**SUPPLEMENTARY MATERIAL**

**Understanding Brazil's Catastrophic Fires: Causes, Consequences and Policy Needed to Prevent Future Tragedies**

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**Resumo**

O Brasil tem vivenciado incêndios sem precedentes na última década. Imagens de imensas áreas queimadas ou animais mortos que não conseguiram escapar dos incêndios em 2020 chocaram o mundo. Para prevenir ou minimizar desastres similares no futuro nós devemos compreender os fatores que levaram a esses eventos catastróficos. As causas e consequências dos incêndios estão vinculadas a interações complexas entre as esferas biofísica e sociocultural, e decisões acertadas de gestão requerem uma sólida base científica. Apresentamos aqui o panorama recente do aumento dos focos de incêndio nos biomas[[1]](#footnote-1) brasileiros e discutimos as causas que têm contribuído para esses incêndios, seus impactos no meio ambiente e as consequências gerais para o bem-estar humano, com base numa extensa revisão da literatura sobre o assunto, no conhecimento especializado dos autores e informações fornecidas por gestores ambientais, pesquisadores e políticos durante uma oficina organizada para debater o tema dos incêndios no Brasil. Esta revisão atualizada é direcionada ao público acadêmico, gestores ambientais, tomadores de decisão e formuladores de políticas. Num primeiro momento, apresentamos evidências dos contrastantes efeitos do fogo nos diferentes ecossistemas. A seguir, traçamos, numa perspectiva histórica, a percepção e as principais políticas relacionadas ao uso e manejo do fogo no Brasil, desde a colonização até o presente. Depois, propomos meios de avançar na prevenção e desenvolvimento de estratégias de gestão do fogo. Finalmente, nós procuramos esclarecer e/ou desmistificar algumas questões nem sempre apropriadamente abordadas pela mídia.

**Sumário Executivo**

**Introdução.** Em 2019 e 2020, incêndios em diferentes biomas brasileiros1 receberam muita atenção na mídia e no debate público, no Brasil e internacionalmente. Incêndios na Amazônia lamentavelmente simbolizam o imenso problema do desmatamento. No Pantanal, os incêndios de 2020 assinalaram o triste recorde de sua maior área queimada registrada nos últimos 20 anos: quase 30% do bioma estavam em chamas. Os outros biomas já passaram por anos com incêndios mais numerosos, mas as altas taxas registradas nas duas últimas temporadas de fogo apontam para os imensos desafios que o Brasil enfrenta com respeito à conservação de seus ecossistemas naturais. Entretanto, o assunto sobre os incêndios em vegetação nativa é extremamente complexo e, não raramente, é discutido sem base científica apropriada, o que pode conduzir a decisões de manejo inadequadas e políticas ineficientes. O objetivo deste *White Paper* é estimular o desenvolvimento de abordagens eficazes para a gestão de incêndios em vegetação nativa em todos os biomas e ecossistemas do Brasil, com base em evidências científicas.

**A relação entre os incêndios e a história evolutiva do Brasil.** Os biomas e ecossistemas do Brasil variam em resposta e vulnerabilidade ao fogo. Ecossistemas caracterizados pela dominância de gramíneas – campos graminosos e savanas – coevoluíram com os incêndios e suas plantas e animais apresentam diversas adaptações e sinergias com o fogo, e por isso, sob uma perspectiva ecológica, são considerados influenciados ou dependentes do fogo. O oposto vale para as florestas tropicais, que não são adaptadas ao fogo e não queimam com facilidade, exceto quando passam por extrema seca ou degradação, que as tornam mais vulneráveis aos incêndios. Quando essas florestas se incendeiam, o fogo pode causar sérios impactos negativos à sua biodiversidade e, sendo assim, são consideradas sensíveis ao fogo. De um modo geral, ecossistemas dependentes do fogo se beneficiam de queimadas para a manutenção de sua biodiversidade e de seus processos ecológicos, enquanto que o contrário ocorre no caso de ecossistemas sensíveis ao fogo. O impacto causado por um incêndio num dado ecossistema – seja ele dependente ou sensível ao fogo – é determinado pelo regime de queima, ou seja, o padrão apresentado pelo tipo de queimada, sua frequência, sazonalidade, intensidade e extensão. Regimes naturais de queima têm sido modificados por atividades humanas – geralmente relacionadas a práticas de uso e manejo da terra ou devido a extremos climáticos ligados ao aquecimento global e às mudanças climáticas – e, geralmente, levam à maior frequência e extensão da área queimada, bem como à alteração da época de queima. Esses regimes alterados de queima costumam trazer efeitos negativos, não apenas para a biodiversidade, mas também quanto aos processos e serviços ecossistêmicos. No entanto, no caso das áreas protegidas, o fogo tem sido banido mesmo em ecossistemas pirofíticos, o que acarreta em importantes mudanças ecológicas e, muitas vezes, numa perda um tanto acelerada de suas características naturais. Um compromisso entre os diferentes efeitos do fogo sobre o meio ambiente – da biodiversidade aos serviços ecossistêmicos – precisa ser levado em conta em qualquer discussão sobre os incêndios em vegetação nativa.

**Manejo, política e legislação sobre fogo no Brasil.** Desde os tempos coloniais, uma política de ‘Fogo Zero’ prevaleceu no Brasil, mesmo em ecossistemas dependentes do fogo. Somente a partir da década de 1970, novos entendimentos sobre o fogo foram sendo desenvolvidos, à medida que o assunto passou a ser considerado pela ciência. Os efeitos negativos da exclusão do fogo em ecossistemas pirofíticos – como perda de biodiversidade e o acúmulo de combustível, que pode levar a incêndios catastróficos – passaram a ser estudados. A partir de 2008, a estratégia do Manejo Integrado de Fogo (MIF) passou a ser concebida e aperfeiçoada, e tem sido cada vez mais aplicada em unidades de conservação federais. Além de controlar o combustível e diminuir o risco de incêndios em vegetação nativa, esta estratégia permite integrar as práticas tradicionais de manejo do fogo ao manejo das unidades de conservação ou, pelo menos, estabelece um quadro para encontrar soluções conjuntas entre a população local e os órgãos ambientais em casos de conflito. Apesar dos sucessos, o MIF ainda não foi amplamente implementado em todo o país e permanece restrito a um número relativamente pequeno de áreas protegidas, principalmente no Cerrado, que é um bioma adaptado e dependente do fogo. Ainda não existe uma estratégia geral para gerenciamento de fogo em terras privadas, onde é usado ​​para diferentes fins: no desmatamento para uso agrícola (queimadas de desmatamento), para manejar sistemas agrícolas ou pastagens, ou como parte de sistemas de corte-e-queima, frequentemente praticados na agricultura de subsistência. Embora o fogo possa ser legalmente utilizado para fins agrícolas (requerendo autorização prévia), grande parte das queimadas atualmente praticadas é ilegal, principalmente quando associadas ao desmatamento e supressão da vegetação nativa, como mais comumente ocorre na Amazônia e no Cerrado. Em alguns casos, políticas ambientais têm sido capazes de reduzir o uso do fogo quando existem alternativas, como por exemplo, em plantações de cana-de-açúcar na região sudeste do país. Em outros tipos de uso da terra, no entanto, o fogo acaba sendo a única alternativa viável para pequenos proprietários que dependem de atividades de subsistência, por ser uma ferramenta de manejo extremamente barata; existem tecnologias alternativas, mas é necessário o apoio para sua implementação, bem como o estímulo a produtores locais para mudar o uso da terra, facilitando-lhes o acesso ao mercado consumidor. Uma clara estratégia para lidar com o fogo em terras privadas ainda precisa ser desenvolvida, permitindo seu uso controlado quando for benéfico e evitando-o onde os efeitos negativos forem evidentes.

**Rumo a um manejo de fogo eficaz no Brasil**. O risco de graves incêndios tende a aumentar no futuro, à medida que os efeitos das mudanças climáticas se tornam mais fortes e causam eventos climáticos extremos. Isso indica a grande importância de aumentar a resiliência de nossos sistemas socioecológicos ao fogo. No Brasil, apesar da recente adoção do MIF como estratégia em algumas áreas que protegem tanto ecossistemas dependentes como sensíveis ao fogo, as ações tomadas em resposta aos incêndios em vegetação nativa por agências governamentais têm sido, em geral, mais reativas do que preventivas e há uma enorme lacuna política para enfrentar o problema. Para avançar, devemos, primeiramente, reconhecer que os incêndios ocorrem em ambientes ecológicos e socioeconômicos complexos. Portanto, uma política para uso e manejo do fogo deve ser desenvolvida integradamente a outras políticas públicas, especialmente aquelas relacionadas à posse e gestão da terra, e de acordo com a agenda de mudanças climáticas. Abordagens de comando e controle são importantes e os incêndios ilegais precisam ser coibidos, mas também é importante incentivar ativamente os agricultores e pecuaristas a adotar técnicas de manejo agrícola e abordagens de uso da terra que independem do fogo (por exemplo, agrossilvicultura, integração lavoura-pecuária-floresta, rotação entre lavoura e pastagem, plantio direto, trituração da vegetação cortada) e, assim, propiciar uma transição para tipos de uso da terra mais sustentáveis ​​e livres de fogo. Em segundo lugar, o gerenciamento de incêndios como tal só poderá ser eficiente se as instituições responsáveis forem devidamente equipadas, supridas em suas necessidades e bem treinadas; a capacitação local, juntamente com o desenvolvimento de sistemas de monitoramento, são, portanto, fundamentais. Terceiro, a pesquisa sobre o fogo deve integrar diferentes áreas de conhecimento, desde ciências biológicas até ciências humanas, em uma agenda de pesquisa nacional voltada a criar uma base para o desenvolvimento de paisagens que sejam mais resistentes ao fogo. Além disso, educação e divulgação são necessárias para proporcionar a todos os profissionais que lidam com a conservação e manejo de recursos naturais um maior entendimento sobre o papel do fogo.

**Conclusões**. Os recentes “mega-incêndios” em diferentes partes do país têm evidenciado despreparo nas capacidades institucionais e políticas, bem como a falta de políticas adequadas para lidar com a questão do fogo, o que também é resultado do recente esvaziamento de órgãos ambientais e de iniciativas políticas não comprometidas com os objetivos do desenvolvimento sustentável. Para efetivamente reduzir incêndios e seus efeitos negativos, o Brasil precisa de um compromisso de longo prazo com a conservação e o desenvolvimento sustentável e que considere as distintas realidades ecológicas, socioeconômicas e culturais em todo o país.

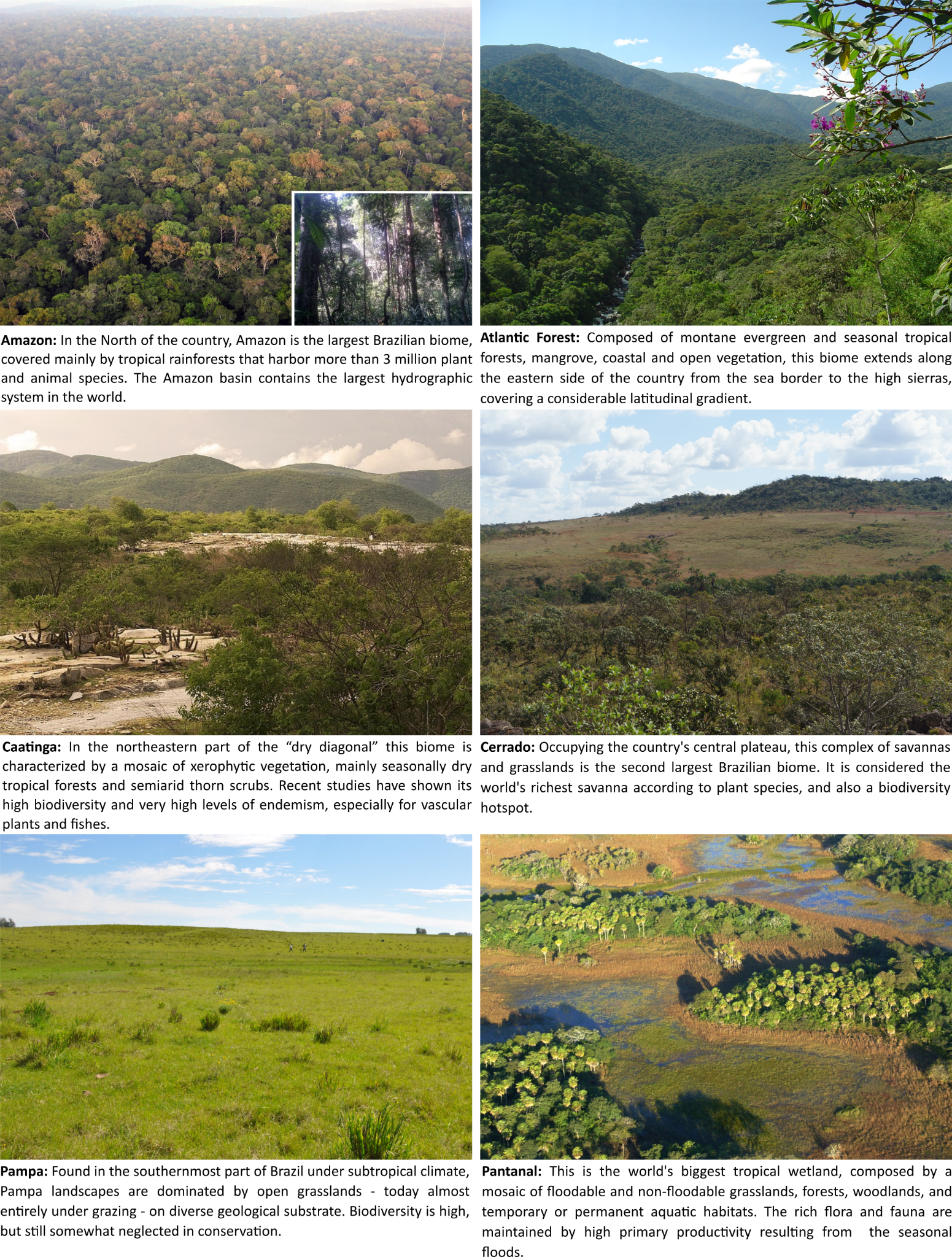
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Fig. 1. Brazilian continental biomes (according to IBGE, 2004). (Photos: Hans ter Steege [Amazon], Dário Amaral [Amazon detail], ICMBio [Atlantic Forest], Wikimedia commons [Caatinga], Valério Pillar [Cerrado and Pampa], Walfrido Tomas [Pantanal]).

**Detailed answers for the frequently asked questions presented in Box 3 (main text):**

**1- Burning vegetation in Brazil is legal?**

Yes, according to specific legislation. Brazilian legislation has allowed the use of fire in agriculture since the First Forest Code of 19341. From that year on, authorization for the practice of fire was required from landowners. The Forest Code of 19652 emphasized the protection of native vegetation integrity and the prevention, combat and control of fire. According to the Law for Protection of Native Vegetation3(Law 12.651/2012, often referred to as *New Forest Code*) controlled or prescribed burning (see Box 1 for definition) is permitted in fire prevention and fighting practices, as well as in subsistence agriculture of traditional and indigenous populations. Federal legislation (Decree 2,661/1998)4 establishes precautionary rules regarding the use of fire in agricultural and forestry practices, but the procedures vary among states according to specific legislation. According to the Environmental Crimes Law (Law No. 9,605/1998)5, starting a wildfire implies a prison sentence of two to four years and a penalty.

**2- Have Brazillian rainforests become more flammable in recent years?**

Yes. Recurrent forest fires are opening up the rainforest canopy, changing its structure and composition, which make them more flammable. The rainforests are strongly connected with hot and humid climate, forming a two-way interacting system, and any unbalance in the water cycle, such as drought, will have impacts on vegetation (Marengo et al., 2018). There is clear scientific evidence of an increase in Amazon flammability (Nepstad et al., 2001), and the interaction between deforestation and drought make the Amazon rainforest more flammable (Aragão et al., 2008; Alencar et al., 2015).

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Forest Code of 1934 was the popular name given to Decree 23.793, of 23 January 1934. This was Brazil’s ﬁrst comprehensive regulation about forests.

2 Forest Code of 1965 was the popular name given to Law 4.771, 15 September 1965.

3 The Law for Protection of Native Vegetation from 2012 (n. 12.651/2012), which substituted the Brazilian Forest Code from 1965. <http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Lei/L12651.htm>

4 Decree 2,661/1998 establish precautionary rules regarding the use of fire in agricultural and forestry practices. <http://www.planalto.gov.br/ccivil_03/decreto/D2661.htm>

5 Law No. 9,605/1998 regulates criminal and administrative sanctions against individuals and companies. <http://www.planalto.gov.br/ccivil_03/leis/L9605.htm>

A lengthening of the dry season in the southern Amazon since the 1970’s has been observed, and, due to the late onset of the rainy season, this may induce a high risk of fire, as observed in the droughts of 2005, 2010, 2016 (Marengo et al., 2018). Drought conditions and higher temperatures can substantially increase fire intensity (Cochrane and Laurance, 2008) and forest flammability by directly increasing air dryness (Brando et al., 2019). According to a recent study (Staal et al., 2020), deforestation has caused 4% of the recent observed drying, with the south-western part of the Amazon being most strongly affected. The link between drought severity, fuel availability, and fire activity has created optimal conditions for mega-fires (defined in Box 1) in the eastern Amazon (Aragão et al., 2018). Also, climate change makes Amazon’s climate hotter and drier particularly in the southern and eastern sections, thus increasing the likelihood of uncontrolled fires (Brando et al., 2019). According to Marengo et al. (2018), forest fires, drought, and logging increase flammability and thus, susceptibility to further burning, while deforestation and smoke can inhibit rainfall, exacerbating fire risk.

**3- How does burning of the Amazon forest affect other regions?**

The Amazon is an important source of incoming moisture for several regions over South America all year round, especially to the La Plata river basin and adjacent areas such as Pantanal and Andean regions (Zemp et al., 2014; Gimeno et al., 2020). The transport of water vapor happens in relatively narrow spaces of the atmosphere nicknamed “atmospheric rivers” (Marengo et al., 2021). The water from the Amazon is exported out of the basin, transported via these atmospheric rivers along the Andes (Arraut et al., 2012; Nobre, 2014), distributing moisture from the entire Amazon basin into the La Plata basin and the Andean Amazon region, producing rainfall over the Pantanal and the agricultural lands of west-central Brazil, in the Cerrado region. This system also transports smoke and aerosols from biomass burning of the Amazon forest to adjacent regions favoring atmospheric pollution over cities in those regions (Marengo et al., 2020). Burning the forest reduces atmospheric water circulation in South America by decreasing the forest ability to contribute to the transport of atmospheric water and cloud formation from evapotranspiration (Staal et al., 2020; Marengo et al., 2018). This affects large parts of the continent, impacting natural ecosystems and economic activities.

**4- Have the 2020 burns been caused by climate change?**

The southern Amazon and Pantanal regions experienced drought conditions in 2019-2020, with weak summertime rainy seasons and below-normal precipitation from July to October across most of Peru, Paraguay, and the Bolivian lowlands. Fires are primarily driven by drier seasonal conditions and occur in association with human management: farmers or ranchers clearing existing farmland, or illegal land-grabbers destroying the forest. As witnessed in 2019, wildfires scorched vast areas of the southern Amazon region and northern Paraguay, fires also burned the Amazonian forests of Bolivia, Brazil, and Peru during the year. Deficient rainfall was detected over the Upper Parana River basin in 2019 and until mid-2020, with up to 300 mm/month below normal, particularly over the Brazilian Pantanal, clearly indicating the severe to exceptional drought (Marengo et al., 2021). The drought situation in Pantanal and the Upper Paraguay River basin has spread devastation, with dry and warm conditions that favor propagation of fires, affect human activities and biodiversity, with an increase in the number of fires in the region. While it is not possible to clearly establish causal relationships, we know that climate change may affect the fire regimes by increasing water stress and the length of the dry season, and thus inducing a higher risk of fire. A drier and warmer regime together with a longer dry season may alter conditions that lead to increased fire season. In 2010, the drought was similar or less intense than the drought of 2005 and perhaps a lot of material that did not burn in 2005 burned in 2010. A similar situation was reported since the end of 2018 with fire consuming in 2020 dry matter stored during the dry year of 2019. However, to attribute the causes of the droughts of 2005, 2010, 2016 and 2019/2020 to climate change is not easy. While extremes may be becoming more frequent and intense under global warming, land use change amplifies this effect. In the Amazon, especially in the south-western part, Staal et al. (2020) attribute greater effect of deforestation on environmental drought - which has increased the length of dry season - than to climatological conditions over the early 21st century. Projections of climate change did not include observed land use (urbanization, deforestation). Recent projections of climate from the CMIP6 models from IPCC (Tebaldi et al., 2021) suggest for the Amazon region a strong drying and warming signal by the end of this century. However, climate models do not project changes in land use due to deforestation, and from what it is seen in the present, drier and warmer conditions together with increased deforestation are a perfect recipe for intense fire seasons.

**5- Is Cerrado a degraded forest associated with fire?**

In Brazil (as in some other countries) there is a tendency to disregard non-forest vegetation in the conservation debate (e.g., Overbeck et al., 2015), partly due to a cultural influence inherited from first European colonists and partly due to lack of knowledge about the richness and specificity of the savannas and grasslands biodiversity. Until today, many people still consider the Cerrado as a degraded forest type, which is totally inappropriate. The Cerrado is clearly not the consequence of forest degradation; it comprises a great variety of environments, from grasslands to woodland, which shelter a very rich flora (more than 12.000 species of plants, Forzza et al., 2012) that have developed over the past 4-5 million years (Simon et al., 2009) under the influence of a seasonal tropical climate and fire. The Cerrado is also extremely diverse in terms of fauna (1573 species of terrestrial vertebrates and thousands of invertebrates), and indeed is considered the richest savanna in the world (Klink and Machado, 2005). The use of the term “savannization” for a degraded tropical forest in reference to a savanna-like physiognomy acquired after strong disturbance is also inappropriate: degradation makes tropical forests more open, and a herb layer with graminoids may develop. This means that structure of a degraded tropical forest may somehow resemble that of a savanna, but, apart from that, these degraded systems do not share similarities with a biodiverse natural savanna.

**6- What are the effects of fire on Brazil's grass-dominated ecosystems?**

Ecosystems dominated by C4 grasses are highly flammable, but the large majority of the species that are found in these systems are well adapted to fire. This is the case for tropical savannas around the world, and also for grasslands and savannas in the Cerrado, Pantanal and Pampa, as well as in the Atlantic and Amazon Forests where they are found in mosaics with fire-sensitive forests. After a grassland or savanna fire, we usually see a quick resprouting of vegetation and, likewise, a return of typical fauna. Soil invertebrate communities and soil processes, such as detritivores and litter decay, return to pre-fire levels within rather short periods - in less than a year in the Pampa grasslands (e.g. Podgaiski et al., 2014) or up to two years for several arthropod groups in the Cerrado (Vasconcelos et al., 2009) - showing the resilience to burnings in fire-dependent ecosystems. Under a natural fire regime, most landscapes will be composed of mosaics of sites with different fire history, e.g. depending on topographic conditions, which leads to high biodiversity on the landscape scale, possibly increased by interactions with grazing animals. In these fire-shaped environments, fire exclusion usually leads to loss of biodiversity (e.g. Abreu et al., 2017). However, when wildfires extend over large areas becoming mega-fires - as in the 2017 Cerrado or in the 2020 Pantanal burns (Fidelis et al., 2018; Marengo et al., 2021), there can be high mortality of wildlife who cannot shelter.

In planted pastures a number of exotic grasses are used as cattle fodder, which under livestock management are not burned. However, several of these exotic grasses (e.g., *Urochloa* spp., *Megathyrsus maximum*, *Andropogon gayanus*, *Melinis minutiflora*, *Hyparrhenia rufa*) become invasive of adjacent natural areas of grasslands, savannas or even at forest borders. These C4 grasses grow very quickly and, when not consumed by native animals, accumulate great amounts of biomass in short periods of time. In the dry season, their biomass dries out and becomes very flammable, bringing high risk of wildfire to the environment. Some of these species have been shown to influence fire behaviour (higher flames, higher temperatures), the fire regimes, and also the recovery of post-fire native communities (D’Antonio and Vitousek, 1992; Silvério et al., 2013; Gorgone-Barbosa et al., 2015). Exotic grasses are an immense problem when not properly managed (in pastures) or when invasive in natural areas.

**7- How do fire and grazing interact?**

Tropical and sub-tropical grass-dominated ecosystems in Brazil (including the Pampa grasslands, open Cerrado physiognomies and Pantanal lowlands) are resilient to periodical fire and grazing, as they have evolved in the presence of these disturbances. Large native herbivores that existed in these regions got extinct about 10.000 years ago, but after the European colonization they were replaced by domestic cattle, who have taken the ecological role of the native megafauna, although grazing effects vary among species. A strong interaction exists between fire and grazing in grassy environments. Recently burned vegetation, especially grasses, have higher nutritious value and soft tissues, which make them much more palatable to both native and exotic grazers (Wright, 1974), who thus concentrate grazing in the burned patches. Biomass, which is the main driver of vegetation fires in these open ecosystems (Rissi et al., 2017), especially when desiccated, is then significantly reduced by grazing, and consequently the risk of fire outbreaks is also reduced in the grazed patches. This dynamics creates a mosaic of high- and low-fuel patches in the landscape (Leonard et al., 2010), where the latter act as firebreaks. The high-fuel patches (less palatable grasses) would be more likely to burn in following years, which in turn would make them more attractive to grazers. Altogether, this leads to a strong and complex interaction between fire and grazing in grass-dominated systems, where positive and negative feedback mechanisms determine spatiotemporal dynamics (see Allred et al., 2011). The maintenance of a mosaic landscape favors the fire-dependent species and also provides shelter for those species less dependent on fire. From a biodiversity conservation perspective, a combination of fire and grazing can thus be very advantageous.

**8- Is cattle husbandry good for preventing fires in the Pantanal?**

In fire-dependent biomes as Pantanal, where dry season is pronounced, grasses tend to dry out completely, being the dry biomass highly flammable; if accumulated over a few years, it can represent high risk of wildfire. Cattle grazing reduces grass biomass, consequently reducing fuel (dry biomass) for subsequent fires. In the Pantanal, traditional livestock farming has been taking place for over 200 years in native pastures and on an extensive basis (Pott and Pott, 2004). Native pasture in Pantanal occupies twice the area of exotic pastures (Souza et al., 2020) and its management includes prescribed fires to reduce unpalatable species or to enhance palatability of those used by cattle (Santos et al., 2004). However, in the last 20 years and mainly in the northern part of the Pantanal, cattle breeding has intensified in higher lands not subjected to periodic flooding and on pastures planted with exotic forage species. Increasing cattle in these areas that are not under a burning management will not reduce the buildup of fuel on native pastures under the typical flooding regime (as they feed on exotic planted species). The claim that more grazing animals prevent wildfires in the Pantanal based on linking total herd numbers and fire risk thus does not make sense; instead, the specific and complex livestock management system in the Pantanal has to be considered, as well as the areas affected by management and disturbances.

**9- What are the effects of ground fires in wetlands?**

Ground fires (definition in Box 1) occur in organic deep soils known as Histosols - formed by the accumulation of a great amount of organic matter (peat, humus) - when they dry out and come in contact with a fire source. This usually happens in wetlands, which in the Brazilian territory include water-logged forests in the Amazon lowlands, wet grasslands and swampy palm groves (*veredas*) in the Cerrado, and periodically flooded grasslands and savannas of the Pantanal. Ground fires can only occur under prolonged drought conditions, such as in 2020 in the Pantanal, and usually bring very harmful effects to the ecosystem. Temperatures at ground fires smoldering combustion are relatively low (500-700°C) compared to flaming fires (Watts and Kobziar, 2013), however, the process is long-lasting (several days or even months) and spreads to great depths in the soil, consuming roots, sprouts and seeds, killing all kinds of plants, damaging the community of soil decomposers, and making ecosystem recovery very difficult. In addition to local effects, these fires can also produce hydrologic changes at larger spatial scales, by changing the soil elevation and the water potential volume of isolated wetlands when these areas are flooded. Still, the burning of large stocks of carbon from biomass accumulated over decades or centuries releases greenhouse gases to the atmosphere. According to Langmann and Heil (2004) such emissions can be 75% higher per hectare than those of aboveground vegetation fires. Besides, the smoke from ground fires - continuously produced over weeks or months - can be a concern for human health (Watts and Kobziar, 2013). Ground fires are very difficult to extinguish because they advance deep into the soil and spread laterally far underground. These fires are still very little understood (Watts and Kobziar, 2013), and in Brazil, studies are even more missing.

**10- What are the economic consequences of wildfires?**

Large wildfires have enormous economic impacts. The 1998 fires in the Amazon caused a damage of US$ 9 billion to local and regional economies (de Mendonça et al., 2004). De Oliveira et al. (2019) estimated that wildfires in the Amazon cause the loss of 2% of the timber that could be harvested between 2012 and 2041; the economic impact of fire-induced degradation amounts to an annual average loss of US$ 29 ± 4 million. Further costs for society can arise from effects on health care systems (e.g., due to air pollution) or of infrastructure and from reduction of ecosystem services that are often very difficult to quantify. Beyond overall costs, burdens can be very high for individual people (e.g., in the case of direct losses of lives, property, or production values). In the long run, catastrophic wildfires and their effects contribute to the aggravation of climate change, with immense costs to society and future generations. While fire management itself leads to considerable costs, e.g. for prevention measures (Thomas et al., 2017), the combat of wildfires is much more costly than prevention. In 2020 the costs only of aerial support to combat the Pantanal burns was around R$ 11,000,000.00 (more than US$ 2,000.0000.00; data compiled by C. Berlinck, ICMBio).

Overall data on economic effects of fire in Brazil, considering prevention, combate and (potential) economic effects, are still scarce and not systematically available. Better information is needed for more efficient fire management in Brazilian ecosystems, be they fire-sensitive or fire-dependent. To invest only in fire suppression is not an economically intelligent decision, especially ecosystems where fire is a component of the ecosystem (Snider et al., 2006). The direct costs of firefighting in the Pantanal in 2020 are at least 5 times higher than those related to prevention activities, including environmental education and articulation with communities, prescribed and controlled burns, environmental surveillance, even with helicopters (data compiled by C. Berlinck, ICMBio).

**11- Do fires affect the biodiversity of aquatic ecosystems and water quality?**

Apart from the direct consequences of fire on riparian and wetland vegetation, there are consequences of fire disturbance on ecosystem processes at two different time scales: in the short-term, seasonal or interannual increases in runoff, and, in the long term, greater erosion. In the short term, fire can reduce cover of macrophyte vegetation, increase insolation and temperature of water, however, the consequences in long term will depend on the velocity of vegetation resprouting (Bixby et al., 2015). In relation to physicochemical conditions, fire can elevate C, N and P concentrations in water and also change turbidity, conductance and reduce dissolved O2. These changes occur just after the wildfire or after the first rains, but pre-fire conditions may not be recovered even after years (Diemer et al., 2015). Concerning aquatic animals, ashes in high concentration can kill native fish (Gonino et al., 2019a; Gonino et al., 2019b) and the toxicity to invertebrates will depend on the ashes chemical composition (Harper et al., 2019). We can expect these effects to greatly depend upon the extent of fires as well: when large areas burn, nutrient and ash concentrations in aquatic systems can be very high over large scales, while smaller fires have less impact. However, this topic is poorly explored for neotropical ecosystems and it needs further investigation.

**12- How do animals cope with fire? How does fire affect wildlife?**

Common effects of fire on the fauna in fire-dependent and fire-sensitive biomes can be summarized as: 1) direct or first-order effects occurring immediately or over a short time period after fire; 2) second-order or indirect effects, such as vegetation succession, which vary according to fire attributes, fire history and vegetation type; and 3) evolutionary responses of animals to fire regimes (Whelan et al., 2002; Engstrom, 2010; Pausas and Parr, 2018). Fire may affect most animal species in a given area depending on the speed, intensity and spatial pattern (Lyon et al., 1978; Sinsch, 1990; Whelan et al., 2002; Silva et al., 2020). Fire often kills individuals (Tekalign and Kebed, 2016), but not all animals die from direct fire effects, thus, fire detection and avoidance are essential for survival, especially for less-mobile animals. The immediate responses of individual vertebrates to fire range from panic to calm escape away from fire (Whelan, 1995). Less mobile species (e.g. *Xenarthra* - Silva et al. 2020) or stages (e.g. egg, young) are more vulnerable and can become exposed to heat, oxygen depletion, flames or smoke. Direct impacts tend to be lower on the more mobile species (e.g. flying birds) that seek refuges in non-burned patches, on species living or nesting deep in the soil (such as some invertebrates; Vasconcelos et al., 2017), and those who seek shelter in burrows (e.g. rodents), as they tend to be eventually protected from the direct effects of heat and flames (Frizzo et al., 2011). However, the surviving portions of wildlife populations, both vertebrate and invertebrates, are often exposed to second order or indirect effects of fire, the most important coming from changes in the vegetation, such as burning impacts on resources quality, availability, and productivity (Komarek, 1963; Lousada et al., 1996; Naves, 1996; Cain et al., 1998; Smith, 2000; Firth et al., 2005; Crowley, 2008; Barlow and Peres, 2006; Roberts et al., 2008; Andersen et al., 2012; Alvarado et al., 2014). Repeated, intense or extensive burnings often increase post-fire starvation for most animals, with potential long-term consequences for small populations or species that require more time to recover (Silveira et al., 1999; Pires et al., 2005; Barlow and Peres, 2006; Woinarski and Legge, 2013; Pausas and Parr, 2018). Indirect effects of fire also include increased predation during displacement from the affected area (Andersen et al., 2012; Woinarski and Legge, 2013) and susceptibility to hunting (Peres et al., 2003).

In fire-dependent biomes (e.g., Cerrado, Pantanal) fire usually stimulates the regrowth, flowering and fruiting of many plant species, which in a short time after fire start to offer a great amount of food (e.g. Jharlya and Raj, 2014; Tunes et al., 2017; Pilon et al., 2018; Pausas and Keeley, 2019; Pilon et al., 2021). But fire effects on animal populations will largely depend on the fire regime (Box 1). Mild fires in a proper frequency maintain habitat heterogeneity, which may increases biodiversity at large spatiotemporal scales (Maravalhas and Vasconcelos, 2014) and contributes to the maintenance of habitat quality for most species that are adapted to open and semi-open physiognomies (Abreu et al., 2017). On the other hand, highly frequent and/or intense fires change overall ecosystem structure and functioning, decreasing habitat suitability and resource availability to the animals, that may lead to species declining and even local extinctions (Bond and Keeley, 2005; Andersen et al., 2012). Therefore, probably the best strategy to conserve endemic, rare, or endangered fauna in fire-dependent biomes is to maintain a mosaic of areas subjected to different fire regimes at landscape scale (e.g., Andersen et al. 2012; Costa et al., 2020). In contrast, fire is a disaster to fauna in fire-sensitive biomes, such as the Amazon and Atlantic rainforests and other similar ecosystems around the world (Kinnaird and O’Brien, 1998). For instance, a single fire is enough to promote local extinction of some forest-specialist species in the Amazon, and drop fruit production - an important food source for many forest-dwelling animals - for many years (Peres et al., 2003, Barlow and Peres, 2006). The endemic fauna that still persists in the highly fragmented Atlantic forest (Tabarelli et al., 2010) is especially threatened by fire, as most fragments are embedded in a matrix of human-managed habitats dominated by pastures, croplands and urban areas where fire may be common (Guedes et al., 2020). In these cases, disturbance by fire may exacerbate the negative impacts of habitat loss and fragmentation (Barlow et al., 2016). Therefore, a proper use of fire to manage the vegetation such as prescribed burnings and other approaches to meet an integrated fire management are of great importance to fauna in fire-sensitive biomes and mosaic landscapes, in both protected areas and private lands of the Atlantic Forest (e.g., the southern and southeastern highland grasslands).

**13- What are the effects of fire on soil properties and soil organic matter?**

Fire effects are mostly visible on vegetation, but fire itself and the altered post-fire conditions can affect soil properties, such as aggregate stability, pore size and distribution (and soil compaction, water repellency), pH, carbon and nutrient 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). However, there is limited knowledge about the impact of vegetation fires on the soils of Brazilian ecosystems; the high variability of soil properties and attributes even in a small spatial scale (Wilding and Dress, 1983) creates a complex backdrop to assess fire effects on ecosystems. Moreover, integrated studies of fire effects on soils are scarce.

Fire frequency, intensity and duration are key aspects that determine the effects of burning on soil nutrient status, C and N stocks and biological properties. Soils are good insulators, and in mineral soils, fire heat mostly affects the topsoil. Quick surface fires that normally happen in fire-dependent ecosystems do not heat depths greater than a few centimeters, and even so, the temperature rise is of a few degrees. In the Cerrado, Coutinho (1990) and Miranda et al. (1993) registered temperatures of 45 to 55°C at 1 cm depth under prescribed fires. Such low temperatures do not change soil physical properties. Regarding soil chemical conditions, the short-term impact is generally an addition of nutrients and reduction of acidity at the surface soil due to ash deposition. Therefore, vegetation burnings temporarily modify the acidic and chemically poor soils of Cerrado. Pivello et al. (2010) studied plots under different fire regimes during 18 years in the Cerrado and found evidence of long-term effects of fire frequency on soil nutrients and acidity: lower pH in the unburned and quadrennially burned plots, and also higher amount of exchangeable cations in these last. However, effects had not been noticed regarding the burning season. In a review of burning effects on soil carbon and nitrogen at 48 sites based on a 65-year time scale Pellegrini et al. (2018) could observe long-term fire effects on C and N pools at surface (20 cm depth) in tropical savannas. Such long-term losses of soil-N could impact plant productivity and decrease C sequestration by 20% of the total carbon emitted from biomass burning in the 63-year period of the simulation. Rheinheimer et al. (2003) found, in southern Brazil, only short-term effects on several soil attributes after a single grassland fire event.

In the Amazon, indigenous peoples and small farmers take advantage of the fertilizing effect of ashes coming from the burned vegetation in swidden cultivation, but the effects are short lived (Silva Neto et al., 2019; Sanchez, 2019). In forests, fire effects on soil are usually more pronounced because there is more organic matter, so the heating is greater and penetrates to greater depths. González-Pérez et al. (2004) summarized some long-lasting effects of fire on soil organic matter composition and dynamics: biomass burning is usually incomplete, producing a range of pyrolysis compounds and particulate organic matter, and giving rise to “pyromorphic humus” - quasi-colloidal macromolecular substances - with chemical and biological recalcitrance. The main transformations exerted by fire on soil humus include the accumulation of new particulate C forms highly resistant to oxidation and biological degradation, including the so-called “black carbon”. The effect of fire on the total soil organic matter content is also variable and dependent on multiple factors. In wetlands but also in rainforest, ground fires (Box 1) may occur under exceptionally dry conditions (see Question 9), causing large impact on soils, in contrast to surface or crown fires. However, their occurrence is restricted to organic soils (Histosols), as mineral soils would not provide enough fuel for sustained combustion. Ground fires usually consume all the soil organic matter and change physical soil properties which lead to increased compaction, decreased permeability and aeration, and water repellency. Moreover, direct severe damages to plants occur, whose roots and seeds are killed, consequently, germination and survival will be negatively impacted (Watts and Kobziar, 2013).

In conclusion, fire might lead to contrasting situations: it may both fertilize or deplete soil nutrients, damage or not affect soil physical properties, depending on a number of factors, essentially fire regime (Box 1), soil type, environmental moisture, vegetation type and composition. With such a high number of variables and limited studies so far it is difficult to make broad generalizations of the effects of fire on soil properties across systems or fire regimes.

**References**

Abreu, R.C.R., Hoffmann, W.A., Vasconcelos, H.L., Pilon, N.A., Rossatto, D.R., Durigan, G., 2017. The biodiversity cost of carbon sequestration in tropical savanna. Sci. Adv. 3, 1–8.

Alencar, A.A., Brando, P.M., Asner, G.P., Putz, F.E., 2015. Landscape fragmentation, severe drought, and the new Amazon forest fire regime. Ecol. Appl. 25, 1493–1505. https://doi.org/10.1890/14-1528.1

Allred, B.W., Fuhlendorf, S.D., Engle, D.M., Elmore, R.D., 2011. Ungulate preference for burned patches reveals strength of fire-grazing interaction. Ecol. Evol. 1, 132–144. https://doi.org/10.1002/ece3.12

Alvarado, S.T., Buisson, E., Rabarison, H., Rajeriarison, C., Birkinshaw, C., Lowry, P.P., Morellato, L.P.C., 2014. Fire and the reproductive phenology of endangered Madagascar sclerophyllous tapia woodlands. South African J. Bot. 94, 79–87. https://doi.org/10.1016/j.sajb.2014.06.001

Andersen, A.N., Woinarski, J.C.Z., Parr, C.L., 2012. Savanna burning for biodiversity: Fire management for faunal conservation in Australian tropical savannas. Austral Ecol. 37, 658–667. https://doi.org/10.1111/j.1442-9993.2011.02334.x

Aragão, L.E.O.C., Malhi, Y., Barbier, N., Lima, A., Shimabukuro, Y., Anderson, L., Saatchi, S., 2008. Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. Philos. Trans. R. Soc. B Biol. Sci. 363, 1779–1785. https://doi.org/10.1098/rstb.2007.0026

Arraut, J.M., Nobre, C., Barbosa, H.M.J., Obregon, G., Marengo, J., 2012. Aerial Rivers and Lakes: Looking at Large-Scale Moisture Transport and Its Relation to Amazonia and to Subtropical Rainfall in South America. J. Clim. 25, 543–556. https://doi.org/10.1175/2011JCLI4189.1

Barlow, J., Peres, C.A., 2006. Effects of Single and Recurrent Wildfires on Fruit Production and Large Vertebrate Abundance in a Central Amazonian Forest. Biodivers. Conserv. 15, 985–1012. https://doi.org/10.1007/s10531-004-3952-1

Barlow, J., Lennox,G.D., Ferreira, J., Berenguer, E., Lees, A.C., Mac Nally, R., Thompson, J.R., Ferraz, S.F.B., Louzada, J., Oliveira, V.H.F., Parry, L., Solar, R.R.C., Vieira, I.C.G., Aragão, L.E.O.C., Begotti, R.A., Braga, R.F., Cardoso, T.M., Oliveira Jr., R.C., Souza Jr., C.M., Moura, N.G., Nunes, S.S., Siqueira, J.V., Pardini, R., Silveira, J.M., Vaz-de-Mello, F.Z., Veiga, R.C.S., Venturieri, A., Gardner, T.A. 2016. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. Nature 535, 144-147. https://doi.org/doi:10.1038/nature18326

Bixby, R.J., Cooper, S.D., Gresswell, R.E., Brown, L.E., Dahm, C.N., Dwire, K.A., 2015. Fire effects on aquatic ecosystems: an assessment of the current state of the science. Freshw. Sci. 34, 1340–1350. https://doi.org/10.1086/684073

Bond, W.J., Keeley, J.E., 2005. Fire as a global ‘herbivore’: the ecology and evolution of flammable ecosystems. Trends Ecol. Evol. 20, 387–394. https://doi.org/10.1016/j.tree.2005.04.025

Brando, P.M., Paolucci, L., Ummenhofer, C.C., Ordway, E.M., Hartmann, H., Cattau, M.E., Rattis, L., Medjibe, V., Coe, M.T., Balch, J., 2019. Droughts, Wildfires, and Forest Carbon Cycling: A Pantropical Synthesis. Annu. Rev. Earth Planet. Sci. 47, 555–581. https://doi.org/10.1146/annurev-earth-082517-010235

Cain, M.D., Wigley, T.B., Reed, D.J., 1998. Prescribed fire effects on structure in uneven-aged stands of loblolly and shortleaf pines. Wildl. Soc. Bull. 26, 209–218.Cochrane and Laurance, 2008

Costa, B.M., Pantoja, D.L., Sousa, H.C., de Queiroz, T.A., Colli, G.R., 2020. Long-term, fire-induced changes in habitat structure and microclimate affect Cerrado lizard communities. Biodivers. Conserv. 29, 1659–1681. https://doi.org/10.1007/s10531-019-01892-8

Coutinho, L.M., 1990. Fire in the Ecology of the Brazilian Cerrado. In: Goldamer, J.G. (Ed.), Fire in the Tropical Biota Ecosystem: Processes and Global Challenges. Ecological Studies 84, pp. 82–105.

Crowley, G., 2008. Cockatoo grass Alloteropsis semialata as a keystone species in northern Australia. N. Terr. Nat. 20, 58–63.

D’Antonio, C.M., Vitousek, P.M., 1992. Biological Invasions by Exotic Grasses, the Grass/Fire Cycle, and Global Change. Annu. Rev. Ecol. Syst. 23, 63–87. https://doi.org/10.1146/annurev.es.23.110192.000431

de Mendonça, M.J.C., Vera Diaz, M. del C., Nepstad, D., Seroa da Motta, R., Alencar, A., Gomes, J.C., Ortiz, R.A., 2004. The economic cost of the use of fire in the Amazon. Ecol. Econ. 49, 89–105. https://doi.org/10.1016/j.ecolecon.2003.11.011

de Oliveira, A.S., Rajão, R.G., Soares Filho, B.S., Oliveira, U., Santos, L.R.S., Assunção, A.C., van der Hoff, R., Rodrigues, H.O., Ribeiro, S.M.C., Merry, F., de Lima, L.S., 2019. Economic losses to sustainable timber production by fire in the Brazilian Amazon. Geogr. J. 185, 55–67. https://doi.org/10.1111/geoj.12276

Diemer, L.A., McDowell, W.H., Wymore, A.S., Prokushkin, A.S., 2015. Nutrient uptake along a fire gradient in boreal streams of Central Siberia. Freshw. Sci. 34, 1443–1456. https://doi.org/10.1086/683481

Doerr, S.H., Cerdá, A., 2005. Fire effects on soil system functioning: new insights and future challenges. Int. J. Wildl. Fire 14, 339–342.

Engstrom, R.T., 2010. First-Order Fire Effects on Animals: Review and Recommendations. Fire Ecol. 6, 115–130. https://doi.org/10.4996/fireecology.0601115

Fidelis, A., Alvarado, S., Barradas, A., Pivello, V., Fidelis, A., Alvarado, S.T., Barradas, A.C.S., Pivello, V.R., 2018. The Year 2017: Megafires and Management in the Cerrado. Fire 2018, Vol. 1, Page 49 1, 49. https://doi.org/10.3390/FIRE1030049

Firth, R.S.C., Jefferys, E., Woinarski, J.C.Z., Noske, R.A., 2005. The diet of the brush-tailed rabbit-rat (Conilurus penicillatus) from the monsoonal tropics of the Northern Territory, Australia. Wildl. Res. 32, 517–523.

Forzza, R.C., Baumgratz, J.F.A., Bicudo, C.E.M., Canhos, D.A.L., Carvalho, A.A., Coelho, M.A.N., Costa, A.F., Costa, D.P., Hopkins, M.G., Leitman, P.M., Lohmann, L.G., Lughadha, E.N., Maia, L.C., Martinelli, G., Menezes, M., Morim, M.P., Peixoto, A.L., Pirani, J.R., Prado, J., Queiroz, L.P., Souza, S., Souza, V.C., Stehmann, J.R., Sylvestre, L.S., Walter, B.M.T., Zappi, D.C., 2012. New Brazilian Floristic List Highlights Conservation Challenges. Bioscience 62, 39–45. https://doi.org/10.1525/bio.2012.62.1.8

Frizzo TLM et al. 2011. Revisão dos efeitos do fogo sobre a fauna de formações savânicas do Brasil. Oecologia Australis 15: 365-379.

Gimeno, L., Vázquez, M., Eiras-Barca, J., Sorí, R., Stojanovic, M., Algarra, I., Nieto, R., Ramos, A.M., Durán-Quesada, A.M., Dominguez, F., 2020. Recent progress on the sources of continental precipitation as revealed by moisture transport analysis. Earth-Science Rev. 201, 103070. https://doi.org/10.1016/j.earscirev.2019.103070

Gonino, G.M.R., Figueiredo, B.R.S., Manetta, G.I., Zaia Alves, G.H., Benedito, E., 2019a. Fire increases the productivity of sugarcane, but it also generates ashes that negatively affect native fish species in aquatic systems. Sci. Total Environ. 664, 215–221. https://doi.org/10.1016/j.scitotenv.2019.02.022

Gonino, G., Branco, P., Benedito, E., Ferreira, M.T., Santos, J.M., 2019b. Short-term effects of wildfire ash exposure on behaviour and hepatosomatic condition of a potamodromous cyprinid fish, the Iberian barbel Luciobarbus bocagei (Steindachner, 1864). Sci. Total Environ. 665, 226–234. https://doi.org/10.1016/j.scitotenv.2019.02.108

González-Pérez, J.A., González-Vila, F.J., Almendros, G., Knicker, H., 2004. The effect of fire on soil organic matter – a review. Environ. Int. 30, 855–870. https://doi.org/10.1016/j.envint.2004.02.003

Gorgone-Barbosa, E., Pivello, V.R., Bautista, S., Zupo, T., Rissi, M.N., Fidelis, A., 2015. How can an invasive grass affect fire behavior in a tropical savanna? A community and individual plant level approach. Biol. Invasions 17, 423–431. https://doi.org/10.1007/s10530-014-0740-z

Guedes, B.J., Massi, K.G, Evers, C., Nielsen-Pincus, M. 2020. Vulnerability of small forest patches to fire in the Paraiba do Sul River Valley, southeast Brazil: Implications for restoration of the Atlantic Forest biome. For. Ecol. Man. 465, 118095. https://doi.org/10.1016/j.foreco.2020.118095

Harper, A.R., Santin, C., Doerr, S.H., Froyd, C.A., Albini, D., Otero, X.L., Viñas, L., Pérez-Fernández, B., 2019. Chemical composition of wildfire ash produced in contrasting ecosystems and its toxicity to Daphnia magna. Int. J. Wildl. Fire 28, 726–737.

IBGE, 2004. Mapa de biomas do Brasil. https://www.ibge.gov.br/geociencias/informacoes-ambientais/15842-biomas.html?=&t=downloads (accessed 27 April 2021).

Jharlya, M.K., Raj, A., 2014. Effects of wildfires on flora, fauna and physico-chemical properties of soil - An overview. J. Appl. Nat. Sci. 6, 887–897.

Kinnaird, M.F., O’Brien, T.G., 1998. Ecological Effects of Wildfire on Lowland Rainforest in Sumatra. Conserv. Biol. 12, 954–956. https://doi.org/10.1046/j.1523-1739.1998.012005954.x

Klink, C.A., Machado, R.B., 2005. Conservation of the Brazilian Cerrado. Conserv. Biol. 19, 707–713. https://doi.org/10.1111/j.1523-1739.2005.00702.x

Komarek, R., 1963. Fire and the changing wildlife habitat. Proc. Tall Timbers Fire Ecol. Conf. 2, 35–43.

Langmann, B., Heil, A., 2004. Release and dispersion of vegetation and peat fire emissions in the atmosphere over Indonesia 1997/1998. Atmospheric Chemistry and Physics 4: 2145- 2160. https://doi.org/10.5194/acp-4-2145-2004

Leonard, S., Kirkpatrick, J., Marsden-Smedley, J., 2010. Variation in the effects of vertebrate grazing on fire potential between grassland structural types. J. Appl. Ecol. 47, 876–883. https://doi.org/10.1111/j.1365-2664.2010.01840.x

Lousada, J.N.C., Schiffer, G., Vaz de Melo, F.Z., 1996. s do fogo sobre a estrutura da comunidade de Scarabaeidae (Insecta, Coleoptera) na Restinga da Ilha de Guiriri-ES, in: Anais Do Simpósio Impacto Das Queimadas Sobre Os Ecossistemas e Mudanças Globais. Brasília, pp. 161–169.

Lyon, L.J., Crawford, H.S., Czuhai, E., Fredriksen, R.L., Harlow, R.E., Metz, L.J., Pearson, H.A., 1978. Effects of fire on fauna: a state-of-knowledge review. U.S. Dept. of Agriculture, Forest Service.

Maravalhas, J., Vasconcelos, H.L., 2014. Revisiting the pyrodiversity–biodiversity hypothesis: long-term fire regimes and the structure of ant communities in a Neotropical savanna hotspot. J. Appl. Ecol. 51, 1661–1668. https://doi.org/10.1111/1365-2664.12338

Marengo, J.A., Souza, C.M., Thonicke, K., Burton, C., Halladay, K., Betts, R.A., Alves, L.M., Soares, W.R., 2018. Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. Front. Earth Sci.

Marengo, J.A., Alves, J., Molina, E., Broedel, E., Cunha, A.P., 2020. SIDEBAR 7.2: Fires in southern Amazonia in the dry season of 2019 [in “State of the Climate in 2019"]. Bull. Amer. Meteor. Soc. 101, S348–S349.

Marengo, J.A., Cunha, A.P.M.A., Cuartas, L.A., Deusdará Leal, K.R., Broedel, E., Seluchi, J.E., Micheline, C., De Praga Bailão, C.E., ngulo, E., Almeida, E.K., Kazmierczak, M.L., Mateus, N.P.A., Silva, R.C., Bender, F., 2021. Extreme Drought in the Brazilian Pantanal in 2019-2020: Characterization, causes and impacts. Frontiers in Water 3, 639204, https://doi.org/10.3389/frwa.2021.639204.

Miranda, A.C., Miranda, H.S., Dias, I.SO., Dias, B.F., 1993. Soil and air temperatures during prescribed Cerrado fires in Central Brazil. J. Trop. Ecol. 9, 313–320, https://doi.org/10.1017/S0266467400007367.

Naves, M.A. 1996. Efeito do fogo na população de formigas (Hymenoptera-Formicidae) em Cerrado do Distrito federal, in: Anais Do Simpósio Impacto Das Queimadas Sobre Os Ecossistemas e Mudanças Globais. Brasília, pp. 170–177.

Neary, D., Leonard, J.L., 2019. Effects of Fire on Grassland Soils and Water - A Review, in: Kindomihou, V.M. (Ed.), Grasses and Grassland Aspects. InTechOpen, London, pp. 1–22.

Nepstad, D., Carvalho, G., Cristina Barros, A., Alencar, A., Paulo Capobianco, J., Bishop, J., Moutinho, P., Lefebvre, P., Lopes Silva, U., Prins, E., 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. For. Ecol. Manage. 154, 395–407. https://doi.org/10.1016/S0378-1127(01)00511-4

Nobre, A.D., 2014. The Future Climate of Amazonia: Scientific Assessment Report. São José dos Campos.

Overbeck, G.E., Vélez-Martin, E., Scarano, F.R., Lewinsohn, T.M., Fonseca, C.R., Meyer, S.T., Müller, S.C., Ceotto, P., Dadalt, L., Durigan, G., Ganade, G., Gossner, M.M., Guadagnin, D.L., Lorenzen, K., Jacobi, C.M., Weisser, W.W., Pillar, V.D., 2015. Conservation in Brazil needs to include non-forest ecosystems. Divers. Distrib. 21. https://doi.org/10.1111/ddi.12380

Pausas, J.G., Keeley, J.E., 2019. Wildfires as an ecosystem service. Front. Ecol. Environ. 17, 289–295. https://doi.org/10.1002/fee.2044

Pausas, J.G., Parr, C.L., 2018. Towards an understanding of the evolutionary role of fire in animals. Evol. Ecol. 32, 113–125. https://doi.org/10.1007/s10682-018-9927-6

Pellegrini, A.F.A., Ahlström, A., Hobbie, S.E., Reich, P.B., Nieradzik, L.P., Staver, A.C., Scharenbroch, B.C., Jumpponen, A., Anderegg, W.R.L., Randerson, J.T., Jackson, R.B., 2018. Fire frequency drives decadal changes in soil carbon and nitrogen and ecosystem productivity. Nature 553, 194–198, <https://doi.org/10.1038/nature24668>.

Peres, C.A., Barlow, J., Haugaasen, T. 2003. Vertebrate responses to surface fires in a Central Amazonian forest. Oryx 37, 97-109. https://doi.org/10.1017/S0030605303000188

Pilon, N.A.L., Hoffmann, W.A., Abreu, R.C.R., Durigan, G., 2018. Quantifying the short-term flowering after fire in some plant communities of a cerrado grassland. Plant Ecol. Divers. 11, 259–266. https://doi.org/10.1080/17550874.2018.1517396

Pilon, N.A.L., Cava, M.G.B., Hoffmann, W.A., Abreu, R.C.R., Fidelis, A., Durigan, G., 2021. The diversity of post-fire regeneration strategies in the cerrado ground layer. J. Ecol. 109:154–166/ https://doi.org/10.1111/1365-2745.13456

Pires, A.S., Fernandez, F.A.S., de Freitas, D., Feliciano, B.R., 2005. Influence of edge and fire-induced changes on spatial distribution of small mammals in Brazilian Atlantic forest fragments. Stud. Neotrop. Fauna Environ. 40, 7–14. https://doi.org/10.1080/01650520412331333747

Pivello, V.R., Oliveras, I., Miranda, H.S., Haridasan, M., Sato, M.N., Meirelles, S.T., 2010. Effect of fires on soil nutrient availability in an open savanna in Central Brazil. Plant Soil 337, 111–123, <https://doi.org/10.1007/s11104-010-0508-x>.

Podgaiski, L.R., da Silva Goldas, C., Ferrando, C.P.R., Silveira, F.S., Joner, F., Overbeck, G.E., de Souza Mendonça, M., Pillar, V.D., 2014. Burning effects on detritivory and litter decay in Campos grasslands. Austral Ecol. 39. https://doi.org/10.1111/aec.12132

Pott, A., Pott, V.J., 2004. Features and conservation of the Brazilian Pantanal wetland. Wetl. Ecol. Manag. 12, 547–552. https://doi.org/10.1007/s11273-005-1754-1

Rheinheimer, D. dos S., Santos, J.C.P., Fernandes, V.B.B., Mafra, Á.L., Almeida, J.A., 2003. Modificações nos atributos químicos de solo sob campo nativo submetido à queima. Ciência Rural 33, 49–55, https://doi.org/10.1590/S0103-84782003000100008.

Rissi, M.N., Baeza, M.J., Gorgone-Barbosa, E., Zupo, T., Fidelis, A., Mariana Ninno Rissi, M. Jaime Baeza, Elizabeth Gorgone-Barbosa, Talita Zupo, Alessandra Fidelis, 2017. Does season affect fire behaviour in the Cerrado? Int. J. Wildl. Fire 26, 427–433. <https://doi.org/10.1071/WF14210>.

Roberts, S.L., van Wagtendonk, J.W., Miles, A.K., Kelt, D.A., Lutz, J.A., 2008. Modeling the Effects of Fire Severity and Spatial Complexity on Small Mammals in Yosemite National Park, California. Fire Ecol. 4, 83–104. https://doi.org/10.4996/fireecology.0402083

Santos, S.A., Crispim, S.M.A., Comastri Filho, J.A., Cardoso, E.L., 2004. Princípios de agroecologia no manejo das pastagens nativas do Pantanal. Embrapa Pantanal-Documentos (INFOTECA-E).

Sanchez, P.A., 2019. Properties and management of soils in the Tropics. Cambridge University Press, Cambridge/New York, 618 p.

Silva, S.M., Santos, P M., Molina, K.T., Lopes, A.M.C., Braga, F.G., Ohana, A., Miranda, F.R., Bertassoni, A,. 2020. Wildfire against the survival of Xenarthra: anteaters, armadillos, and sloths. Bol. Mus. Para. Goeldi. 15: 523–532

Silva Neto, E.C. da, Pereira, M.G., Frade Junior, E.F., Silva, S.B. da, Carvalho Junior, J.A. de, Santos, J.C. dos, 2019. Temporal evaluation of soil chemical attributes after slash-and-burn agriculture in the Western Brazilian Amazon. Acta Sci. Agron. 41, e42609, https://doi.org/10.4025/actasciagron.v41i1.42609.

Silveira, L., Henrique, F., Rodrigues, G., de Almeida Jácomo, A.T., Filho, J.A.F.D., 1999. Impact of wildfires on the megafauna of Emas National Park, central Brazil. Oryx 33, 108–114. https://doi.org/10.1046/j.1365-3008.1999.00039.x

Silvério, D.V, Brando, P.M., Balch, J.K., Putz, F.E., Nepstad, D.C., Oliveira-Santos, C., Bustamante, M.M.C., 2013. Testing the Amazon savannization hypothesis: fire effects on invasion of a neotropical forest by native cerrado and exotic pasture grasses. Philos. Trans. R. Soc. B Biol. Sci. 368, 20120427. https://doi.org/10.1098/rstb.2012.0427

Simon, M.F., Grether, R., de Queiroz, L.P., Skema, C., Pennington, R.T., Hughes, C.E., 2009. Recent assembly of the Cerrado, a neotropical plant diversity hotspot, by in situ evolution of adaptations to fire. Proc. Natl. Acad. Sci. 106, 20359–20364. https://doi.org/10.1073/pnas.0903410106

Sinsch, U., 1990. Migration and orientation in anuran amphibians. Ethol. Ecol. Evol. 2, 65–79. https://doi.org/10.1080/08927014.1990.9525494

Smith, J.K., 2000. Wildland fire in ecosystems: effects of fire on fauna. USDA Forest Service General Technical Report RMRS-GTR-42-Volume 2,. Fort Collins.

Snider, G., Daugherty, P.J., Wood, D., 2006. The Irrationality of Continued Fire Suppression: An Avoided Cost Analysis of Fire Hazard Reduction Treatments Versus No Treatment. J. For. 104, 431–437. https://doi.org/10.1093/jof/104.8.431

Souza, C.M., Z. Shimbo, J., Rosa, M.R., Parente, L.L., A. Alencar, A., Rudorff, B.F.T., Hasenack, H., Matsumoto, M., G. Ferreira, L., Souza-Filho, P.W.M., de Oliveira, S.W., Rocha, W.F., Fonseca, A. V, Marques, C.B., Diniz, C.G., Costa, D., Monteiro, D., Rosa, E.R., Vélez-Martin, E., Weber, E.J., Lenti, F.E.B., Paternost, F.F., Pareyn, F.G.C., Siqueira, J. V, Viera, J.L., Neto, L.C.F., Saraiva, M.M., Sales, M.H., Salgado, M.P.G., Vasconcelos, R., Galano, S., Mesquita, V. V, Azevedo, T., 2020. Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine. Remote Sens. https://doi.org/10.3390/rs12172735

Staal, A., Flores, B.M., Aguiar, A.P., Bosmans, J.H.C., Fetzer, K., Tuinenburg, O.A. 2020. Feedback between drought and deforestation in the Amazon. Environ. Res. Lett. 15, 044024 https://doi.org/10.1088/1748-9326/ab738e

Tabarelli, M., Aguiar, A.V., Ribeiro, M.C., Metzger, J.P., Peres, C.A. 2010. Prospects for biodiversity conservation in the Atlantic forest: Lessons from aging human-modified landscapes. Biol. Cons. 143, 2328-2340. https://doi.org/10.1016/j.biocon.2010.02.005

Tebaldi, C., Debeire, K., Eyring, V., Fischer, E., Fyfe, J., Friedlingstein, P., Knutti, R., Lowe, J., O’Neill, B., Sanderson, B., van Vuuren, D., Riahi, K., Meinshausen, M., Nicholls, Z., Tokarska, K.B., Hurtt, G., Kriegler, E., Lamarque, J.-F., Meehl, G., Moss, R., Bauer, S.E., Boucher, O., Brovkin, V., Byun, Y.-H., Dix, M., Gualdi, S., Guo, H., John, J.G., Kharin, S., Kim, Y., Koshiro, T., Ma, L., Olivié, D., Panickal, S., Qiao, F., Rong, X., Rosenbloom, N., Schupfner, M., Séférian, R., Sellar, A., Semmler, T., Shi, X., Song, Z., Steger, C., Stouffer, R., Swart, N., Tachiiri, K., Tang, Q., Tatebe, H., Voldoire, A., Volodin, E., Wyser, K., Xin, X., Yang, S., Yu, Y., Ziehn, T., 2021. Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. Earth Syst. Dyn. 12, 253–293. https://doi.org/10.5194/esd-12-253-2021

Tekalign, W., Kebed, Y., 2016. Impacts of Wildfire and Prescribed Fire on Wildlife and Habitats: A Review, Journal of Natural Sciences Research.

Thomas, D., Butry, D., Gilbert, S., Webb, D., Fung, J., 2017. The costs and losses from wildfire. NIST Special Publication 1215.

Tunes, P., Alves, V.N., Valentin-Silva, A., Batalha, M.A., Guimarães, E., 2017. Does fire affect the temporal pattern of trophic resource supply to pollinators and seed-dispersing frugivores in a Brazilian savanna community? Plant Ecol. 218, 345–357. https://doi.org/10.1007/s11258-016-0695-5

Vasconcelos, H.L., Pacheco, R., Silva, R.C., Vasconcelos, P.B., Lopes, C.T., Costa, A.N., Bruna, E.M., 2009. Dynamics of the Leaf-Litter Arthropod Fauna Following Fire in a Neotropical Woodland Savanna. PLoS One 4, e7762.

Vasconcelos, H.L., Maravalhas, J.B., Cornelissen, T., 2017. Effects of fire disturbance on ant abundance and diversity: a global meta-analysis. Biodivers. Conserv. 26, 177–188. https://doi.org/10.1007/s10531-016-1234-3

Watts, A.C., Kobziar, L.N., 2013. Smoldering Combustion and Ground Fires: Ecological Effects and Multi-Scale Significance. Fire Ecol. 9, 124–132. https://doi.org/10.4996/fireecology.0901124

Whelan, R., 1995. The Ecology of Fire. Cambridge University Press, Cambridge.

Whelan, R.J., Rodgerson, L., Dickman, C.R., Sutherland, E.F., 2002. Critical life processes of plants and animals: developing a process-based understanding of population changes in fireprone landscapes, in: Bradstock, R.A., Williams, J.E., Gill, A.M. (Eds.), Flammable Australia: The Fire Regimes and Biodiversity of a Continent. Cambridge University Press, Cambridge, pp. 94–124.

Wilding, L.P., Dress, L.R., 1983. Spatial Variability and Pedology, in: Wilding, L.P., Smeck, N.E., Hall, G.F. (Eds.), Developments in Soil Science 11. Elsevier, pp. 83–116.

Woinarski JCZ, and Legge S. 2013. The impacts of fire on birds in Australia’s tropical savannas. EMU 113: 319-352.

Wright, H.A., 1974. Range burning. J. Range Manag. 27.

Zemp, D.C., Schleussner, C.-F., Barbosa, H.M.J., van der Ent, R.J., Donges, J.F., Heinke, J., Sampaio, G., Rammig, A., 2014. On the importance of cascading moisture recycling in South America. Atmos. Chem. Phys. 14, 13337–13359. https://doi.org/10.5194/acp-14-13337-2014

1. Aqui usamos o termo “bioma” seguindo a classificação do IBGE (2004) para os biomas do Brasil que, a rigor, representam domínios morfoclimáticos, conforme a definição de Ab’Saber (1977). [↑](#footnote-ref-1)