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Challenges in the conservation and management of legal reserve areas in Brazilian grassland and savanna ecosystems in the face of global climate change

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Abstract – Legal reserve areas (LRAs) are a fundamental part of the Brazilian conservation strategy, together with permanent preservation areas. The LRAs are intended to maintain biodiversity and can be managed sustainably. When these areas are home to ecosystems that depend on fire and grazing, such as native grasslands and savannas, management practices that are suitable for their conservation and for dealing with the effects of global climate change should be adopted. However, this subject is still poorly discussed in Brazil, and public policies are not clear on this matter. This review article describes the grassland and savanna ecosystems in Brazil, the legal aspects related to the management of LRAs, the current and future climate scenarios, and the relationship between climate and fire risk. It also presents a review about the use of fire and grazing in grassland and savanna ecosystems, the legal challenges related to their application in LRAs, and the use of geotechnologies to monitor these practices. The conclusion is that grazing and fire, as management tools, are adequate for LRA functions, as long as they are practiced in accordance with legal and scientifically based standards to avoid the negative effects of their incorrect use.

Index terms: biodiversity, biomass fuel, fire, integrated fire management, grazing, sustainable use, wildfire.

Introduction

Legal reserve areas (LRAs) are defined by Lei de Proteção da Vegetação Nativa (LPVN), nº 12.65, of May 25, 2012 (Brasil, 2012), the Brazilian law for the protection of native vegetation, as the percentage of rural property that, together with permanent preservation areas (PPAs), must be maintained with original or restored vegetation. This percentage varies according to the different Brazilian biomes, considered, here, as large ecological systems, distinguished one from the other, mainly, by climate, in the sense adopted by Instituto Brasileiro de Geografia e Estatística (IBGE, 2013, 2023).

In the Legal Amazon, for example, the rural landowner must maintain the following percentages of native vegetation in the different biomes: 80% in case of forest, 35% in the Cerrado (type of savanna), and 20% in grassland areas; in the other regions of the country, this percentage is 20%, regardless of the type of vegetation. In the Pantanal biome, the LRA percentage varies according to the region in which it is located: in the state of Mato Grosso, within the limits of the Legal Amazon, the percentage to be maintained is of 35% for Cerrado areas and 80% for forest areas; however, in the state of Mato Grosso do Sul, the LRAs should comprise 20% of the property.

The LRAs maintained in the different biomes have multiple functions, among which the following stand out: promoting the conservation of biodiversity, sheltering and protecting wildlife and native flora, assisting in the conservation and rehabilitation of ecological processes, and ensuring the sustainable and economic use of the natural resources of the rural property (Metzger et al., 2019). Since they were established as a strategy for conservation and sustainable use since the former Forest Code of 1934 (Metzger et al., 2019), the LRAs are one of the pillars of the Brazilian policy for conservation on private properties in rural areas (Guerra et al., 2020), in addition to the PPAs. The LRAs are also associated with the socioenvironmental function of rural properties, established in sections I and II of article 186 of the Brazilian Constitution and fulfilled when the requirements for a rational and adequate use of these areas, appropriate use of the available natural resources, and preservation of the environment, among others, are met simultaneously.

Despite this, the Brazilian legislation is unclear as to the management practices that can be adopted in the LRAs containing non-forest types of natural vegetation, such as the savanna and grassland ecosystems. These ecological systems are, in general, adapted and even dependent on fire and herbivory (Myers, 2006; Simon et al., 2009; Walter & Ribeiro, 2010; Andersen et al., 2012; Durigan, 2020; Pivello et al., 2021; Fidelis et al., 2022), which poses a considerable challenge for their management, when aiming to achieve the objectives established by the legislation.

In the face of current and future scenarios of global climate change in several regions of the country and, especially, in grassland and savanna ecosystems, the adoption of appropriate management forms is a key aspect for the conservation of biodiversity and ecosystem services (Pivello et al., 2021). In this context, this review article aims to provide a panoramic analysis of the ecological characteristics of grassland and savanna ecosystems in Brazil, discuss current climate change scenarios and fire risks, and analyze the details of the current legislation at the national and subnational levels regarding the possibility of managing combustible plant biomass in the LRAs. The article also intends to disseminate knowledge and recommend management strategies for these areas, using prescribed burning and grazing, considering the emerging and more frequent and intense extreme climatic events.

These different issues are addressed in the six following sections of this article, which present: 1. a general description of the grassland and savanna ecosystems in Brazil; 2. the aspects of LRA management according to the LPVN; 3. the current climate scenarios, the relationship between climate and fire risk, and future perspectives in the face of global climate change; 4. an overview of management through the use of fire and grazing in the grassland and savanna ecosystems; 5. a general overview of the national and subnational legislation regarding the use of fire and grazing in LRAs; and 6. the use of geotechnologies for monitoring the effects of management through these practices and for fire prevention.

1. Grassland and savanna ecosystems

Grasslands and savannas are often considered, together, as open or grassy ecosystems due to their continuous herbaceous layer composed of grasses, other herbaceous plants, subshrubs, and occasionally scattered shrubs. The herbaceous layer determines the dynamics of these ecosystems as it constitutes most of the biomass that serves as fuel for natural or anthropogenic fire, whereas the grasses serve as fodder for grazing animals. Specifically in savannas, there is also the characteristic shrub-tree layer, albeit discontinuous (Ribeiro & Walter, 2008; Gibson, 2009; Pivello, 2011; Baggio et al., 2021; Overbeck et al., 2022), whose plant species, in many situations, serve as food for herbivores.

The grassland and savanna ecosystems are rich in biodiversity. The Cerrado, for example, is considered as the most biodiverse savanna in the world, with a flora that shows adaptations to fire, which evolved during the expansion of the C_4 grass-dominated ecosystems in the late Miocene and early Pliocene (Simon et al., 2009). The Pantanal, despite being relatively poor in endemism, is the richest wetland area in bird species worldwide (Tubelis & Tomas, 2003).

In addition, the Pampa grasslands cover a little over 2% of the Brazilian territory but harbor about 9% of the known biodiversity in the country (Andrade et al., 2023). According to Coutinho (1978b), the diversity of environments along the gradient from more open (grasslands) to more closed (savannas and forests called *cerradão*) vegetation contributes to this high biological diversity.

Originally, open ecosystems covered approximately 27% of Brazil's land surface (Overbeck et al., 2022), being present in all biomes of the country. In total, 6.17% of Brazil are still covered by grassland environments (525,208.4 km^2) and 13.47% by savanna environments (1,147,183 km^2), distributed across all biomes (Table 1 and Figure 1). In the Amazon, for example, the enclaves of savanna and grassland environments are distributed in isolated patches, totaling approximately 43,000 km^2 in the Lavrado region of the state of Roraima (Barbosa et al., 2007; Morais & Carvalho, 2015; Carvalho & Morais, 2020), 15,453 km^2 in the state of Pará (Overbeck et al., 2022), from 10,000 to 13,000 km^2 along the coast of the state of Amapá (Carvalho & Mustin, 2017; Borghetti et al., 2019; Overbeck et al., 2022), 35,000 km^2 in the state of Amazonas, and 12,000 km^2 in the state of Rondônia (MapBiomas, 2023). However, in the Cerrado and Pampa biomes, a considerable part of the native open ecosystems has already been converted into lands for alternative soil use, mainly for agriculture, livestock farming, and planted forests (Alencar et al., 2020; Bolfe et al., 2023), which reduces the proportion of native grasslands in the Pampa and of grasslands and savannas in the Cerrado (Table 1).

Table 1. Area and percentage of remaining native grassland and savanna environments in the different Brazilian biomes according to MapBiomas (2023).

Biome	Grasslands		Savanna	
	(km^2)[(1)]	(%)	(km^2)[(2)]	(%)
Amazônia	163,552.0	0.24	20,868.2	0.31
Caatinga	37,275.2	4.41	0.0	0.0
Cerrado	165,042.1	8.10	605,135.7	29.72
Atlântic Forest	28,035.5	2.53	12,320.8	1.11
Pampa	63,434.5	35.59	0.0	0.0
Pantanal	67,869.1	48.48	32,410.7	23.15

[(1)]Includes flooded grasslands, represented by codes 11 and 12 in the classification of MapBiomas (2023). [(2)]Code 4 in the MapBiomas (2023) classification.

According to Overbeck et al. (2022), two fundamental processes have contributed to the evolution and maintenance of the grassland and savanna ecosystems: fire and grazing. Other authors added that both fire and grazing are factors responsible for the great variety of physiognomies in these ecosystems, which often occur in mosaics or gradients (Pivello & Coutinho, 1996; Oliveira & Pillar, 2004; Pillar et al., 2009; Pivello, 2011; Blanco et al., 2014). However, the effect of these types of management vary, as observed for the different Brazilian biomes.

In the Caatinga, most of the ecosystems are not considered fire dependent (Pivello et al., 2021), and forests are harmed by this type of management. However, in other biomes, fire can play a relevant role in their dynamics and biodiversity. This is the case of the enclaves of savanna in the Amazon (Carvalho & Mustin, 2017) and in the Caatinga (Costa et al., 2004; Oliveira et al., 2019), as well as of the enclaves of savanna and grasslands in the Amazon and Atlantic Forest biomes (Pivello et al., 2021), already rich in biodiversity, and in the open ecosystems of the Cerrado (Coutinho, 1990; Moreira, 2000; Pivello, 2011; Oliveras et al., 2013; Durigan, 2020).

In the Cerrado, fires occur in cycles of 3–6 years (Pivello et al., 2021), caused mainly by lightning at the beginning of the rainy season (Ramos-Neto & Pivello, 2000), usually with a low intensity and consuming quickly the herbaceous layer (Rissi et al., 2017). Such fire events promote the cycling of the nutrients that were retained in the dry vegetation, in addition to stimulating grass regrowth, flowering, and fruit and seed formation (Coutinho, 1977; Zirondi et al., 2021; Zupo et al., 2021; Fidelis et al., 2022).

In the Pantanal, the fires, together with seasonal floods, are fundamental for defining plant communities and landscape structure (Damasceno-Junior et al., 2021a). In this biome, most of the grasslands and savannas are influenced by annual flood pulses, which generate a dynamic ecosystem with a predictable alternation between wet and dry phases (Cunha & Junk, 2010; Girard, 2010; Junk et al., 2010). Because it determines vegetation productivity, the hydrological regime also influences fire dynamics. Therefore, these two factors act together to maintain the grassland and savanna ecosystems in the Pantanal (Poser & Nogueira, 2004; Ivory et al., 2019; Damasceno-Junior et al., 2021a; Moraes et al., 2022). As the Pantanal, other

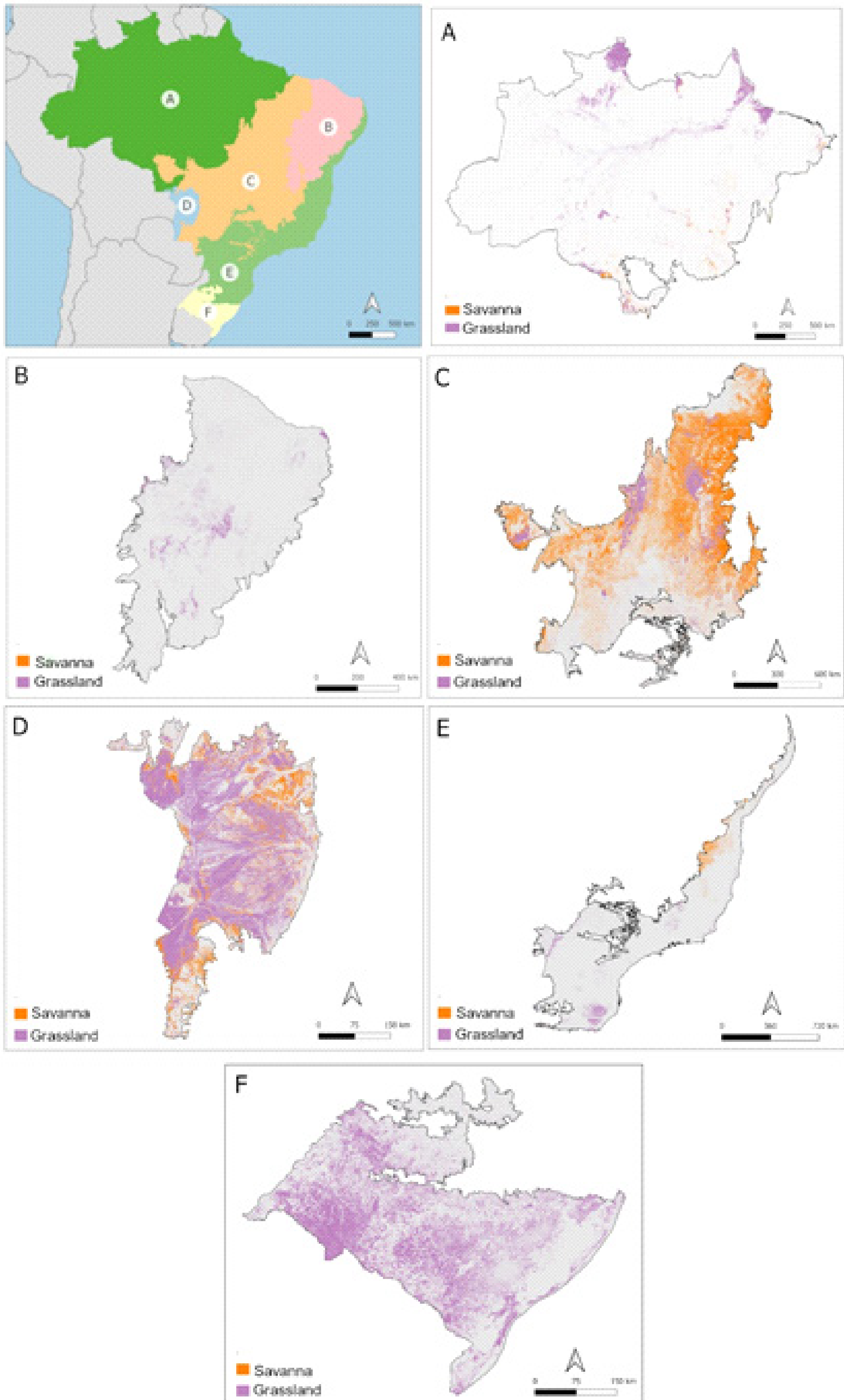

Figure 1. Remnant grassland and savanna ecosystems in the different biomes of Brazil: A, Amazon; B, Caatinga; C, Cerrado; D, Pantanal; E, Atlantic Forest; and F, Pampa.

Source: IBGE (2023) and MapBiomas (2023).

large floodplains, such as those along the Araguaia (in the state of Mato Grosso, Goiás, and Tocantins), das Mortes (in the state of Mato Grosso), Guaporé (in the state of Mato Grosso and Rondônia), and Paraná (in the states of Paraná, São Paulo, and Mato Grosso do Sul) rivers, present extensive seasonal grassland formations and flooded savannas, where both water and fire are defining factors in ecosystem dynamics and landscape structure (Marimon & Lima, 2001; Martins et al., 2006).

In the Southern region of Brazil, where seasonality is less defined by rainfall but influenced by temperature, grassland ecosystems are referred to generically as *Campos Sulinos* (Southern grasslands) and include the Pampa biome and plateau grasslands in the southern Atlantic Forest biome (Behling et al., 2009; Hasenack et al., 2023). Without a long dry season and due to the coexistence of tropical (C_4) and hibernating (C_3) grasses, these ecosystems, which harbored large native herbivores until their extinction at the end of the Pleistocene/early Holocene era (Lopes et al., 2020), are excellent for grazing and cattle farming. These activities are, until today, economically relevant in the region and can contribute to maintain the high biodiversity of these ecosystems (Andrade et al., 2023).

The remnants of highland grasslands in the plateaus of the states of Paraná, Santa Catarina, and Rio Grande do Sul occur in mosaics with Araucaria forests and originate from cooler and drier periods (Behling & Pillar, 2007), which have been maintained to this day by the action of herbivores, mainly of cattle (Nabinger et al., 2009; Baggio et al., 2021), as well by fires used for cattle management.

Among the Brazilian open ecosystems, the rocky (edaphic) and highland grasslands (Vasconcelos, 2011; Zappi et al., 2017, 2019) are both considered resilient to fire (Le Stradic et al., 2018; Fernandes et al., 2020b; Silveira, 2021). The so-called rocky grasslands are rich in species and show a very high degree of endemism, being found at altitudes above 800 m on rocky or sandy substrates, poor in nutrients, with different geological origins (Silveira et al., 2016). The variations in soil characteristics are the main factor responsible for the formation of grassland patches dominated by graminoid species, by other herbaceous plants, or by sections containing subshrubs, shrubs, and even small trees, but always interspersed with typical rocky outcrops (Fernandes et al., 2020a). In the Espinhaço mountain range, Harley (1995) observed that rocky grasslands occur: in the southern part, in the Atlantic Forest biome, in the state of Minas Gerais; in the middle part, in the Cerrado biome; and in the northern part, in the Caatinga biome, in the state of Bahia. Overbeck et al. (2022) only did not register rocky grasslands in the Pampa biome.

The altitude grasslands are located in the highlands of the Atlantic Forest and in the Mar and Mantiqueira mountain ranges, where they do not present a nuclear distribution, but occupy disjointed areas separated by forested valleys, plateaus, and watersheds (Caiafa & Silva, 2005; Vasconcelos, 2011). According to Vasconcelos (2011), these grasslands are generally located above 1,500 m altitude and associated with igneous or metamorphic rocks, such as granite and gneiss, among others. Although partly located in less elevated areas, the grasslands on the plateaus of the region are also, technically, considered altitude grasslands by some authors (Longhi-Wagner et al., 2012). For legal purposes, according to Law nº 11,428/2006 (Brasil, 2008), these grasslands occur in the Atlantic Forest biome from 400 m altitude in some regions of the country, as shown in the map of IBGE (2012). The vegetation is expressed in mosaics, whose most common physiognomy found on the plateaus, which can be extensive, is composed of shrubs inserted in a matrix of grass and graminoid clumps, with sparse herbs and ferns (Safford, 1999).

Contrastingly, the grassland areas in the Atlantic Forest biome occur at low altitudes in the alluvial plains of the Paraná river, most of which have already been lost due to the implementation of hydroelectric plants. Only a stretch remains between the Itaipu lake, downstream, and the Sergio Motta hydroelectric plant, upstream, consisting of flooded grasslands (Agostinho et al., 2004; Osório & Rodrigues, 2021; Schmitz et al., 2023). These wet grassland areas are often subject to fires, even in protected areas such as the Ilha Grande national park and Várzeas do Rio Ivinhema state park (Koproski et al., 2004, 2006; Tiepolo et al., 2004, 2010).

2. Management of the LRAs according to the LPVN

The LPVN, in article 3, section III (Brasil, 2012), defines legal reserves as the area within a rural property or possession, whose limits are fixed in accordance with article 12 and whose functions are to: promote the conservation of biodiversity, shelter and protect wild fauna and native flora, assist in the conservation and rehabilitation of ecological processes, and ensure the sustainable and economic use of the property's natural resources.

Therefore, any activity, planning, and decision regarding the legal reserve must focus on achieving the objectives defined by the legislation, which include the specific needs of rural producers, as long as they are compatible with the conservation of these areas according to the LPVN. In chapter IV (on the legal reserve area), in section I, this law sets the delimitation of the LRA, whose native vegetation should be maintained as indicated in section II (on the legal reserve protection regime), in article 17, which also allows of the exploitation of the area through an economic and sustainable management, in paragraph 1 (Brasil, 2012).

In articles 20, 21, 23, and 24 of the LPVN (Brasil, 2012), the possible forms for forest vegetation management and for the use and exploitation of forest resources are mentioned, but refer, exclusively, to the exploitation of timber and non-timber products, such as fruits, vines, leaves, and seeds, listed in article 21. Although the heading of the LPVN states that the law deals with the protection of native vegetation – which would supposedly encompass all types of vegetation formations –, non-forest vegetation types, such as grasslands or savannas, are not addressed or even mentioned, which indicates that, in the LPVN, there is a bias towards forest terminology, common to and entrenched in the Brazilian legislation. Thus, the LPVN omits possibilities for the sustainable use of LRAs with non-forest vegetation, such as through grazing. However, different types of non-forest vegetation are common in the predominantly savanna and grassland biomes in Brazil, such as the Cerrado, the Pampa, and the Pantanal (Figure 1 and Table 1), also being found, although to a lesser extent, in forest biomes of the Atlantic Forest and the Amazon (Borghetti et al., 2019, 2023; MapBiomas, 2023).

Even though it does not refer explicitly to other types of vegetation that may occur in LRAs, because its focus is on forest environments, the LPVN clearly indicates, in article 22, that the functions of these areas are maintaining native vegetation and species diversity. In sections I, II, and II of the same article (Brasil, 2012), it defines the following premises for the forest management of LRAs, respectively: maintain vegetative cover and promote the conservation of native vegetation, maintain species diversity, and manage exotic species through measures that favor the regeneration of the species of the area.

However, the ways to maintain the functions of the LRAs are not well established when it comes to grassland and savanna ecosystems, especially in the face of climate change scenarios, biological invasion processes, and the consequent increase in fire risk, as well as of their impacts on the biodiversity and ecosystem services of these areas.

3. Climate change scenarios and wildfire risk

3.1. Present climate

Climate change is drastically altering the frequency, duration, and severity of extreme events such as droughts and heatwaves, posing a new challenge to the Brazilian environmental and socioeconomic sectors related to wildfires and forest fires (Libonati et al., 2022b). According to the Brazilian panel on climate change, Painel Brasileiro de Mudanças Climáticas (PBMC, 2014), between 1901 and 2012, increasing temperature trends were observed in most parts of Brazil, with the highest increases of 1.75ºC registered in the central region of the country. In several regions, there was an increase in the number of consecutive dry days, especially in the southern part of the Northern region, the northern and western parts of the Northeastern region, the Midwest, and the Southeast (Santos et al., 2020; Regoto et al., 2021; IPCC, 2022), as well as an increase in the number of days with extreme maximum temperatures, mainly in the Midwestern, Northern, and Northeastern regions. In the southern Amazon, in the north and center of the Cerrado (states of Tocantins and Goiás), and in the Northeastern region, there are trends toward a drier climate, particularly in summer and autumn. Therefore, the number of days in heatwave conditions has increased significantly in all regions of the country since 1980 (Geirinhas et al., 2018; Santos et al., 2024), although there are exceptions, such as in the Pampa, located in the Southern region, where there is a trend towards an increased precipitation, with a reduction in consecutive dry days, mainly in spring (Regoto et al., 2021). In addition to their greater frequency, duration, and extent in the affected areas, these climatic phenomena are increasingly occurring simultaneously with other extreme events, such as droughts, especially in the Northeastern and Southeastern regions and in the Amazon and Pantanal biomes (Libonati et al., 2022a, 2022b; Marengo et al., 2022a, 2022b).

In the Cerrado, for example, there was an increase of 2.2 to 4.0ºC in maximum temperatures and 2.2 to 2.8ºC in minimum temperatures between 1961 and 2019, with a 15% reduction in relative humidity (Hofmann et al., 2021).

In the Pantanal, Libonati et al. (2022a) reported an increase of 0.76ºC per decade in maximum temperature, resulting in an increase of approximately 3ºC since 1980. In addition, the annual percentage of the Pantanal area under heatwave conditions increased over the past four decades, reaching its maximum value of 45% in 2020 (Libonati et al., 2022a). Prolonged rainfall deficits have been observed in the Pantanal region since 2000, with the last three years culminating in extreme droughts (Marengo et al., 2021; Thielen et al., 2021). According to Getirana et al. (2021), the prolonged drought that began in mid-2018 spread to various regions of the South-Midwest of Brazil, culminating, in 2021, in a severe drought in this part of the country.

In the Southeastern region, an increase in temperature has been observed in the high-altitude grasslands of the Atlantic Forest, as well as an increase in the number and severity of heatwaves and droughts (Geirinhas et al., 2018, 2021; Cunha et al., 2019). In the Pampa, temperature increase trends are stronger in winter, with increases in nighttime temperature in all seasons (Marengo & Camargo, 2008).

In the Amazon, temperature increase trends are noted throughout the region, particularly in the southern, central, and northeastern parts, at a rate of 0.5°C per decade for the period from 1979–2012 (Jiménez-Muñoz et al., 2013), with an increase in the frequency of hot days and heatwaves (Geirinhas et al., 2018; Regoto et al., 2021). Associated with temperature rise, there are reports of an increased frequency and intensity of droughts and floods (Coelho et al., 2012; Marengo & Espinoza, 2016; Espinoza et al., 2022). From 2000 to 2015, the frequency of droughts in the Amazon was almost three times higher than the decadal incidence of the last century, representing a major threat to its forest ecosystems (Panisset et al., 2018). Recent studies indicate that heatwaves and droughts have been occurring simultaneously in the region (Costa et al., 2022; Libonati et al., 2022b).

All these scenarios establish facilitating conditions for large fires in several Brazilian regions.

3.2. Climate and fire

The occurrence of large fires is expanding worldwide, driven by socioeconomic and environmental changes, but, mainly, by changes in temperature and precipitation patterns caused by global warming (Hardesty et al., 2005; Andersen et al., 2012; Bowman et al., 2020). In general, the occurrence of fires is linked to the lack of an adequate management, associated with high temperatures, low relative humidity, low precipitation, and strong winds, although the conditions during the vegetative growth stage also play an important role in vegetation modulation and, consequently, in the amount of combustible material (Bowman et al., 2020).

In Brazil, several studies have evaluated the relationship between fire and climatic/meteorological conditions; however, due to the extension of the country's territory and variety of ecosystems, these relationships differ among biomes and even at a regional scale (Pivello et al., 2021). The natural fire regime also presents significant seasonal variations and is not uniform across the Brazilian territory (Menezes et al., 2022; Schumaker et al., 2022). The natural fires are more common in spring and less frequent in autumn (Menezes et al., 2022; Schumaker et al., 2022), whereas atmospheric discharges cause less large natural fires in summer than in spring due to humidity conditions (Menezes et al., 2022; Schumaker et al., 2022).

In the Pantanal, the fires occur mainly over a five-month period, from July to November, during the dry season (Correa et al., 2022; Menezes et al., 2022). However, in the northern region of this biome, which is wetter, the return period for fires is longer, while, in the southern region, which is drier, it is often shorter (Marengo et al., 2021; Correa et al., 2022; Libonati et al., 2022a). In the Pantanal, on average, only 1% of the fires are caused by atmospheric discharges, corresponding to about 5% of the total area burned annually (Menezes et al., 2022). For other reasons, in 2020, one-third of the Pantanal area was burned, representing a 376% increase compared with the annual average of the last 20 years (Libonati et al., 2020; Garcia et al., 2021). In this same year, more than a third of the areas in the biome that had not been affected by fires in the two previous decades were burnt; most of these areas were low-lying and flooded during most of the year, but dried up after 2019 (Garcia et al., 2021). The major fires of 2020 were associated with extreme weather conditions, such as extreme drought and exceptional heatwaves (Libonati et al., 2022a, 2022b; Marengo et al., 2022b), confirming the relationship between climate extremes and the occurrence of catastrophic fires. The flooding in the Pantanal, in 2020, was the lowest in 36 years, as evidenced by the level of the Paraguay River, which, during the rainy season, reached extremely low values (Damasceno-Junior et al., 2021b; Garcia et al., 2021), practically not flooding the plain. Since they occurred mainly in areas of natural vegetation, these fires caused substantial impacts even in conservation areas, affecting threatened species (Tomas et al., 2021; Barbosa et al., 2022; Kumar et al., 2022; Ferreira et al., 2023b). Therefore, the areas whose vegetation is affected by high-severity fires and that harbor fire-sensitive species should be prioritized for restoration through enrichment techniques focused on the reintroduction of these species when they are locally extinct (Martins et al., 2022).

In the Cerrado, the vast majority of the ecoregions show an increase in the frequency and intensity of fires from June to October, during the dry season (Sano et al., 2019), which corresponds to 90% of the burned area (Silva et al., 2021). Of the fires, part are caused by lightning and occur mainly in the transition between the rainy and dry seasons (Ramos-Neto & Pivello, 2000; Schumacher et al., 2022), but most of them are caused by human action (intentional or accidental) during the dry season for several reasons, such as species and landscape management, cattle grazing in native pastures, and subsistence and industrial agriculture, among others (Schmidt & Eloy, 2020; Pivello et al., 2021).

As to the annual variability in the burned area of the Cerrado, 71% is explained by the climate (Silva et al., 2019). In the Cerrado, fire intensity is well-marked by seasonality, with higher values occurring at the end of the dry season, between September and October (Silva et al., 2021). Throughout the dry season, the vegetation gradually loses moisture and the fires become more intense, tending to spread more widely, depending on the level of fragmentation and fire history of the landscape (Alvarado et al., 2020). These high-intensity fires routinely affect fire-sensitive vegetation, such as gallery forests and riparian forests (Flores et al., 2021). In the rainy season and early dry season, the rate of fire spread is limited by the high fuel moisture and, consequently, the fires that occur are of a lower intensity and the size of the burned areas is smaller (Nogueira et al., 2017).

In the Cerrado, the fires also show a marked interannual variability, associated with large-scale climatic patterns (Silva et al., 2021). In 2007, for example, when the largest extent of fire in the biome in the last two decades was recorded, there was a severe drought induced by a La Niña event (Araújo et al., 2012). In 2010, a strong positive phase of the Multidecadal Atlantic Oscillation caused record dry conditions over the eastern and southern regions of the Amazon and the adjacent regions of the western Cerrado (Panisset et al., 2018), resulting in high values of burned area in almost all ecoregions. The extensive wildfires that occurred in the ecoregions of the Northeast, in 2012 (Silva et al., 2021), were also a consequence of an extreme drought in the region (Marengo et al., 2018).

In the Amazon, human activities aligned with climate change and variability contributed to almost-periodic peaks of wildfires in various ecosystems of the biome (Cano-Crespo et al., 2021; Libonati et al., 2021). The role of climate in the occurrence of fire in this region is particularly relevant during extreme droughts, which have increased fire incidence, intensity, and severity (Panisset et al., 2018). During the 1997–1998 drought event, related to one of the most intense El Niño episodes ever recorded, one-third of the region became susceptible to fires and approximately 40,000 km^2 were burned (Nepstad et al., 2004). In 2005, the lack of precipitation induced by anomalies in the surface temperature of the tropical North Atlantic Ocean mainly affected the western part of the Amazon, causing an extended and extreme fire season in the region (Jolly et al., 2015). In 2010, the co-occurrence of the El Niño phenomenon and the Atlantic Multidecadal Oscillation resulted in a record drought and large fires in the western and southern Amazon (Marengo & Camargo, 2008; Chen et al., 2017). Because of the extreme temperature and precipitation values, exacerbated by the strong El Niño event of 2015, unprecedented dry conditions occurred in the tropical forest during this year, but resulted in a relatively low level of fire activity due to decreased deforestation rates (Jiménez-Muñoz et al., 2013; Libonati et al., 2021).

In the Caatinga, an ecosystem classified as independent of fire, natural fire events are rare (Althoff et al., 2016) since its vegetation does not provide continuous and easily flammable fuel (Queiroz et al., 2017). However, human actions and climatic extremes have contributed to the occurrence of fires and, consequently, to the degradation of this ecosystem (Melo, 2017). Given the lack of adaptation of the dominant flora of this biome to fire, it is estimated that its natural regeneration after fires of human origin would require at least 50 years (Althoff et al., 2016).

Just as the Amazon, the forests of the Atlantic Forest biome and other biomes are sensitive to fire, mostly associated with human action and exacerbated by extreme weather conditions. For example, extreme drought events in 2005, 2010, and 2015 significantly increased the number of fires during winter and spring in remaining Atlantic Forest regions in the state of Rio de Janeiro (Andrade et al., 2019). The drought in 2014/2015, one of the severest ever observed in Southeastern Brazil (Geirinhas et al., 2022), led to a significant increase in forest fires in the mountainous region of Rio de Janeiro (Rodrigues et al., 2018); although the fires were triggered by criminal action, they were intensified by the atypical drought. In general, the fires in these forests occur during winter and spring, which are dry periods with a significant reduction in relative humidity and precipitation (Silva Junior et al., 2020).

In the Pampa, the number of fires and the burned area have been relatively constant throughout recent years, but there was also an increase in 2020 due to extreme drought (Pivello et al., 2021). Overall, the Pampa biome is the less affected by wildfires since the forests usually do not burn and, in native grasslands, the biomass is constantly removed by grazing, which results in a low fuel availability for fires, despite the dominance of C_4 grasses. Therefore, grazing management contributes to reducing the risk of fires. Historically, larger fires occur mainly in wet areas during summer when there is dry biomass, such as the fire in the Taim ecological station in 2013 (Nascimento et al., 2021). However, the fires in 2020 are an indicative that this situation may change as extreme weather events increase and other ecosystems become more prone to wildfires. It is important to note that the controlled burns used for cattle management in the Pampa are much less common than in the southern grasslands of the Atlantic Forest biome, where the so-called *sapecadas* (traditional low-intensity fires) are part of the traditional management during winter, a season with a lower risk of extreme fires (Brunel et al., 2021).

3.3. Future projections

The future pattern and intensity of global fires are still uncertain in climate change scenarios, as they depend greatly on the climatic zone and local human factors (Moritz et al., 2012; Williams & Abatzoglou, 2016). Given the continuous anthropogenic changes that have significantly altered the fire regimes on the planet, especially in the past 250 years, predicting the interactions of fire, climate change, and different land management practices is challenging, representing vulnerability and a significant knowledge gap (Sayedi et al., 2024). In addition, with distinct fire regimes among biomes, management options are considerably limited in scenarios of higher greenhouse gas emissions, particularly in the case of forest and savanna biomes (Sayedi et al., 2024).

In Brazil, the projected trend is of an increasing risk of fires across several biomes under different climate change scenarios (Fonseca et al., 2019; Silva et al., 2019; Burton et al., 2022). In the case of the Cerrado, projections indicate that the region will undergo a continuous increase in temperature and a decrease in relative humidity and precipitation until the end of the 21st century (Silva et al., 2016b; Feron et al., 2019; Blázquez & Solman Silvina, 2020). Considering the RCP2.6, RCP4.5, and RCP8.5 climate change scenarios from the Intergovernmental Panel on Climate Change (IPCC, 2019, 2022), the burned area in the Cerrado is expected to increase annually, associated with a higher probability of extreme precipitation events and, mainly, drought (Silva et al., 2019). Still according to these same authors, compared to historical periods, the average scenario of CO_2 stabilization (RCP4.5) predicts a 39% increase in the burned area by 2100, whereas the more ambitious CO_2 mitigation scenario (RCP2.6) predicts a 22% increase by 2050, followed by a decrease to 11% by 2100. The conditions predicted in RCP2.6 show the importance of limiting global warming to 1.5°C up to the end of this century to minimize the environmental and social costs associated with fires in the Cerrado (Silva et al., 2019).

Projections of climate change scenarios in the Pantanal region indicate that, by the end of the century, temperatures could increase by up to 7°C and precipitation could decrease both in summer and winter (Marengo et al., 2016; IPCC, 2019). However, the uncertainties regarding climate projections are still high, especially for precipitation. The decrease in precipitation in the Pantanal region, associated with the South American Monsoon System, could result in a reduction in the rainy season, for example (Gomes et al., 2022). The percentage of the Pantanal area under heatwaves will increase in the future, reaching 35% by 2100 under RCP2.6 and up to 80% under RCP8.5, implying a greater susceptibility to the occurrence of fire in the region (Silva et al., 2022a). In addition to extreme heat and drought, extreme floods are also expected. Considering that pasture areas hold a large part of the Pantanal's livestock production, huge economic losses accompany these extremes, as already reported in previous years (Marengo et al., 2016, 2021).

In the Amazon, climate change scenarios point to an increase of more than 4°C in average air temperature and a reduction of up to 40% in precipitation (Marengo et al., 2018), mainly in the south and east of this biome (Gomes et al., 2022). It is expected that the climate anomalies triggered by the large-scale atmospheric patterns related to El Niño and the Atlantic Multidecadal Oscillation will continue to impact the Amazon, causing a higher frequency of extreme droughts (Duffy et al., 2015). These increases in hydroclimatic extremes, particularly in droughts, together with anthropogenic changes in land use, may further increase fire activity in this biome (Richardson et al., 2022). The warming trends in the region may also increase evapotranspiration (Regoto et al., 2021), leading to a decrease in soil moisture and, consequently, to an increase in vegetation flammability (Choat et al., 2012; Le Page et al., 2017).

Given this overall future scenario, the current legal framework in Brazil, both at the national and subnational levels, should be aligned with the management requirements for vegetation biomass and include preparations for extreme fire, drought, and/or flood events, as well as for the consequent ecological conditions, regardless of whether the area is protected or not.

4. Overview of management through fire and grazing in the grassland and savanna ecosystems

Open ecosystems are generally dependent on disturbances to maintain their ecological processes, which explains why the plants present in these systems show adaptations related to fire and grazing (Pivello, 2011; Baggio et al., 2021; Pivello et al., 2021; Zirondi et al., 2021; Zupo et al., 2021; Fidelis et al., 2022; Paruelo et al., 2022; Teixeira et al., 2022). Therefore, in the absence of these types of disturbance, these ecosystems undergo changes in their structure and composition that can lead to losses in diversity and ecosystem services (Abreu et al., 2017; Pivello et al., 2021; Teixeira et al., 2022). In the absence of fire, for example, there is a greater accumulation of combustible material, which can lead to large intense and uncontrollable fires (Fidelis et al., 2018; Correa et al., 2022; Teodoro et al., 2022). Another effect of fire exclusion, in many regions of the Cerrado biome, is the increase in woody species, altering open physiognomies to forested ones, resulting in a loss of herbaceous and shrubby diversity, as well as in a loss of ecosystem services such as water provision (Honda & Durigan, 2016; Abreu et al., 2017; Archer et al., 2017; Wilcox et al., 2018).

4.1. Prescribed burning

Fire as a tool for the conservation and maintenance of open landscapes, as well as for the reduction of fire risks, has been used for decades in many countries around the world, but is still incipient in Brazil (Schmidt et al., 2016, 2018). In the country, the zero-fire policy that was in force until recently, even in fire-dependent biomes and ecosystems (Moura et al., 2019), is currently considered misguided (Pivello et al., 2021), being created due to the doubts related to the best times for prescribed burning, the frequency in which fire should be used, and the types of burning to be implemented.

The misuse of fire (time of the year, type of vegetation, and fire frequency, for example) can cause significant impacts on the biodiversity, structure, and composition of the plant communities in ecosystems, compromising the recruitment of new individuals and reducing and altering the density and abundance of species, respectively (Medeiros & Miranda, 2005; Lima et al., 2020), interfering significantly in the dynamics of ecosystems. A recent example are the fires that occurred in the Pantanal in 2020, which reached catastrophic levels due to the long dry period and consequent accumulation of biomass (Libonati et al., 2020, 2021; Garcia et al., 2021; Marengo et al., 2021; Correa et al., 2022; Kumar et al., 2022; Teodoro et al., 2022), causing substantial impacts to the ecosystem (Tomas et al., 2021; Arruda et al., 2022; Barros et al., 2022). Other authors pointed out that fire can be catastrophic in high-altitude grasslands, considered high-mountain vegetation refuges in the Atlantic Forest, which consist of small and isolated areas, with a high degree of endemism (Scarano, 2009; Vasconcelos & Rodrigues, 2010; Pinto et al., 2016). However, in other biomes, fire is beneficial.

In the Cerrado, fire, used by traditional and indigenous populations during thousands of years, is still an important part of the traditional slash-and-burn agriculture (Mistry et al., 2005; Borges et al., 2023), cattle ranching in native ecosystems (Eloy et al., 2019), and landscape management practices to protect crops and homes and to reduce combustible biomass (Eloy et al., 2019; Welch & Coimbra Jr., 2021). In privately owned areas, these fires are carried out, on average, every two years, in the middle or end of the dry season, in order to stimulate grass regrowth for livestock production. However, burnings with a higher intensity can cause wildfires and alter the natural cycle of these environments (Pivello, 2011; Pivello et al., 2021). Several studies have pointed out the effects of fire on specific groups, especially on trees (Ribeiro et al., 2012; Garda, 2018; Silva, 2018) and vertebrates (Vieira & Briani, 2013; Coelho et al., 2023), but also on grassy plants (Overbeck et al., 2006; Fidelis et al., 2012; Santos, 2019; Durigan, 2020; Rodrigues & Fidelis, 2022), invertebrates (Alcolea et al., 2022), and ecosystem processes such as biomass production (Furley et al., 2008; Pereira Júnior et al., 2014) and nutrient cycling (Pivello & Coutinho, 1992; Oliveras et al., 2013); however, the available studies rarely consider multiple decades and/or several biological groups. In the protected areas of the Cerrado, since 2014, an integrated fire management has been implemented, aiming to reduce wildfires, protect fire-sensitive vegetation (forests), and reduce conflicts between environmental management and local residents (Schmidt et al., 2018). It should be noted that such actions, which use fire as a landscape management tool, are not yet institutionally implemented in private areas, such as the LRAs.

In the Southern region, especially in the so-called Campos de Cima da Serra and Campos Gerais (grasslands on the plateaus of the states of Rio Grande do Sul, Santa Catarina, and Paraná), burning is often used to remove accumulated dry biomass during winter, when frosts can occur and lead to the death of aboveground biomass, mainly of grasses (Brunel et al., 2021; Overbeck et al., 2022). This type of quick and low-intensity fire (regionally referred to as *sapecada*) facilitates vegetation regrowth after winter. However, in the grasslands of the Pampa biome, burning is rarely used as a management tool. Both in the Pampa and high-altitude grasslands of the Southern region, the absence of cattle and fires results in the accumulation of tall-grass biomass, in the increased coverage of shrub species, and in the spread of pioneer trees over the grasslands, reducing species richness and typical biodiversity (Oliveira & Pillar, 2004; Ferreira et al., 2020; Sühs et al., 2021). Therefore, management through fire or grazing is a key tool for maintaining biodiversity in the Southern grasslands (Overbeck et al., 2016, 2022). However, excessive cattle stocking in these grasslands triggers changes in the plant community, which may lead to the loss of diversity and productivity due to dominance of prostrate species in the system (Fedrigo et al., 2018).

Therefore, to avoid losses in biological diversity and ecosystem services, management through fire or grazing must be tailored to each system, but not prohibited. According to Moura et al. (2019), the prohibition and criminalization of burning have led to the abandonment of traditional vegetation management practices and to an increase in the occurrence of fires, both natural and anthropogenic.

In the Cerrado, a study based on 32 years of monitoring showed that the absence of periodic fire or grazing caused changes in vegetation structure due to the colonization of grassland areas by woody plants, known as woody encroachment (Abreu et al., 2017; Gonçalves et al., 2021). This process results in a loss of the biodiversity associated with open vegetation, since the vast floristic richness of the Cerrado lies in its non-arboreal flora (Mendonça et al., 2008; Zappi et al., 2015; Amaral et al., 2022; Flora e Funga do Brasil, 2023). In Cerrado enclaves in the Amazon, Coelho et al. (2023) found that fire plays a key role in determining the structure and composition of bird communities. These authors concluded that fire exclusion and the consequent alteration in the structure of the savanna vegetation cause deep changes in the avifauna, favoring forest species over those from savanna ecosystems.

4.2. Grazing

Grazing in open ecosystems has both positive and negative impacts, depending on the environment and management objectives. In the Cerrado, low-intensity grazing in regenerating planted pastures can influence the structure and composition of open savannas, reduce the coverage and biomass of exotic grasses, and favor native herbaceous plants (Durigan et al., 2022). According to the same authors, with the reduction of the biomass of exotic grasses, there is a reduction in the flammability of the system, which reduces the risk of high-severity fires. In Cerrado areas in the state of São Paulo, the exclusion of cattle grazing, combined with the suppression of fire, caused the open ecosystem to evolve into forest formations (*cerradão*), excluding shade-intolerant plants and causing the loss of savanna species diversity (Pinheiro & Durigan, 2009; Abreu et al., 2017). In these cases, grazing can be adopted as a practice to prepare areas to be used for the restoration or revegetation of non-woody vegetation in Cerrado savanna physiognomies, aiming to reduce exotic grasses and allow of the establishment of native species (Andrade, 2021; Marçon & Ferreira, 2021).

In the Southern grasslands, the exclusion of grazing or fire increased the biomass of tussock grasses and shrubs and also the loss of diversity of typical grassland species (Ferreira et al., 2020). However, grazing favored the diversity of herbaceous plants in native grassland ecosystems (Zanella et al., 2021). Ferreira et al. (2020) also observed negative effects of cattle exclusion on plant diversity, but an increase in plant and arthropod diversity under light and rotational grazing conditions.

In the Pampa, grazing can be used as a tool for natural regeneration in projects for the restoration of natural grasslands, acting as a biomass controller and vector in the transport of seeds from conserved areas; however, it shows limitations regarding the control of invasive exotic species (Silva et al., 2022b). Other studies in the Pampa relating grazing to the diversity of species, such as spiders, however, suggested there are no significant differences between grazed and ungrazed areas (Silva & Ott, 2017).

In the Pantanal, the exclusion of cattle from native pastures caused negative impacts on the beetle community, regarding both species and functional diversity (Correa et al., 2020), also favoring the proliferation of woody species in grassland areas (Silva et al., 2016a).

In rocky grassland areas, livestock use has been insufficiently evaluated, although some authors recommend extreme caution when adopting this practice due to the unique abiotic environmental conditions, rich biodiversity (Oliveira et al., 2015; Abrahão et al., 2020), and high degree of endemism of these ecosystems (Kolbek & Alves, 2008; Zappi et al., 2015; Colli-Silva et al., 2019; Silveira, 2021).

Although the use of grazing as a management tool for conservation is still little discussed outside certain niches of the scientific community and is rarely included in the agenda of decision-makers (Baggio et al., 2021), the practice has been adopted as a strategy in several regions of the world and is beginning to be used in Brazil (Bardgett et al., 2021). However, considering the carrying capacity of the grassland and savanna vegetation, it is important to better investigate the impact of stocking rates on the biodiversity of each biome, in order to provide a more informed basis for management decisions. Specific management techniques, such as rotational grazing (Boavista et al., 2019) or deferred grazing (Fedrigo et al., 2018), are especially interesting as they promote increases both in the biodiversity and productivity of the area.

4.3. Fire and grazing in LRAs

For the management of combustible plant biomass in LRAs containing grassland and savanna ecosystems, it is necessary to take into account the carrying capacity of these ecosystems, which depends on a series of factors related to the climate-soil-plant-animal system and, many times, is lower than one animal unit (bovine) per hectare (Abreu et al., 2019). In the Southern grasslands, for example, the number of animals to be grazing should be appropriate to the availability of forage and the maintenance of a heterogeneous grassland physiognomy, with more and less intensively grazed patches, dominated by prostrate and erect plants, respectively (Carvalho et al., 2009; Caram et al., 2023). This is important because overgrazing can cause the degradation of natural pastures due to the loss of vegetation cover (Nabinger et al., 2009; Dlamini et al., 2016). Therefore, controlling grazing intensity is a central point to maintain the dynamics of the native vegetation and the floristic richness and diversity of these areas (Nabinger et al., 2009). However, it is hard to evaluate the sustainable use of LRAs when animal load is used as a control parameter due to the variation in carrying capacity between seasons, years, and regions (Carvalho et al., 2009; Nabinger et al., 2009), which also makes it difficult for landowners to adopt appropriate practices, which they often carry out empirically. In addition, controlling the length of time cattle spend in protected areas requires relatively more complex management practices, which can hinder their application and entail a greater investment in human resources. However, when applied correctly, grazing can be used as a management tool to maintain the functions of the LRAs established in article 3 of the LPVN (Brasil, 2012).

Regarding the use of fire for management, one of the most relevant and controversial factors is the time interval considered adequate between burnings, since the caused impacts depend on fire intensity, frequency, and duration (fire regime), which can interfere with plant survival, growth, and phenology, and, consequently, with flower and fruit availability for fauna, as well as with nutrient dynamics (Ribeiro et al., 2012; Ferreira et al., 2023a). Several burning intervals have been proposed for different biomes (Pivello & Coutinho, 1992; Rodrigues et al., 2002; Chidumayo, 2003; Cianciaruso et al., 2010; Miranda et al., 2010; Pereira Júnior et al., 2014; Garda, 2018; Silva, 2018), based on localized studies or comparisons between different ecosystems. However, establishing fixed disturbance regimes, with pre-defined times and frequencies for burning, may not be the best strategy for maintaining biodiversity (Bowman et al., 2016), considering that the requirements of species vary during their different reproductive stages, including flowering, fruiting, and nesting (Braithwaite, 1987; Miller et al., 2019; Ferreira et al., 2023a, 2023b).

Both grazing and burning in LRAs should be seen primarily as management instruments aimed at maintaining the biological diversity and ecological processes of these areas and also at preventing catastrophic fires, according to article 3 of the LPVN (Brasil, 2012). Furthermore, given the extreme variability of the impacts of burning and grazing, any recommendation for LRA management using these practices as tools for native vegetation conservation and/or restoration should be evaluated based on their local effect, considering the physiognomy and biome in which these areas are inserted.

For evaluations of the state of vegetation and ground cover, Myers (2006) and Baggio et al. (2021) recommend the adaptive management, based on learning through practice, with the temporary use of LRAs as a strategy. This process involves the analysis of reality, action planning and implementation, monitoring, and research to reorient the next management steps, instead of rigidity due to a lack of information for decision-making (Lee, 1999). In this case, different indicators can be used to define grazing limits and dynamics. For native vegetation restoration, indicators of ecological outcome and not of management have been adopted by some state environmental agencies (Lima et al., 2020; Campos Filho et al., 2022), using defined values for recommended attributes. To define the frequency of burning, ecological indicators of easy assessment can be used, such as minimum values to be maintained for grass biomass and/or grass height and maximum values to be admitted for soil exposure and compaction and for colonization by woody species (Baggio et al., 2021). In a scenario where there are several knowledge gaps for a better adoption of management actions, this may be a good alternative to define objectives and monitor and evaluate results for a better planning and implementation of future actions (Gillson et al., 2019).

However, the adoption of burning, combined or not with grazing, as a management tool for conservation is still little discussed and rarely adopted in public policies. Despite this, the occurrence or necessity of fire to maintain savanna and grassland environments has been discussed for many decades (Eiten, 1972; Coutinho, 1977, 1978a, 1979; Pivello & Coutinho, 1992; Moreira, 2000; Durigan & Ratter, 2006; Miranda et al., 2010), continuing up to nowadays (Rissi et al., 2017; Garda, 2018; Pivello et al., 2021; Rodrigues & Fidelis, 2022). It should be noted that the absence of rules and, consequently, the eventual suppression or misuse of burning and grazing may be even more negative than adopting the best possible strategy, locally, even if it is not the most suitable from a technical-scientific point of view. Therefore, the ability to instruct decision-makers and landowners on the use of ecological indicators is a crucial aspect to achieve an effective management within LRAs, whether through burning, grazing, or both.

5. Legislation for and management of LRAs in the face of climate change scenarios

According to the functions established by the LPVN for LRAs, the management of these areas must be consistent with the conditions necessary for the conservation of their biodiversity. However, in the case of ecosystems dependent on disturbance (see sections 1 and 2 of this work), such as most grassland and savannah ecosystems, these conditions require the correct management through burning and/or grazing, including within LRAs and other categories of protected areas. Despite this, the presumption in the LPVN that LRAs are strictly composed of forests, according to the articles cited in section 2 of this review, excludes the possibility of management through sustainable practices of burning and/or grazing, even though their objectives are absolutely congruent with the functions of these areas listed in article 3 of this law (Brasil, 2012).

In article 38 of chapter IX (on the prohibition of fire use and fire control) of the LPVN (Brasil, 2012), vegetation fires are prohibited, except in the three situations described in sections I to III, respectively: in areas where the use of fire is justifiable for agricultural or forestry practices; in the case of burning for the conservative management of conservation units, where fire is a key element in the evolution process of the ecological system; and in scientific researches linked to a research project carried out by a recognized institution under the approval of the competent authorities. The first two sections directly recognize the need of using fire where it is a relevant factor in maintaining the diversity of open ecosystems (Walter & Ribeiro, 2010; Durigan, 2020; Pivello et al., 2021). Despite these sections, since its focus is on forests, the LPVN does not explicitly mention open non-forest vegetation.

Although it is not part of the categories defined in Law nº 9,985, of July 18, 2000 (Brasil, 2000), which establishes the national system of conservation units (Sistema Nacional de Unidades de Conservação, SNUC), the LRA is, strictly speaking, a protected area according to article 3, section 3, of the LPVN (Brasil, 2012), which highlights the area's conservationist purpose (to conserve biodiversity and ecological processes) and possibility of being managed. However, the fact that LRAs have a protected area status does not alter their intrinsic ecological processes, relevant for biodiversity conservation, such as their relationship with fire and grazing events. In this sense, it would be incongruent for the LRAs containing ecosystems dependent on fire or grazing to not be managed with the strategies indicated for conservation units by SNUC and partially considered in article 38, section II, of the LPVN (Brasil, 2012). In addition, since LRAs contain ecosystems that evolved with these disturbance factors, it is important to consider the impacts originating from the exclusion of fire and grazing in face of the objectives of these areas.

According to article 40 of the LPVN (Brasil, 2012), the federal government should establish a national policy related to fire management and use, as well as to the prevention and control of forest fires, even in "protected natural areas", a concept that includes both the conservation units defined by SNUC, as well as PPAs and certainly LRAs. Therefore, in accordance with articles 1, 2, 12, 17, 22, 28, and 38 of the LPVN (Brasil, 2012), in PPAs and LRAs, especially when they are covered by non-forest vegetation, management actions should be adopted to maintain the original typology of the vegetation and minimize fire impacts. This is reinforced in article 40, paragraph 2, which determines that the national fire policy must observe scenarios of climate change and potential increases in the risk of occurrence of forest fires. For ecosystems dependent on fire, this evaluation is of great relevance, since climate change tends to create more favorable conditions for catastrophic fires due to the reduced rainfall and increased temperature predicted for several regions of the country, as described in section 3 of this review and reported by Pyne (2020) and Santos et al. (2020).

5.1. The national policy for integrated fire management

Brazil is on the verge of establishing a national policy related to the use of fire. Since 2018, bills have been under consideration in the Brazilian National Congress aiming to establish the national policy for integrated fire management, called Política Nacional de Manejo Integrado do Fogo (NPIFM). Initially, the proposal was addressed in bill nº 11276/2018 (Brasil, 2018), replaced by bill nº 1818/2022 (Brasil, 2022), which aims to regulate and promote an inter-institutional articulation for an integrated fire management, to reduce the incidence and damage of forest fires nationwide, and to recognize the ecological and cultural role of fire, according to sections I, II, and III of article 1. Because they are related matters, in the latest proceedings on July 10, 2023, the bill was received and referred to the plenary of the Federal Senate together with bill nº 135/2020, which amends the Forest Code, establishing the reforestation of rural areas that contain native forest and have subjected to illegal fires (Brasil, 2020). The NPIFM, therefore, is currently under consideration in the Senate, awaiting a vote for its subsequent promulgation.

In article 2 of bill nº 1818/2022 (Brasil, 2022), definitions are given for forest fire (section I), controlled burn (section II), prescribed burn (section III), uses of fire (sections IV and V), and other important concepts related to the subject (sections VI to XII). According to section XI, an integrated fire management is considered both as a planning and management model. Its main objectives are: conserving and protecting the biodiversity (article 2, section XI, and article 3, section IV) and ecosystemic functions of the areas (article 3, section IV); reducing the incidence, intensity, and severity of forest fires (article 2, section XI, and article 5, section III); and increasing the capacity to control forest fires (article 5, section V). The content of these three articles is entirely congruent with the use of fire for vegetation management in LRAs containing grassland and savanna environments, both to maintain the biodiversity of these areas and to reduce the risks of forest fires. According to article 3, section VI, fire is an integral part of ecological, economic, and sociocultural systems, and should be used in prescribed, traditional, or controlled forms, respecting environmental and sociocultural diversity, as well as the seasonality in each ecosystem (article 5, section II). Therefore, it is essential to evaluate climate change scenarios and the potential increase in the occurrence and severity of forest fires (article 4, section V).

According to article 40 of the bill (Brasil, 2022), an integrated fire management will aid in fulfilling the objectives of each protected area (regarding their creation, recognition, and conservation), applying conservationist principles and practices to native vegetation and its biodiversity. This type of fire management is also valid for indigenous lands or territories occupied by traditional peoples and communities, according to article 41. Therefore, the LPVN provides LRAs with a specific protection regime, whereas the bill also aligns with the suitability of fire use for LRAs to fulfill their objectives within a conservationist management.

The PNMIF bill, however, should explicitly allow burning in LRAs. Currently, the use of fire in these areas depends on the interpretation of two sections of article 30 (Brasil, 2022), which indicate the situations in which it is allowed: in locations or regions whose characteristics justify the use of fire in agrosilvopastoral practices, under prior authorization from the competent environmental agency (section I); and in the prevention and control of forest fires, as well as in the associated training (subsection IV). However, only the interpretation of these sections is not ideal since the bill does not mention burning in LRAs but only in conservation units. The negative effect of the lack of clarity as to the use of fire causes an undesirable legal uncertainty regarding burning in LRAs.

5.2. State-level policies on integrated fire management

Several states are establishing specific laws regarding the use of fire. In the state of Mato Grosso do Sul, for example, decree nº 15,654 of April 15, 2021, which institutes the state plan for an integrated fire management, advocates, in section VI, article 38, chapter IX, the replacement of native pastures for cultivated ones, mixed grazing, and rotational grazing as strategies to reduce the need for fire management

(Mato Grosso do Sul, 2021). However, replacing native grasslands with cultivated pastures to avoid the need for fire management is incongruent as it implies relinquishing a conservation management tool and, consequently, deeply impacting the biological diversity in the Pantanal (Garcia et al., 2021). This strategy, under the guise of fire prevention, is a subterfuge that increases the areas with highly invasive exotic species in cultivated pastures (Barbosa et al., 2008), which does not establish conditions to prevent fires.

In the state of Minas Gerais, decree nº 47,919 of April 17, 2020 (Minas Gerais, 2020), regulates the use of fire for the prevention and control of forest fires within and around the conservation units (including privately owned ones) established by the state government. Through article 5, this decree considers fire as a management tool for preventing forest fires and establishes a prescribed burning plan as a planning instrument for fire use, to be prepared by a person qualified in the prevention and control of forest fires, as stipulated in section II of article 1 of Ordinance IEF nº 86, of August 4, 2020 (IEF, 2020). Moreover, the joint resolution SEMAD/IEF nº 2,988, of July 24, 2020 (Semad, 2020), establishes the criteria for fire use, monitoring, and control in agricultural, forestry, or phytosanitary activities, as well as for scientific and technological research purposes. In article 2, in the last section, the resolution describes the situations in which the use of fire for controlled burning is allowed upon the technical recommendation of a qualified professional. However, in article 5, in section II, the use of fire in LRAs is restricted.

In the state of Mato Grosso, bill nº 728/2020 institutes the state fire control program (Mato Grosso, 2020). Its structure is similar to that of the PNMIF, with the same definitions of terms, principles, guidelines, objectives, and instruments for fire management. This bill also resembles the national policy when it allows fire to be used in locations whose peculiarities justify its adoption (article 19, section I). Even if not explicitly, according to article 19, paragraph 2, this bill also raises the possibility of managing LRAs that contain fire-dependent ecosystems through prescribed burns, which must be authorized by the competent environmental agency after the analysis of integrated-fire management plans.

In Tocantins, the state policy for the sustainable use of golden grass and buriti (Law nº 3594/2019) defines the expressions controlled burning, fire, and integrated fire management to stimulate the flowering of golden grass (*Syngonanthus nitens* Ruhland, Eriocaulaceae) on public and private lands, that is, in LRAs and PPAs, in wet grassland areas (Tocantins, 2019). The use of burning with other objectives, although foreseen in privately owned lands, is not mentioned explicitly for LRAs.

In São Paulo, law nº 17,460/2021 institutes the state policy for integrated fire management, its objectives, set of definitions and concepts, principles, and guidelines (São Paulo, 2021b). However, the articles dealing with the implementation, creation, and attributions of the state committee for integrated fire management were vetoed by the then governor (São Paulo, 2021a). Although, currently, the state is discussing the regulation of an integrated fire management in its protected areas, the law will only be reviewed and regulated after its implementation. Another law, law nº 10,547/2000, addresses the use of fire for agricultural, livestock, and forestry purposes, but disregards the possibility of any management in LRAs and only mentions the need to double the width of firebreaks to protect these areas when controlled burning is authorized (São Paulo, 2000). According to decree nº 56,571/2010, which regulates the aforementioned law, the use of fire is only allowed as a factor for agricultural, livestock, and forestry production and management, not for ecological purposes (São Paulo, 2010).

In the state of Goiás, there is an ongoing discussion, based on the work of a committee established for forest fire management and on a bill under review since 2021 (Goiás, 2021). Regarding the other states of Brazil, it is expected that they will develop their own legislation based on the eventual approval of the country's PNMIF.

The fact that fire use is not explicitly mentioned in the management of LRAs, both under the terms of the PNMIF bill and of the majority of existing state legislations, leaves an undesirable gap considering the relevance of burning as a management tool for biodiversity conservation, reduction in combustible biomass, and prevention of catastrophic fires, as observed in the works of Santos et al. (2021) and Oliveira et al. (2022). A likely explanation for these legislations not to explicitly mention fire use in LRA management lies in their need to comply with the LPVN, which adopts the term "forest fire", whose bias, in some of its articles, limits the inclusion of other approaches aimed at open ecosystems. In an attempt to correct this distortion, section I of article 2 of the PNMIF defines forest fire as any uncontrolled and unplanned fire, regardless of ignition form, that occurs in forests and other forms of native or planted vegetation in rural areas and that requires a response (Brasil, 2022).

5.3. State legislations allowing livestock use in LRAs

Although grazing alone may not be sufficient to control the accumulation of combustible biomass and prevent fires, especially in extreme climatic conditions, it cannot be denied that it is a fundamental tool in the management of several types of grassland and savanna ecosystems, as already discussed in this article. In this sense, regulations on grazing use in LRAs are welcome, although still lacking detail and refinement and needing to be implemented at the subnational level.

In the state of Mato Grosso do Sul, decree nº 14,273 of October 2015, which deals with restricted-use areas in the Pantanal, allows grazing both in LRAs and PPAs, according to certain criteria (Mato Grosso do Sul, 2015). In article 4, paragraph 1, the decree allows the presence of low-impact cattle in native pastures in the PPAs of rivers, streams, and lakes, for example. In article 9, paragraph, 2, it allows extensive grazing by cattle only in LRAs that are not restricted to forested areas or native vegetation with tree species and that contain areas with native pastures within it. In addition, livestock use should be carried out in a way that reduces vegetative biomass and, consequently, the risk of forest fires and cannot alter vegetative cover, harm the conservation of native vegetation, or compromise the maintenance of species diversity and the resilience of the LRA. However, without parameters for monitoring and decision-making by the owner, there is room for the degradation of these environments.

In the state of Mato Grosso, law nº 11,861/2022, which amends law 8,830/2008 (Mato Grosso, 2022) in article 9, paragraph 3, allows LRAs in the Pantanal that contain native grasslands to be accessed and used for extensive livestock grazing and for grassland restoration activities, but prohibits replacing native vegetation by exotic pastures. Currently, the regulation of this provision of the law is being developed to define criteria for a use of LRAs compatible with the objectives of these areas.

In the high-altitude grasslands in the south of the Atlantic Forest biome, traditional extensive grazing is considered an indirect use and does not need to be authorized by environmental agencies as long as the native vegetation is not suppressed and exotic species are not introduced, in alignment with article 29 of federal decree nº 6,660/2008 (Brasil, 2008). Although this decree does not specifically define this use in LRAs, it is understood that the activity is permitted and there is room for state regulations.

In the Pampa biome, resolution CONSEMA 360/2017 (Rio Grande do Sul, 2017) establishes environmental guidelines for the practice of sustainable livestock activity on remnants of native grassland vegetation in PPAs and LRAs. However, this resolution is still little adopted and lacks monitoring and even discussion. It should be noted that this resolution is conflicting with the original concept of LRA since it allows the introduction of exotic species, fertilization, and irrigation, practices that alter native plant communities (Pañella et al., 2022).

6. Use of geotechnologies for management monitoring and fire prevention in LRAs

Considering the continental geographic scale of Brazil and the significant regional differences between ecosystems, types of land use, and LRA composition, the guidance parameters for the management of these areas should also be established regionally. However, the feasibility of the adopted criteria depends on the definition of management indicators and use of technologies that allow of monitoring activities and their outcomes, aiming at the conservation of the biodiversity and ecological processes of LRAs, as well as of the environmental services provided by these areas.

Fortunately, Brazil has developed a territorial management strategy that facilitates the inspection of LRA management. This strategy is the environmental registry for rural properties, called Cadastro Ambiental Rural (CAR), implemented by the LPVN, under the national system on environmental information, Sistema Nacional de Informação sobre Meio Ambiente, and regulated by normative instruction MMA nº 2, of May 5, 2014 (Brasil, 2014). CAR is a national mandatory public electronic registry for all rural properties, integrating environmental information regarding PPAs, LRAs, restricted use areas, native vegetation remnants, and converted and used areas, treated as consolidated areas. Therefore, because it contains a set of georeferenced information, CAR can be used as a basic tool for controlling, monitoring, environmental and economic planning, and combating deforestation, covering monitoring and inspection of LRA management. This monitoring can be carried out using geotechnologies fully available and widely adopted in the country, such as data on hotspots, burned areas, and deforestation. However, to achieve the degree of effectiveness that CAR could allow, there are still issues to be solved as the slowness in validating registrations, resolution of overlapping areas (low quality of registrations), and technological deficiencies (Chiavari et al., 2021).

Based on the geospatial information provided by CAR, LRAs can be inspected and monitored using other data sources available in the country. The national institute for space research, called Instituto Nacional de Pesquisas Espaciais (INPE), through the fire program, Programa Queimadas, for example, provides data on hotspots, which are updated daily, by biome, region, and state, separated by year and month (INPE, 2024), by monitoring and modeling the occurrence and spread of vegetation fires, using remote sensing techniques, geoprocessing, and numerical modeling. Although hotspots are detected through images from different satellites, INPE uses a "reference satellite" that adopts the same method and time to capture images, enabling the formation and analysis of time series.

Among the systems used to support environmental agencies in fire-fighting actions, ALARMES stands out. This system was developed by the Laboratory of Environmental Satellite Applications of Universidade Federal do Rio de Janeiro, in collaboration with Instituto Dom Luiz of Faculdade de Ciências of Universidade de Lisboa and with Instituto Português do Mar e da Atmosfera. It is operational on a platform that serves as a rapid and agile alert tool regarding increasing areas affected by fire (Alarmes, 2024). The system combines satellite images obtained by National Aeronautics and Space Administration, hotspots, and artificial intelligence to identify new areas affected by fire, monitoring daily the location and extent of burned areas, which allows of, for example, estimating the speed in which the affected areas increase. Since then, ALARMES has been contributing significantly to mapping fires in the Pantanal, Cerrado, and Amazon.

The fire risk alert system for the Pantanal, called Sistema de Alerta de Risco de Incêndio para o Pantanal, developed by Embrapa Pantanal together with Embrapa Arroz e Fejijão (Saripan…, 2024), is based on climatic data recorded in automatic meteorological stations located in the Pantanal and its surroundings. The system provides different methods to calculate fire risk, issuing warnings for fire risk for each sub-region of the Pantanal, allowing of the adoption of preventive measures by authorities or stakeholders.

The Pantanal em Alerta system was developed by the Public Prosecutor's Office of Mato Grosso do Sul in partnership with the military firefighter corps of the state (Pantanal em Alerta, 2024). The input data of this system are spatialized hotspots combined with the base of the national rural environmental registry system, called Sistema Nacional do Cadastro Ambiental Rural. The purpose of Pantanal em Alerta is to identify places where probable fires are occurring and the existence of properties, so that authorities, owners, and volunteer firefighters in the region can be activated to minimize consequent damages.

The national institute of meteorology, Instituto Nacional de Meteorologia, also indicates fire risk for Brazil (Inmet, 2024). The danger index shows the possibility of fire occurrence, enabling the adoption of more effective and economical preventive measures.

Finally, Universidade Federal de Minas Gerais developed the FISC platform for the simulation of fire propagation in the Cerrado (Projeto Monitoramento Cerrado, 2024), focused on the analysis of fire-propagation risk in this biome, including in protected areas (Oliveira et al., 2021).

Concluding Remarks

Because of their important role in maintaining the biodiversity and ecological processes of LRAs, the use of grazing and fire for vegetation management is an essential strategy for the conservation of Brazilian open ecosystems, where the natural vegetation is non-forest but dependent on fire, such as savannas and grasslands. Both types of management prevent the accumulation of combustible material, minimizing the conditions for catastrophic fires, and cause environmental disturbances that favor biodiversity, as long as they are practiced within appropriate and science-based criteria. Like fire, grazing is also a useful management tool for biological conservation, which is becoming a well-established practice in several countries and ecosystems (Holechek et al., 2020; McKenna et al., 2021; McDonald et al., 2023; Oikonomou et al., 2023), although it is still little known and discussed outside the Brazilian academic community.

However, both grazing and, especially, fire should not be used illegally, in short time intervals, which would cause harm to biota. In this context, the available geospatial technologies increasingly allow of a greater efficacy in the monitoring, remote monitoring, and regulation of fire use and even grazing, enabling the government to monitor the correct application of these practices.

Therefore, for an adequate use of fire and grazing in LRAs, it is necessary to develop strategies to: 1. create and improve the legal mechanisms aimed at the management of LRAs, based on the best available science and under periodic reviews; 2. train multi-professional rural extension teams for the management of LRAs through the use of fire and grazing; 3. carry out awareness and clarification campaigns on the new national integrated fire management strategy to prevent the occurrence of catastrophic fires, whose results are negative for both civil society and biodiversity; 4. monitor management to ensure it is done properly from the point of view of the available scientific knowledge; and 5. conduct scientific research aimed at better understanding the responses of grassland and savannah ecosystems to the use of fire and grazing, in order for these practices to be adopted as management tools for LRAs, aiming to provide continuous improvements in the definition of good management practices.

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