to implement experiments that will lead to safer burning conditions and to invest in training and tools necessary to prevent the spread of uncontrolled fires (Bilbao et al., 2019). Also, there is a need to design and implement an intercultural fire management policy based on indigenous knowledge (Bilbao et al., 2019). This will demand an integration of environmental agencies and institutions to generate joint actions and advance in the implementation of a new governance for participatory fire management.

Fire use for land management on private properties

While IFM has clearly led to progress in fire management, it is restricted to protected areas, which is a problem as a large proportion of intentional fires in Brazil occur on private lands. Three main types of intentional fires exist, all with the risk of spreading into adjacent areas: (1) deforestation fires associated to the commercial use of natural resources and the expansion of the agricultural frontier, (2) grassland/savanna and agricultural field burns for grazing and agricultural management, and (3) fallow fires set as part of slash-and-burn agricultural systems (see Fonseca-Morello et al., 2020).

Article 38 of Law 12,561 (Law for Protection of Native Vegetation) prohibits the use of fire applied to vegetation, with the exception of fires conducted for research purposes and in the context of agriculture and silviculture (see also Decree 2661/1998), where the specific local or regional conditions justify the use of fire, similarly to that in the Forest Code of 1965. For any use of fire, authorization by state agencies is necessary. In the extreme fire years 2019 and 2020, the use of fire was even more restricted.[4] Nonetheless, many fires are set without the mandatory permissions, and there is evidence that a recent rise in anti-environmental political discourse has stimulated illegal burning (Caetano, 2021). Human-lit fires may spread accidentally into areas not targeted, especially in years with extreme dry climatic conditions, as in 2005, 2010 and 2016 in Amazonia, and 2020 in Pantanal. The reduced transport of humid air from the Amazon region to the Pantanal resulted in prolonged and extreme drought conditions that facilitated fires and can help to explain their extreme extent (Marengo et al., 2021). Clearly, the high number of wildfires in both the Amazon and Pantanal in 2019–2020 is the result of combined effects of dry weather, human activities, and problems with the implementation of environmental policies (Barlow et al., 2020; Staal et al., 2020; Barbosa et al., 2021; Marengo et al., 2021).

Activities within the first fire type – deforestation fires, mostly in the Amazon – are usually illegal, occur uncontrolled and are often associated with other environmental crimes: they have greatly contributed to wildfires of great proportions throughout Brazil, with disastrous consequences, also in the extreme wildfires of 2019 and 2020. For instance, Silveira et al. (2020b) have noted that one-third of the fires between 2003–2019 in the Amazon occurred within 1 km of areas deforested in the same year, clearly indicating the association between fire and deforestation. Indeed, deforestation fires in the Amazon increased considerably in 2019 when compared to the previous years (Fig. 1), reaching one-third of total number of fires (based on fire foci; Alencar et al., 2020).

The use of fire for grazing and agricultural management occurs in different production systems and at different spatial scales. For example, fire is used in sugarcane production, as burning facilitates the manual harvesting of culms. However, due to the negative effects of smoke from the large areas burned, policies are underway to eliminate the use of fire in these systems. In São Paulo, for example, Law 11.241/2002 establishes the obligation to gradually reduce the use of fire to zero until 2021 in areas where mechanical farming is possible, and until 2031 where this is not the case. This shows that clear information (in this case, on the impact of fire on human health) and proper policies can contribute to a reduction of detrimental fires and their negative effects. Fire is also used as a management tool for cattle raising in natural grasslands and savannas, for instance in the southern part of the Atlantic Forest, in the Pantanal and in the Cerrado, to remove excess biomass and to stimulate resprouting (see item *Human-altered fire regimes and consequences*). But the main reason for using fire is a matter of costs: fire management is very cheap. More fences could facilitate a more effective management of grazing animals without fire, and undesirable woody species in grassland could also be removed by mowing, but these practices are simply more expensive. Technical assistance by extensionists and financial resources could help to reduce the use of fire.

The use of fire in slash-and-burn systems is practiced by subsistence farmers and indigenous populations. These fires are restricted locally, and consequently, impacts are also more local; however, they may lead to accidental wildfires (see item *Human-altered fire regimes and consequences*). Following extreme fire events in the Amazon in 1997/1998, efforts towards reducing the use of fire resulted in policies and management initiatives to prevent uncontrolled fires in the region. Indigenous and local people were dissuaded from burning, usually by prohibiting or limiting the use of fire (Carmenta et al., 2013). However, the anti-fire discourse often does not consider the cultural significance of fire to these communities, nor the fact that small farmers often do not have any alternative technique for vegetation and land management, and no appropriate training or alternatives are offered to local communities (Carmenta et al., 2019). In consequence, fire policies in the Amazon which criminalize practices of smallholders have failed, as evidenced by the high number of accidental fires (Carmenta et al., 2019; Eloy et al., 2019a,b). Without alternatives, farmers burn with poor control, which increases the risk of escaping fires. There is a need for dialogue and the search for alternatives for smallholders especially those working in fire-sensitive regions. Under climate change scenarios, the fire risk also increases with any accident or loss of control during traditional fire practices for agriculture: if fire is used, it needs to be done well and be adequately controlled.

Other uses of fire, more restricted to specific regions and practiced by traditional communities exist across the country, for instance, for agricultural activities in *veredas* ('roças de esgoto'; Borges et al., 2016), the use of annual or biennial burns to stimulate growth or flowering of species with relevance for handicraft, such as the "capim-dourado" (*Syngonanthus nitens* Ruhland) (Schmidt et al., 2011; Fichino et al., 2012) or 'everlasting flowers' (species from the Eriocaulaceae family; Giulietti et al., 1987; Oliveira et al., 2015). Even though these practices are part of the cultural her-

[4] In 2019 and 2020, presidential decrees (Decree 9.992/2019 and Decree 10.424/2020) banned the population from using fire altogether for limited periods (60 and 120 days, respectively), except when used by authorities to combat fires, or those being employed by traditional or indigenous communities.

itage and the local economy, they often conflict with conservation objectives. To solve these conflicts, the exploration of options that move beyond forbidden fire and can in fact serve to reduce fire risk seem important (Carmenta et al., 2019). Initiatives to build fire management solutions that incorporate traditional knowledge and integrate local communities in decision making are under way for the Cerrado (Eloy et al., 2019c).

Unlike other parts of the world, in Brazil no regional planning for the use of fire in private lands exists. In North America and the Mediterranean region, where fire-prone forests dominate and wildfire risk has increased due to climate and land use change, the 'fire-smart management' approach has been more and more accepted. It implies the management of the whole landscape in order to reduce wildfire risk, fire severity and socio-economic impacts. For that, fuel is reduced by conducting controlled burnings and/or the planting of low-flammable species in natural managed forests and silviculture, and fire spread is contained through barriers at the landscape level (Hirsch et al., 2001; Fernandes, 2013). In areas with processes of rural abandonment in the Mediterranean region, this same fire-smart management approach is able to improve carbon sequestration and biodiversity conservation, thus combining the benefits of fire risk control, ecosystem service supply and biodiversity conservation (Pais et al., 2020). This approach could be used in Brazil to design fire-smart landscapes in rural areas.

Towards effective fire management in Brazil

The objectives of fire management across Brazil's different ecosystems will always differ. In fire-sensitive ecosystems, fire effects on biodiversity, ecosystem processes and ecosystem functions are overall negative. In fire-dependent ecosystems, adequate fire-regimes contribute to the maintenance of biodiversity and ecological processes typical of these systems (Durigan, 2020). However, what is an 'adequate fire regime' is not easy to determine and will depend on a careful evaluation of different effects of fire and clear objectives for burning (Pivello and Norton, 1996). At any rate, we need to understand what causes fire and which processes influence fire regimes, such as climate change and deforestation, so that severe and possibly catastrophic fires can be avoided (Cardil et al., 2020).

The problem of fire will likely get more severe under climate change effects and with stronger anthropogenic drivers, underlying the need to develop management strategies. Despite the recent implementation and acceptance of IFM in protected areas, the actions taken in response to wildfires in Brazil by governmental agencies overall have been more reactive (and even then, often insufficient), than preventive. Indeed, the problem of fire often is only recognized when extremely severe wildfire events become visible to the public, as in the 2019 and 2020 fire seasons. A huge policy gap to face the fire problem exists, especially outside of protected areas. In the following, we discuss essential steps to advance in fire management in Brazil, and thus be able to reduce the risk of extreme fire events and their negative consequences.

Here, we focus on three strategic issues. First, any effective fire management policy requires actions that go beyond management and prevention of fires and must include poverty reduction and climate change mitigation to reduce fire risk. Second, there is a need to implement effective fire management systems on the ground, including monitoring systems. Third, despite the recent increase of studies on fire, mostly on the relation of fire and biodiversity in fire-dependent systems, fire management still suffers from major knowledge gaps regarding biophysical aspects (e.g., drivers of fire, fire effects in specific ecosystems such as wetlands) and the human dimension of fire (e.g., cultural issues, conflicts and their solutions), therefore, a research agenda should be established.

Fire management and policies

In principle, adequate environmental legislation exists against deforestation and forest degradation, but suitable policies and implementation of effective law enforcement, essential to curb deforestation and fire (Cardil et al., 2020), are lacking. The possibility of wildfire reduction in many regions of the country is strongly linked to addressing social and environmental justice and accounting for climate change. Current projections indicate that greenhouse gas emissions from wildfires will compromise the goals of the Paris Agreement in Brazil (da Silva Junior et al., 2020), with wildfires from the Amazon contributing most to emissions, as already the case (1999–2018: Amazon 60,7% of emissions, and Cerrado 32,0% of emissions; da Silva Junior et al., 2020). It is clear that the goals set to avoid dangerous climate change can only be reached under considerable changes in environmental policies that lead us back to a path of rapid reduction of deforestation and fire, among other measures such as ecological restoration.

As most fires in Brazil are lit illegally, law enforcement should be the first response, and collection of fines can contribute to financing of enforcement. However, current overall policy is not favorable: recently, resources for land cover and fire risk monitoring by INPE were reduced by 67% in 2019 (compared to 2018), and resources for enforcement on the ground were reduced by 38,9% in the Brazilian annual budget bill 2020 (PLOA, *Projeto de Lei Orçamentária*) (from R$ 3,2 billion to R$ 2 billion; INESC, 2020). These cuts increase the fragility of the relevant institutions and impede law enforcement. This, together with the general dismantling of environmental policy (Vale et al., 2021) and institutional capacity (evidenced, e.g., by the demission of INPE director Ricardo Galvão; Escobar, 2019b), the general political discourse (Caetano, 2021) and the current economic and social crisis encourage criminal activities that lead to deforestation, illegal mining, and burning of forest, especially in the Amazon region.

An essential first step to improve fire management – from the strategic to the ground level – requires the established law be followed, and adequate public policy formulated and implemented, including law enforcement. Given the role of the Amazon Forest for regional and global climate regulation, the halting of deforestation and the rapid reduction of fires associated with such activities needs to remain a policy priority. The obligatory restoration of illegally deforested areas as required by law should be enforced as deforested or degraded areas raise the occurrence of uncontrolled fires.

For reduction of fires not associated with deforestation and practiced as part of traditional land use, it is essential to include local communities that use fire into the development and implementation of fire management plans (Fonseca-Morello et al., 2017), as well as to support these communities with technical assistance and credit allowing them to adopt land use practices without the use of fire. A transition to more sustainable agricultural practices can occur when efficient technologies are made accessible to the land users. Agroforestry systems are an example of such a system whose implementation can lead to the reduction of deforestation and the use of fire, while providing a wide range of products and services for local communities (e.g., Cardozo et al., 2015). Alternatives to the slash-and-burn technique that have been used for millennia exist; what is needed are policies that inform and capacitate stakeholders to use them, offer them financial support for the implementation of new techniques when necessary, and also help them to integrate their uses into the regional production matrix facilitating access to markets (Sá et al., 2007). Regularization of land ownership for traditional peoples should improve their economic and social conditions, and thereby alternatives to fire for managing their land could become more feasible and the risk of escaping fires reduced. Needless to say, sufficient federal and state budgets for the responsible environmental agencies are necessary.

Reduction of fires and deforestation will only be possible through the integration of information and policies in decision making, and available resources at the federal, state and municipal levels. The improvement of socio-economic conditions that will enhance the chance to implement efficient fire management is important as well. Fortunately, we have good examples of partnerships among government, stakeholders and commodity buyers that show it is possible to reduce deforestation by collective action and territorial approaches (e.g., Nepstad et al., 2014). Such initiatives may inspire the establishment of a national fire policy that shares common goals with all those sectors involved, and thus enhance the chance to achieve the goals of fire management. At the moment, lack of integration of knowledge, actions and strategies reduces effectiveness of policy (Fonseca-Morello et al., 2017).

Similar to the Amazon, large parts of the Cerrado have lost natural vegetation due to agriculture expansion (crops and livestock husbandry), and fire has often been used in land clearing/conversion. Carbon emissions from land use change in the Cerrado have contributed considerably to the total CO_2 emissions in Brazil. While Mato Grosso do Sul and Goiás are the states with greatest losses in terms of natural areas over the past 20 years, today the so-called MATOPIBA region (Maranhão, Tocantins, Piauí, Bahia states) is especially affected by loss of natural vegetation, contributing with approximately 45% of the native vegetation loss in the Brazilian Cerrado between 2001 and 2019 (Noojipady et al., 2017; INPE, 2021a, b). The dynamics of land use in these states is intrinsically associated with deforestation and fires, the use of pesticides on a large scale and the intensification of monoculture (Silva, 2018). Enforcement of legislation – prosecution and reduction of illegal fires – should be the main strategy for this region. The implementation of a moratorium for the conservation of the native ecosystems, similar to the soybean moratorium in the Amazon, has been considered urgent (Soterroni et al., 2019).

In fire-dependent ecosystems, fire can also be an interesting management tool for farmers as it is cheap and easy to use and can contribute to biodiversity conservation, for instance in a grazing context (e.g., Fuhlendorf and Engle, 2004). However, despite clear positive effects on biodiversity (see above), we still lack studies that quantify positive and negative impacts (including on carbon dynamics or grazing productivity) and evaluate alternatives or identify the most adequate fire regimes. Where fires are overall considered negative, policies that discourage the use of fire need to be developed, e.g., by offering training to land users and/or assisting them in terms of infrastructure (e.g., fences and water tanks to improve grazing management or equipment for mowing), thus allowing the substitution of fire by other management approaches.

Ecological restoration is a priority environmental policy globally and until recently also in Brazil, as evidenced by the National Plan for Recovery of Native Vegetation (PLANAVEG; Brasil, 2017). Wildfires can reduce the success of restoration, and thus it seems important to consider the potential effects of fire into restoration projects, especially in regions that undergo rapid land use change or where fire-dependent and fire-sensitive ecosystems are found in an intricate mosaic. In fire-dependent ecosystems, fire can be used as a restoration tool to increase resilience of restored ecosystems (Barros et al., 2018), even though fire-risk reduction and other conservation objectives do not always coincide (e.g., Shinneman et al., 2012). For restoration in fire-sensitive ecosystems, future fire regimes need to be taken into account to set realistic restoration goals.

Box 2: General guidelines for fire management in fire-dependent and fire-sensitive ecosystems.

All ecosystems:
- Prevent and combat illegal fires
- Systematically monitor occurrence and effects of fire, and use the acquired information for fire management
- Develop clear goals for fire management, and periodically check if they have been reached
- Based on fire effects and management efficiency, periodically revise the fire management strategy

Fire-dependent ecosystems:
- Recognize the role of fire for keeping biodiversity and ecological characteristics of fire-dependent ecosystems
- Consider fire as a management tool, together with other options
- Avoid high-severity fires with undesirable impacts
- Consider trade-offs among different management objectives when defining fire management strategies

Fire-sensitive ecosystems:
- Recognize that fire negatively influences the biological characteristics of fire-sensitive ecosystems
- Overall, avoid fires and combat wildfires
- Respect the culture of traditional communities, which may include sporadic use of fire at small scales, but work towards promotion of alternative strategies to the use of fire

Increasing the effectiveness of fire management on the ground

Fire management must be implemented based on sound information. As state and municipality levels have an important role on fire prevention, local authorities that are engaged in fire management need clear criteria and adequate information to decide when fire can be allowed, where it should be prescribed, and where it should be prevented or fought (see Box 2). The basis for this includes data on drivers and consequences of fires collected at fine spatial scales and, ideally, over long periods. High-quality information is important to define regional goals of fire management, including local specificities (e.g., fire-dependent vs. fire-sensitive vegetation, climate, season, surroundings, needs and practices of local people).

An adequate fire management policy requires partnership between experienced staff in environmental agencies and academics to share knowledge and training (e.g., towards risk-assessment), including collective learning, as well as monitoring of fire and effectiveness of fire management. State committees for prevention and fighting of fire and deforestation (*Comitês Estaduais de Prevenção e Combate a Queimadas e Desmatamento*) exist in some Brazilian states, in particular in the Amazon and in the Pantanal, but they need to be sufficiently staffed, equipped and funded so that they are able to implement state plans. Fonseca-Morello et al. (2017) have shown that the lack of success of federal and state policies derives from both insufficient institutional capacities to implement policy and adverse socioeconomic conditions that lead to increased risk and use of fire that are not integrated in fire management.

To complement available data, a targeted national fire management program for collecting data at all relevant spatio-temporal scales should be considered. Currently, information on forecasts of risk of natural disasters triggered by extreme rainfall conditions (e.g., CEMADEN www.cemaden.gov.br) and weather forecasts from INMET (https://portal.inmet.gov.br/) and INPE (www.inpe.br) are used in fire prediction/prevention models that can be used in fire management and prediction decision making (e.g., Pivello and Norton, 1996; Martell, 2015; Fonseca-Morello et al., 2020). A large number of frameworks and models to decide on fire management strategies based on different sets of input variables have been developed in other parts of the world and can serve as a basis (e.g., Étienne et al., 2008; Niazi et al., 2010; Spies et al., 2017). Even with the current data limitations and associated uncertainties, a more effective fire management probably can be implemented if transparent, easy-to-understand rules on fire use are established, and fire licenses issued (or not) accordingly. This requires reducing bureaucracy related to fire permits where it is indeed important for management, and at the same time enhancing capacity building in public agencies supplied by adequate budgets. Capacity building and regular financing are essential to increase the professionalization of fire management as well as of firefighting staff, improving their work quality and reducing risks during firefighting operations. This would, at the same time, raise the acceptance of firefighting operations in local communities.

In the absence of a more structured national fire policy, we see repeatedly surrogate emergency measures, such as the use of military apparatus in the Amazon region to combat fires. Although possibly efficient in achieving some short-term goals, this strategy does not appear to be effective to reach persistent changes in fire policy. Military personnel cannot replace specialist technical staff in the field, as they have no specific training in environmental issues and are prohibited from imposing fines when necessary; the use of such emergency measures may actually delay the building of appropriate capacities.

Achieving a reduction of illegal fires and of firefighting costs demands positive incentives to farmers and local stakeholders, which could be attained through partnerships among public and private sectors across the supply-chain (Nepstad et al., 2014, see also above). In this context, financial institutions could, for instance, benefit farmers that have a good fire governance record with better loan conditions and payment rates. Commodity buyers could provide better terms for farmers or slaughterhouses that follow the rules; importantly, this can already today be traced back, allowing to identify regions and actors that have contributed to deforestation (zu Ermgassen et al., 2020). While policy on the national level is relevant here, it must be assured that a vertical integration across administrative levels occurs, and incentives should be given to people that manage their lands in the way that it contributes to the overall policy goal. This rewarding approach should also apply to traditional peoples. In both the case of farmers and traditional peoples dialogue is necessary for developing win-win solutions.

A big challenge to implement a national fire management strategy is to incorporate the implications of ongoing climate changes that may lead to changes in fire regimes. To face this, a flexible fire management strategy that follows an adaptive management approach is needed, using, again, the best data available and establishing long-term partnership among environmental agencies and academia. Forecasting, monitoring and warning systems are fundamental for fire management. In the Amazon, for example, where fire is associated with deforestation (Silveira et al., 2020b), plans to combat and prevent fires should be developed months in advance, based on alerts of areas with high deforestation indices launched by the Real Time Deforestation Detection System (DETER) of the National Institute for Space Research (INPE). Every year, technical notes with scientific evidence, analyses and prognoses on the current status of deforestation, fire and climate conditions that can contribute to fire prevention in Brazil are made available (Alencar et al., 2020; Aragão et al., 2020). Also, there are initiatives (Anderson et al., 2020) that identify priority areas with a high probability of fire threat in the Amazon. In the Pantanal, a near real-time fire alert system (ALARMES NRT – LASA/UFRJ) has been used since March 2020 to support environmental agencies in wildfire fighting.

Is it clear that fire management policies need to cover the entire country of Brazil, however, this seems not realistic at the moment, at least not in the short term. The legal framework for fire management has been evolving very slowly. Advances in the past have often been triggered by the involvement of international partners, and less been stimulated by national policy. The current reduction of capacities and budgets of environmental agencies to deal with fire, land use change and related problems is tenebrous as it impedes even executing the existing policies, which are insufficient, and will not allow for training staff and acquiring equipment, that are paramount for the necessary institutional advances.

Research agenda

Recently, due to increasing mega-fire events around the world (Fidelis et al., 2018) fire has received growing attention in science and research (see. e.g., Overbeck et al., 2020). For example, in Brazil a federally funded call for research projects related to fire issues in the natural environment was launched in 2018 (CNPQ/PrevFogo-IBAMA call). In Brazil, the impacts of fire on vegetation have been much studied in fire-dependent systems, mainly the Cerrado, but much less so in fire-sensitive regions. Even so, studies in fire-dependent ecosystems are generally local in scale and focused and restricted to few aspects of interest, mostly on plant and vegetation responses. Research on the impacts of fire on soil biogeochemistry, especially in relation to carbon and water cycles, is scarce, and even more so under longer temporal perspectives. Despite that more research on fire has been developed in the Cerrado, the assessment of its resilience to fire under climate and land use change is lacking. Combining modelling and experimental approaches, the establishment of a network of experimental sites would be desirable across the country, integrating existing long-term study sites (e.g. PPBio, Rosa et al., 2021; PELD, Brito et al., 2020), working with common research protocols and approaches.

As occurrence of fire is often related to anthropogenic actions and also affects ecosystem services, the socio-economic context of wildfires requires adequate consideration (Oliveira et al., 2020). We still have little data about the economic drivers and consequences of wildfires in Brazil (e.g., costs of fire prevention, firefighting, economic consequences of fire events). Models that take into account multiple variables that contribute to the likelihood of fire can be used to save resources allocated for firefighting (Fonseca-Morello et al., 2020), and data on avoided carbon emissions from wildfires can lead to financial returns through global initiatives (such as REDD). Additional costs caused by indirect collateral impacts of wildfires (e.g., health effects, stopping of air and road traffic due to smoke, damage to crops and livestock) are rarely included in costing fire damage. Likely, these externalities will show large variation among ecosystems, depending on their fire-resiliency and fire scale, but their consideration is of high relevance to establish priorities in fire management. Importantly, a full understanding of the motivations and ways in which traditional and local peoples use fire is fundamental for a peaceful coexistence between the conservation of natural resources and the maintenance of the conditions of sustenance and culture of these populations. Bringing traditional and scientific knowledge together is required to develop appropriate management approaches for traditional populations, which consider both their culture and the needs of conservation and climate change mitigation.

Research outcomes should be used in university courses such as Biology, Forest Science and Agronomy to introduce a deeper understanding about the role and impact of fire in Brazilian ecosystems. There is also a need to provide effective outreach and training programs for farmers, students and local authorities in order to enhance awareness and literacy about fire and its consequences related to environment and well-being.

Concluding remarks

Wildfires in fire-sensitive ecosystems are a severe threat to biodiversity and climate, and it is urgent to address the complex underlying issues of land use and climate change. On the other hand, in fire-dependent ecosystems we need to advance in the development of ecosystem management strategies that work with, not against, fire. The recent mega-fires in different parts of the country shocked the world and evidenced unpreparedness in institutional capacities and policies, also in consequence of recent defunding of environmental agencies and of political initiatives not committed to sustainable development goals. It also showed that the debate on fire issues often is not objective enough, and that we need to invest in the availability of data on fire drivers and effects, as well as on good communication of them. Brazil cannot risk going back to a path of increasing numbers of catastrophic wildfires, after years of progress. More and extended fires, in particular in regions with high rates of deforestation and other types of land use change, will have disastrous impacts on the environment and climate, and also on human populations and their culture. Brazil needs a long-term commitment with conservation and sustainable development, independent of specific government mandates and as a true State policy, where fire management is a central issue. This needs to go beyond protected areas – where advances have been made in recent years – but should also include private lands. Successful initiatives in Brazil that bring the public and private sectors together have shown it is possible to achieve socio-economic development with conservation goals (Nepstad et al., 2014). This gives us hope that we will also advance in fire management across the country, with solutions that are adequate for the distinct ecological, socio-economic and cultural realities of Brazil.

Misconceptions on fire in the public debate and in policy

From the text above, it becomes clear that fire cannot be generalized to be always harmful (Fidelis, 2020). A nuanced perspective is needed that considers regional particularities including ecosystem types and their historical evolution as well as the socio-economic context to support policy. In the following (Box 3) and backed by the previous description of fire regimes and their drivers we answer

Box 3: Answers to frequent doubts concerning fires in Brazilian ecosystems.

Question	Answer
1- Burning vegetation in Brazil is legal?	Yes, as long as landowners follow guidelines established by legislation (Law 12,651/2012; Decree 2,661/1998). Outside the provisions of law, anyone who starts a wildfire will be subject to prosecution (penalty and imprisonment of 2–4 years).
2- Have Brazilian rainforests become more flammable in recent years?	Yes. Recurrent forest fires open up the rainforest canopy, changing its structure and composition, and make it more flammable. This process is on course over vast areas of the Amazon (Flores et al., 2016) and also in the Atlantic Forest (Sansevero et al., 2020).
3- How does burning of the Amazon forest affect other regions?	Burning, which in the Amazon is very much associated with deforestation, reduces atmospheric water circulation in South America by decreasing the forest capacity to contribute to atmospheric water transport and cloud formation from evapotranspiration (Staal et al., 2020; Marengo et al., 2018). This affects large parts of the continent, and impacts natural ecosystems and economic activities.
4- Have the 2020 burns been caused by climate change?	In both the Amazon and Pantanal, the high occurrence of wildfires in 2020 was the result of a combination of dry weather, human activities and lack of adequate environmental policies and surveillance. In the Amazon, human action (deliberate fires) (Staal et al., 2020) was a major driver of fires, while in the Pantanal the extreme drought in the 2019–2020 period (Marengo et al., 2021) and insufficient response appear to have contributed more. Therefore, burns in 2020 were due to drought, and more extreme droughts are linked to global warming; such extreme droughts may occur more frequently in a warmer climate.
5- Is the Cerrado a degraded forest associated with fire?	The Cerrado is clearly not a result of forest degradation, but a highly biodiverse complex system composed of natural savanna ecosystems. Because of this, the use of the term "savannization" for tropical forests degraded by strong disturbance is inappropriate: even though tropical degraded forests may acquire a savanna-like structure, their biodiversity and ecological complexity are not similar at all to those of natural savannas such as the Cerrado.
6- What are the effects of fire on Brazil's grass-dominated ecosystems?	Brazil's grass-dominated ecosystems have evolved under the influence of fire, and their biotas have natural adaptations to fire. These fire-dependent ecosystems need a proper fire regime to keep biodiversity and the ecological natural cycles. However, human-induced fires with increased frequency and intensity are of great concern, as well as invasive exotic grasses that produce abundant flammable biomass. On the other hand, fire exclusion in some areas may lead to woody encroachment and biodiversity loss.
7- How do fire and grazing interact?	In grassy ecosystems, fire and grazers interact in positive-and-negative feedback. After burning, grasses quickly resprout, offering palatable and nutritious tissues that attract herbivores, which thus concentrate grazing in these burned patches and reduce biomass and fire risk. Less-grazed patches, with more biomass, will eventually burn, thus creating a mosaic of grazed and ungrazed patches that control fires at the landscape level. Such spatio-temporal mosaic of burned and unburned patches favors fire-dependent species, and also maintains species that are more sensitive to fire, being thus positive in terms of biodiversity conservation.
8- Is cattle husbandry good for preventing fires in the Pantanal?	Yes, cattle may help in preventing wildfires because they consume biomass that otherwise would become fuel, and fire is also used to reduce fuel when needed. Importantly, this only applies to traditional cattle management, which relies on native grasses, on the flood plains. Intensive cattle ranching in areas not subject to a natural flooding regime is often based on exotic grasses, where pastures have different carrying capacity and are not managed with fire; thus the interaction with the cattle is very different.
9- What are the effects of ground fires in wetlands?	Ground fires (defined in Box 1) last for a long time, slowly consuming roots, sprouts and seeds, killing plants, damaging soil decomposers, and making the ecosystem recovery very difficult. They can emit much more greenhouse gases than aboveground vegetation fires (Langmann and Heil, 2004), and the smoke they continuously produce over weeks or months can be harmful for human health (Watts and Kobziar, 2013). Advancing deep into the soil and spreading laterally far underground, they are very difficult to extinguish. Ground fires are still little understood and studies in Brazil are rare.

10- What are the economic consequences of wildfires?	Large wildfires have enormous direct economic impacts, considering fire extinction operations, loss of infrastructure, and human health. Indirect and medium-long term consequences include immense costs to society due to biodiversity loss and reduction of ecosystem services, as well as aggravation of climate change. Moreover, losses can be very high for individuals, as in the loss of lives, property or valuables.
11- Do fires affect the biodiversity of aquatic ecosystems and water quality?	Fires increase runoff, erosion and nutrient transport in the boundaries of aquatic habitats, reduce macrophyte vegetation and thus increase insolation and water temperature. Water turbidity, conductance, C, N and P concentrations also change, and dissolved O_2 is reduced (Diemer et al., 2015). Ashes in high concentration can kill native fish (Gonino et al., 2019) and be toxic to invertebrates depending on their chemical composition (Harper et al., 2019).
12- How do animals cope with fire? How does fire affect wildlife?	Fire effects on animals can be direct/immediate (e.g., death, harm), indirect (e.g., changing habitat and food sources), or, in the long-term, induce animal evolutionary responses to fire regimes (Whelan et al., 2002; Engstrom, 2010). Animals from non-flammable ecosystems are usually much affected by wildfires, while those (some endemic) of fire-prone ecosystems are adapted or may even need fire to survive because of the ecological cascade associated with post-fire ecosystem regeneration.
13- What are the effects of fire on soil properties and soil organic matter?	Depending on the characteristics of soil, vegetation and fire effects on soil properties may vary substantially, from fertilization of the top layers due to ash deposition (which adds cations and balances pH) to changes in soil aggregate stability, pore size and distribution, water repellency, nutrients stocks and availability, and soil biota, thus influencing soil functions and ecosystem services (González-Pérez et al., 2004; Doerr and Cerdá, 2005; Neary and Leonard, 2019). Our knowledge about the effects of fire on soils from different Brazilian ecosystems is still very limited.

some commonly asked questions about fire in Brazilian ecosystems, ranging from much debated practical and political issues to questions on the scientific bases of fire management. An extended version of the answers in Box 3 is available in the Supplementary material.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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