Economic Losses and Cross Border Effects Caused by Pantanal Catastrophic Wildfires

Camila Scur, Mayara and Centuriao, Daniel and Niel Berlinck, Christian and Kelly Luciano Batista, Eugênia and Libonati, Renata and Rodrigues, Julia and Valle Nunes, André and Couto Garcia, Leticia and Fernandes, G. Wilson and Alves Damasceno-Junior, Geraldo and de Matos Martins Pereira, Alexandre and Anderson, Liana and Manuel Ochoa-Quintero, Jose and da Rosa Oliveira, Maxwell and Bandini Ribeiro, Danilo and O. Roque, Fabio

13 October 2023

Economic losses and cross border effects caused by Pantanal catastrophic wildfires.

Mayara Camila Scur [a,*], Daniel Centurião [b], Christian Niel Berlinck [c], Eugênia Kelly Luciano Batista [d], Renata Libonati [e], Julia A. Rodrigues [e], André Valle Nunes [f], Letícia Couto Garcia [a], Geraldo Fernandes Wilson [d], Geraldo Alves Damasceno-Junior [a], Alexandre de Matos Martins Pereira [a,g], Liana Anderson [h], Jose Manuel Ochoa-Quintero [a,i], Maxwell da Rosa Oliveira [a,d], Danilo Ribeiro [a], Fabio de Oliveira Roque [a,e].

[a] Instituto de Biociências, Universidade Federal de Mato Grosso do Sul, Campo Grande, Brazil

[b] Regional Research Institute, West Virginia University, 886 Chestnut Ridge Road, Morgantown, WV 26506.

[c] National Research Center for Carnivores Conservation, Chico Mendes Institute for the Conservation of Biodiversity, Ministry of the Environment. Estrada Municipal Hisaichi Takebayashi 8600, Atibaia, SP 12952-011 Brazil

[d] Departamento de Genética, Ecologia & Evolução, ICB, Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil

[e] Departamento de Meteorologia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

[f] Laboratory of Biodiversity Monitoring and Food Security, Knowledge Center on Biodiversity, Belo Horizonte 31270-901, Brazil

[g] Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA). Rua Euclides da Cunha, 975, 79020-230, Centro, Campo Grande, MS, Brazil.

[h] CEMADEN - Centro Nacional de Monitoramento e Alertas de Desastres Naturais - Cemaden/MCTI, Estrada Doutor Altino Bondensan, 500 - Parque Tecnológico, Eugênio de Melo, São José dos Campos/SP, CEP: 12247-016

[i] Alexander von Humboldt Institute, Bogotá, Colombia

* Corresponding author at: Instituto de Biociências, Universidade Federal de Mato Grosso do Sul, Campo Grande, Brazil. Email address: mayarascur@gmail.com (M.C. Scur)

Abstract:

The Pantanal, the Earth's largest continuous wetland, experienced severe impacts from wildfires in 2019 and, particularly, in 2020. The surge in wildfires can be attributed to several factors, including climate extremes, inadequate fire management, ineffective policymaking, as well as commercial and demographic dynamics. Understanding the economic effects of wildfires is crucial for guiding resource allocation toward prevention, firefighting efforts, and policymaking. This study aims to examine the economic losses resulting from the catastrophic wildfires in the Brazilian Pantanal region during 2019 and 2020. By utilizing new publicly available datasets and data obtained from representatives of institutions, we constructed scenarios to simulate the fire's impacts on the economic input-output system. Through the application of structural impact analysis, we were able to verify an impact in MS GDP of -0.79% and MT had an impact of -0.98% resulting from fire damages. The industries impacted most were livestock, wholesale and retail trade, electricity, gas, and other utilities, agriculture, other food products, land transportation, and slaughtering and meat products. The impact of fire per square kilometer burned reaches 10 thousand dollars in MS. Our findings reveal that the economic impact of the wildfires extends beyond the burned areas, affecting other states of Brazil, such as São Paulo and Paraná.

Keywords: structural impact analysis, natural disasters, input-output models, S2iD portal, tele-coupling

1. Introduction

The occurrence of catastrophic wildfires worldwide has increased over the past decades. This phenomenon is now acknowledged as a significant stressor of the Anthropocene era and has been linked to various complex factors, including climate change, demographic and socioeconomic dynamics, errors in fire management policies, and global trade of agricultural commodities (Pausas and Keeley, 2021; Kim et al., 2021). Evidence of the escalating frequency and intensity of fires has been documented in several regions, such as Australia (Abram et al., 2021), Canada (Hanes et al., 2018), Chile (Bowman et al., 2019a), Indonesia (World Bank, 2016), the Mediterranean region (Pausas and Millán, 2019), Tasmania (Bowman et al., 2019b), western USA (Williams et al., 2019), and Brazil (Brando et al., 2020; Libonati et al., 2020; Correa et al., 2022). While fire plays a crucial ecological role in many non-forest environments, the increasing incidence of catastrophic fires can result in widespread destruction and have detrimental effects on the economy, society, and the environment, leading to substantial losses for both local and global economies (Stephenson et al., 2013; Wang et al., 2018).

Numerous studies have focused on evaluating the economic costs and impacts of fires in various areas, including hydrology, environment, tourism, and health, with primary emphasis on the Australian, Mediterranean, and North American regions (Reid et al., 2016; Wang et al., 2018; Wagenbrenner et al., 2021; Cohen et al., 2022; Otrachshenko and Nunes, 2022, among others). For instance, in the western United States, the 2018 California fires resulted in direct and indirect losses amounting to a mean value of US$148.5 billion, with US$88.6 billion attributed to indirect losses in various industry sectors, half of which occurred beyond the regional scale. Notably, service sectors (e.g., tourism, real estate, health, restaurants, government, and financial services) and industries such as manufacturing, agriculture, trade, construction, transport logistics, and mining were particularly affected, underscoring the spatial distribution of wildfire economic impacts (Wang et al., 2018). Understanding the impacts of wildfires and their associated costs is crucial for various purposes, including assessing government responses, designing recovery programs, shaping policies, informing business decisions, and allocating resources for fire prevention and suppression (Stephenson et al., 2013; Wang et al., 2018).

The Pantanal, the world's largest continuous tropical wetland, where the economic losses caused by wildfires remain unstudied. This lack of research is concerning since considering the economic component is essential for devising strategies to prevent, combat, mitigate, and adapt to wildfires. In the Brazilian Pantanal, there has been an unprecedented surge in wildfires during the last decade (Libonati et al., 2022; Garcia et al., 2021; Marques et al., 2021; Pivello et al., 2021; Correa et al., 2022, Menezes et al. 2022). The wildfires in 2020 alone led to the burning of one-third of the biome, with 43% of the affected area having remained unburnt in the previous two decades, causing further threats to already endangered animal species' refuge areas. Estimates indicate that the 2020 wildfires immediately killed around 17 million vertebrates (Tomas et al., 2021) and 4 billion invertebrates (Berlinck et al., 2021), with the actual numbers likely higher. The primary causes of these wildfires are the combined effects of climate factors (prolonged droughts and heatwaves), significant land use changes from natural areas to agriculture and pasture, resulting hydrological alterations, inadequate fire management strategies, environmental regulations, and budget constraints affecting firefighting efforts (Libonati et al., 2022; Garcia et al., 2021; Marques et al., 2021; Correa et al., 2022; Damasceno-Junior et al., 2021).

Cattle ranching, utilizing native grasslands as pastures, and tourism are the main economic activities in the Pantanal, with limited agriculture for subsistence purposes in small farms and traditional communities. However, the emergence of soybean farming poses a new threat to the floodplain (Tomas et al., 2019). The economic activities in the region suffer negative impacts from wildfires, including infrastructure destruction (residences, businesses, recreational areas), damage to crops and livestock (Botzen et al., 2019), and disruptions in supply chains that extend to different local and higher-scale regions (Wang et al., 2018; Botzen and Sanders, 2019). In this article, we employ the Structural Impact Analysis to describe the economic impact pathway of the wildfires that occurred in the Brazilian Pantanal in 2019 - 2020. This method enables the prediction of how losses in directly impacted areas can affect the macroeconomy (Botzen and Sanders, 2019).

We discovered and utilized a newly underutilized public database for research purposes. This database served as an excellent proxy for assessing the damage caused by wildfires. In conjunction with primary survey efforts, these findings enabled us to create scenarios, paving the way for the first economic assessment of wildfire impacts in the Pantanal.

Through simulations conducted in a pioneering manner, we were able to estimate the most affected economic sectors, analyze the behavior of macroeconomic indicators, and understand the economic repercussions extending through inter-industry linkages. These wildfire events not only influence regions beyond the immediate impacted zone but also incur economic costs per square meter of burned area in each municipality covered by the Pantanal. This highlights the heterogeneous effects of large fires. We advocate for the application of input-output models in analyzing wildfire impacts. This contribution enhances our understanding and facilitates efforts to address major wildfires in the Pantanal. Additionally, we outline a research agenda aimed at mitigating future losses.

2. Material and methods

2.1 Study area

The Pantanal, covering an area of approximately 180,000 km^2, is situated in the central portion of the Upper Paraguay Basin (UPRB) and spans Brazil (80% of its territory, with 35% in Mato Grosso and 65% in Mato Grosso do Sul states), Bolívia (19%), and Paraguay (1%) (Tomas et al., 2019). In Brazil, it is found in the states of Mato Grosso (13 municipalities) and Mato Grosso do Sul (9 municipalities), with an estimated population of around 750,000 people (IBGE, 2021) (Figure 1).

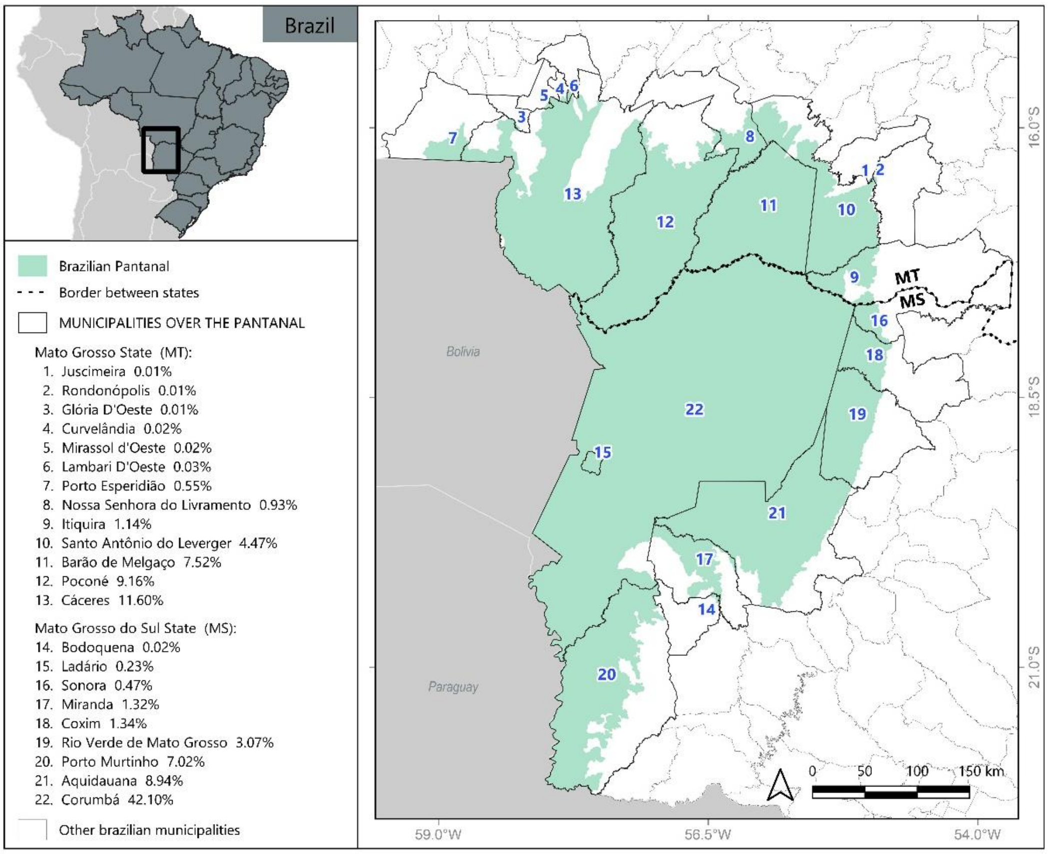

Figure 1. Brazilian Pantanal Biome limits in the Mato Grosso do Sul and Mato Grosso states and municipalities. Values correspond to the percentage that each municipality is part of the Pantanal.

Characterized by seasonal floods and droughts caused by the overflowing of the Paraguay River and its tributaries, the Pantanal ecosystem is significantly influenced by the Cerrado (savanna), Atlantic rainforest, Chaco (seasonally dry forest), and the Amazon rainforest. This results in a diverse array of ecosystems, including forestland, humid areas, shrubland-savanna, grassland, pasture, and cropland (Souza et al., 2021; Marengo et al., 2021; Correa et al., 2022; Higa et al., 2022). The Pantanal provides vital ecosystem services, such as hosting rich biodiversity (e.g., over 2500 native plant species), freshwater supply, food security, climate regulation, scenic beauty, and diverse sociocultural elements, including indigenous and traditional populations (Pott & Pott, 2021).

Economically active for centuries, the Pantanal region supports activities such as beef cattle production, gathering Cerrado fruits by extractives communities, ecotourism, and commercial fishing (Seidl et al., 2001). The region's biodiversity plays a crucial role in cultural ecosystem services, particularly for ecotourism, and the fishery industry holds significant economic value. For instance, the professional fishing sector generated ≈$50,000.00 related to approximately five thousand kg of fishery landings and involved nearly 9,700 professional fishers (ANA, 2020). The region has also witnessed the expansion of the mining industry, especially iron and manganese, generating a total of $75.09 million in 2022 (SEMAGRO, 2022). Additionally, the Pantanal municipalities export products like cotton, various meat products, cement, and agricultural machinery and soil preparation items to countries such as Thailand, China, Indonesia, United Arab Emirates, and Uruguay (Estatísticas de Comércio Exterior - Comex stat https://comexstat.mdic.gov.b).

2.1 Assumptions and model building

The occurrence of significant fire events, as observed in the Pantanal, poses a trade-off for economic agents. This trade-off involves deciding whether to allocate resources to prevent or combat fires. These resources, expressed in monetary values, carry an implicit opportunity cost, as they could be used for more profitable, productive, or social purposes. The decision-making process involves assessing the size of the fire, the potential for damage, and implementing the most cost-effective prevention measures. However, contingency expenses come into play in the event of larger fires or greater-than-expected damage.

This decision-making environment is constrained by incomplete information available to economic agents. They lack comprehensive knowledge about the fire's size, speed, and weather effects on fires and consider only material damages. Meanwhile, intangible damages, such as environmental services and the destruction of fauna and flora, are disregarded.

On the other hand, after a major fire, it is almost impossible to monetize all the damage caused, as it adds up to several layers of damage in different regions and with different characteristics. This lack of information makes it difficult for researchers and specialists to account for the extent of the damage and its real impact on the economy, which consequently limits the ability of economic agents to react to these situations and, for example, formulate policies.

To overcome this problem, we propose using new publicly available data as a proxy for the material damage caused by fires. This data consists of damage estimates by category and requests for funds from municipal public officials to the federal government to repair this damage caused by extraordinary events such as fires, floods, landslides, and earthquakes. These requests are made by declaring a situation of emergency or public calamity, which additionally allows municipal governments to make emergency expenditures in the face of extreme events. We added to this data an effort to collect primary information from public, private, and third-sector entities that contributed to fighting the 2019/2020 fires in the Pantanal since firefighting is not one of the expenditure items listed in the data set. These data were merged, and the values were allocated to the respective economic industry where the potential damage was recorded to create Table 1, which describes the monetary value of the damage caused by the fires each year in each of the states (MS and MT) by industry.

Considering that these amounts are damages that need to be repaired and that, as reported, are borne by municipal governments, these resources are redirected from their ordinary functions in the budgets of these municipalities and then directed to cover these extraordinary damages caused by the fires. This extraordinary expenditure reduces the municipality's ordinary budget, which in turn alters its original demand vector (g). This has economic impacts on the aggregated demand vector in the economy (Y) which impacts output, value-added, and income. To simulate the unanticipated damages resulting from fire incidents, an impact structural analysis was conducted using the multi-regional input-output matrix estimated by Haddad et al. (2017) covering 68 industries and 27 Brazilian states.

The input-output matrix is a systematic database that follows the national accounting system and allows us to access macroeconomic aggregates including the components of aggregate demand in the economy of each state where c_i is the production of industry i that is consumed domestically by households, g_i is the production of industry i that is consumed domestically by the government in the ordinary way, I_i is the production of sector i that is destined for investment, and e_i is the production of sector i that is exported.

$$y_i = c_i + g_i + I_i + e_i \quad (1)$$
$$i = 1, 2, \dots, 68$$

To model this impact of reallocating the ordinary budget of local public spending to cover damages caused by the fires, let this be a vector g_i^e (which is the now identifiable component, and which is a proxy for the intensity of the damage caused by the fires) that is subtracted from the vector g that represents the ordinary government spending of each state for the year 2019/2020. This subtraction results in a decrease in aggregate demand, which will have to be met by additional resources from the federal government, which has items in its budget earmarked for this purpose.

$$\Delta g_i = g_i - g_i^e \quad (2)$$

$$\Delta y_i = c_i + \Delta g_i + I_i + e_i \quad (3)$$

This vector g_i^e has dimensions of 1 x 1836, representing the 68 industries of the economy of each Brazilian state. Industries and regions not affected according to the formulated scenarios are assigned zero values in this vector. The variation in final demand generalized throughout the industries Δy is then applied to simulate the economic output through the following equation (Leontief, 1936):

$$x = (1 - A)^{-1} * \Delta y \quad (4)$$

2.2 Data and Analysis

The data used in this study was constructed using various governmental sources, including the "Sistema Integrado de Informações Sobre Desastres" (Integrated Disaster Information System) - S2iD, and the "Portal da Transparência" (Transparency Portal) of the Brazilian federal, and Mato Grosso state governments. Using S2iD, it was possible to access estimates made by the municipal government of the damage that occurred within the boundaries of each municipality that makes up the Pantanal during the occurrence of fires in 2019 and 2020, grouped by industry/characteristic of the damage. It was also possible to monitor whether local governments have requested permission to declare a state of emergency or calamity from the federal government, which allows them to make emergency expenditures. The Transparency Portal allowed us to find out what amount the state government was spending on firefighting. Additional information was acquired by reaching out to representatives from public and private institutions, including the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBIO), and the Centro Nacional de Prevenção e Combate aos Incêndios Florestais (PREVFOGO), along with NGOs and private companies focused on the Pantanal region.

Two impact scenarios were formulated for the years 2019 and 2020 (see Table 1). In these years, fire affected the largest areas of the Pantanal region, allocating monetary values representing damages and firefighting expenses among the states of Mato Grosso and Mato Grosso do Sul, for each industry that incurred such expenses or experienced fire-related damages. The resulting values were then converted to USD using the annual exchange rate in Purchasing Power Parity (PPP) calculated by the Organization for Economic Cooperation and Development (OECD). Finally, choropleth maps were created to visualize the areas most affected by fires using GIS data from the intersection between the biome (IBGE, 2019) and the municipalities (IBGE, 2022). Data of burned areas in Pantanal were collected and organized by LASA - Environmental Satellite Applications Laboratory from ALARMES 500 m, alongside the AQM-LS product prototype, generated from Landsat image composites at 30 m. This mapping process allowed for a better understanding of the spatial distribution of the economic losses caused by the wildfires in the Pantanal during 2019 and 2020.

We used the burned area data as a proxy for the intensity of the fire and consequently, the damage caused by the fire in each municipality, which allowed us to regionalize the impact calculated using the input-output simulations and calculate an indicator of damage per municipality and square kilometer of burned area, as shown in Table 2 and Figure 3.

Table 1. Scenarios in monetary values of the impacts of fires in the Pantanal municipalities per activities impacted (MS: Mato Grosso do Sul; MT: Mato Grosso). Values are presented in USD using the exchange rate accumulated by the Organization for Economic Cooperation and Development (OECD) (data.oecd.org/).

	2019		2020	
	MS	MT	MS	MT
Agriculture*	78,680.2	0.0	0.0	0.0
Associative organizations**	0.0	0.0	630,931.6	788,185.1
Livestock*	131,596,446.7	0.0	194,174.7	9,786,407.7
Construction*	0.0	0.0	1,247,250.9	976,590.2
Commerce*	0.0	0.0	0.0	19,417.4
Housing*	0.0	0.0	0.0	38,834.9
Public administration***	215,736.0	0.0	3,929,077.8	9,440,226.4
Health Assistance*	98,984.7	63,451.7	0.0	0.0
Total	131,989,847.7	63,451.7	6,001,435.1	21,049,662.0

Source: *Based on the S2ID portal. **Based on the Rede Pantanal interviews and organizations websites. ***Based on the S2ID portal, on the Transparency Portal and the Rede Pantanal database.

Economic agents incur these monetary expenditures in both the public and private sectors to put out the fire. However, it is important to note that these expenses do not contribute to the developing productive capacity and are not typically part of long-term planning. In some cases, they are not even accounted for in the regular budgets of local agents. Instead, these expenditures are regarded as emergency measures employed to address contingencies or to repair damage. The main aim of these expenditures is to maintain the continuity of existing economic and environmental activities, however, they allow us to count the intensity of the damage during disruptions.

3. Results

3.1 Overview

In 2019, the S2iD recorded eight wildfires in the Pantanal cities, all from the MS state. However, only five cities officially reported financial losses. For example, Aquidauana recorded losses in health assistance (~$50,000), public administration (~$250,000), agriculture (~$5,000), and livestock (~$500,000). Corumbá registered economic losses in Health Assistance (~$50,000) and livestock (~$125,000), while Miranda reported losses in Health Assistance (~$22,000), Public Administration (~$88,000), Agriculture (~$75,000), and Livestock (~$300,000). Porto Murtinho registered losses in Livestock (~$250,000). No economic losses related to wildfires were recorded for the Pantanal cities in MT in the S2iD portal in 2019 (Supplementary material).

In 2020, a total of 57 wildfires were registered in the S2iD system, with 15 records in 9 cities from MS and 43 records in 12 cities from MT, indicating more widespread wildfires. However, only three occurrences reported financial losses. From MS, only Porto Murtinho registered losses in livestock (~$200,000). From MT, Barão do Melgaço reported losses in water supply (~$8,000), fuel distribution (~$5,000), livestock (~$80,000), and business (~$20,000), while Poconé recorded losses in medical assistance (~$50,000), water supply (~$10,000), livestock (~$10,000,000), and services (~$40,000). Together, these three wildfire records resulted in financial losses of up to $10 million from the 2020 wildfires. However, the government responses did not fully recognize the registered expenses, as Porto Murtinho's registration was not acknowledged, Barão do Melgaço received ~$80,000, and Poconé received ~$210,000, which is less than the total amount registered in the S2iD web system (Supplementary material).

In addition to the funds directly sent to Barão do Melgaço and Poconé, Civil Defense allocated ~$2.0 million to actions of defense and protection for each MS and MT state, approximately 3% of the Civil Defense's yearly budget. The federal and state governments declared an emergency in MS and MT in September 2020, which streamlined the response actions and reduced bureaucratic processes for contracting services and purchasing equipment, fuel, flight hours, etc., which are not available in public databases.

To fill the information gaps, the amounts raised with the support of the Rede Pantanal, including the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBIO), Centro Nacional de Prevenção e Combate aos Incêndios Florestais (PREVFOGO), and army forces, show a significant volume of resources allocated, especially for fighting the 2020 wildfires in the Pantanal. These amounts encompass salaries of professionals involved in firefighting, transfers, and donations made by the private sector to purchase supplies and enhance firefighting efforts, including aerial support, resulting in a value up to $6.0 million (Supplementary material).

Information available on the states' Transparency Portals (https://www.transparencia.mt.gov.br/; http://www.transparencia.ms.gov.br/) reveals the budget spent on the restoration of wooden bridges destroyed by the 2020 wildfires, amounting to about 1.1 million dollars for each state to restore 700m of structures in 20 bridges. To obtain more data, fourteen non-profit organizations and one private organization were contacted to provide information regarding direct firefighting or related activities during the 2020 Pantanal wildfires. Out of these, seven institutions provided financial reports related to direct firefighting, animal rescue, or food supply, while four other institutions had information available in economic reports on their websites, totaling ~1.5 million dollars in expenses (Supplementary material). These expenses were sourced from: (a) the organizations annual budget, reallocated to firefighting on an emergency basis; (b) international organizations; (c) international and national companies; and (d) crowdfunding.

3.2 Input-output analysis

Implementing of the shock scenario using the input-output matrix yielded detailed impacts on industries and Brazilian states. Here, we provide a summary of the results, focusing on the impacts on GDP, Value Added, and Income for each state in 2019 and 2020 (see Figure 2).

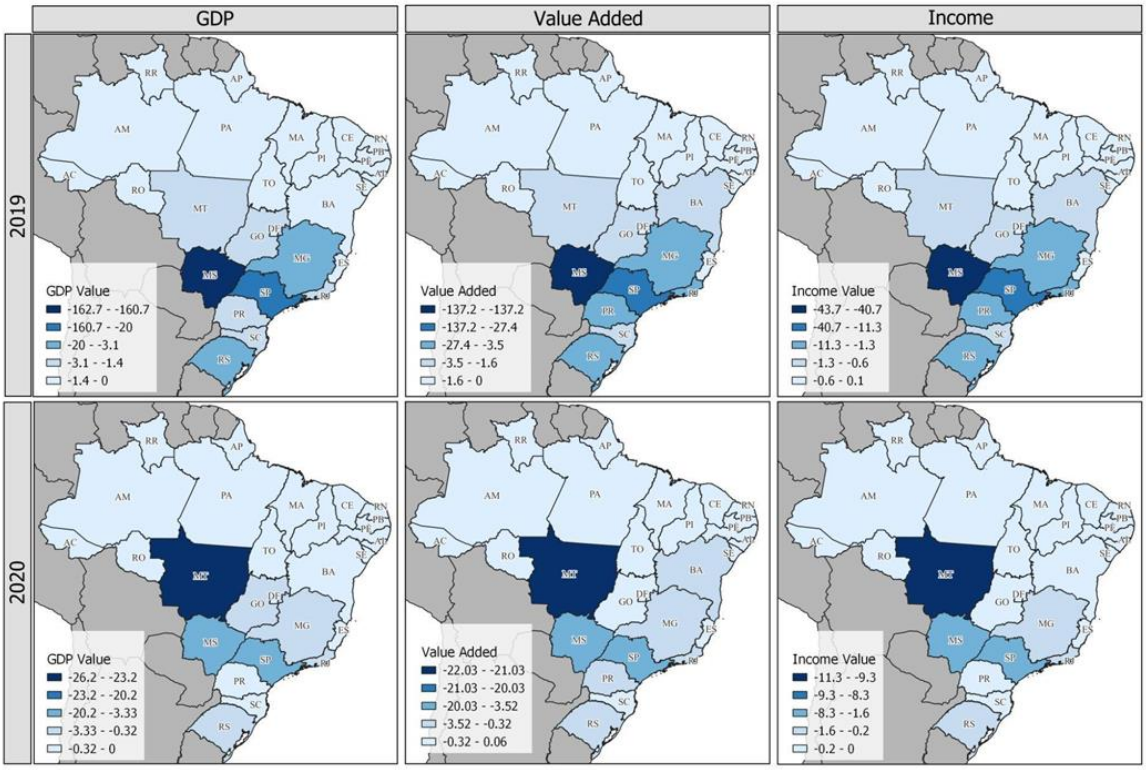

Figure 2: Wildfire impacts on Gross Domestic Product (GDP), Value-added, and Income for the years 2019 and 2020. Source: Own preparation based on the scenario data presented in Table 1 and the updated input-output model for 2020. Monetary values in millions of dollars.

The presented impact variations can be interpreted as the amount that each state failed to achieve in GDP due to the necessity of economic agents to allocate resources to firefighting and wildfire damages instead of directing them toward productive efforts. This impact is evident because the interactions of buying and selling products and inputs involve cross-border relationships, and industries located in other states depend on products produced by industries in MS and MT, and vice versa. Any disruptions in the functioning of parts of the chains located in these states can systematically affect local businesses and those in other states. In the case of wildfires, this disruption reduces their capacity to operate normally and, consequently, reduces the state GDP.

In 2019, MS experienced an impact on its GDP of -0.79%, and MT had an impact of -0.98% relative to the total impact verified for the Brazilian economy (204.3 million). Besides MS and MT, it is evident that other states' GDPs are affected by the occurrence of wildfires in the Pantanal, such as São Paulo (SP, -9.78%), Minas Gerais (MG, -1.8%), Rio Grande do Sul (RS, -1.52%), and others. This result demonstrates that the impacts of wildfires in the Pantanal extend beyond the geographic and geopolitical borders of MS through interstate economic interactions of industries.

The industries most impacted in the MS and MT economies, considering the 2019 scenario, were livestock, wholesale and retail trade, electricity, gas, and other utilities, agriculture, other food products, land transportation, and slaughtering and meat products. The high impacts verified in São Paulo due to the 2019 wildfires are justified by the state's connections with various industries that were heavily impacted in Mato Grosso do Sul. Given São Paulo's high density of industries engaged in diverse activities, these effects had repercussions (directly and indirectly) above the average of other states.

Value-added is a measure that represents the ability of industries in an economy to add value to their products through their production processes, technology, and marketing, for example. The wildfires in the Pantanal also caused a reduction in the Value-added of the Brazilian economy ($193.9 million). MS lost -0.70% of the value added to its economy due to the redirection of resources to recover damages and firefighting, while MT lost - 0.86%.

The industries that showed the greatest impact on their ability to add value to the MS and MT economies were the same industries impacted by GDP. A potential mechanism that can explain the reduction in Value Added when large-scale wildfires occur is the paralyzation or reduction in production capacity of productive plants in certain areas due to extreme proximity to burned areas or the inability to access inputs or equipment due to blocked roads, missing bridges, or other disruptions in transportation or energy infrastructure, and also due to the reduction of government purchases.

The last indicator is labor income, which refers to the amount that individuals (usually families) receive for the time they supply for work. The results demonstrate that wildfires also impact labor income. The impact on the Brazilian economy is $65.18 million. This impact on labor income is usually spent on consumption. The reduction in labor income can limit future consumption and reduce economic activity. In the 2020 scenario, the impact on MS income was -0.22%, while for the state of MT, it was -0.61%. The impact on the Brazilian economy was $18.9 million (BRL 94.9 million).

The simulation exercise using the 2020 scenarios yielded results very close to those of 2019 for the three reported indicators. The main difference is that the monetary impacts for 2020 also include the state of MT. For the year 2020, MT had the greatest impact on all three indicators. São Paulo remained the third most impacted state in terms of GDP, Value Added, and labor income. However, given the links between the economies of MS and MT, the state of Mato Grosso do Sul becomes the second most affected, and in 2020 it also incurred an extensive area of fires.

By comparing the impacts and the burned area, it is possible to establish a measure of the cost in monetary values of GDP, Value Added, and income per square kilometer of burned area. The burned area in the Pantanal municipalities has increased since 2018 and reached critical dimensions in 2019 and especially in 2020. The municipalities located in the state of

MT showed a much larger burned area than those in MS throughout the entire historical series. The municipalities with the largest burned areas were Corumbá and Porto Murtinho in MS, and Caceres and Barão de Melgaço in MT (Figure 3).

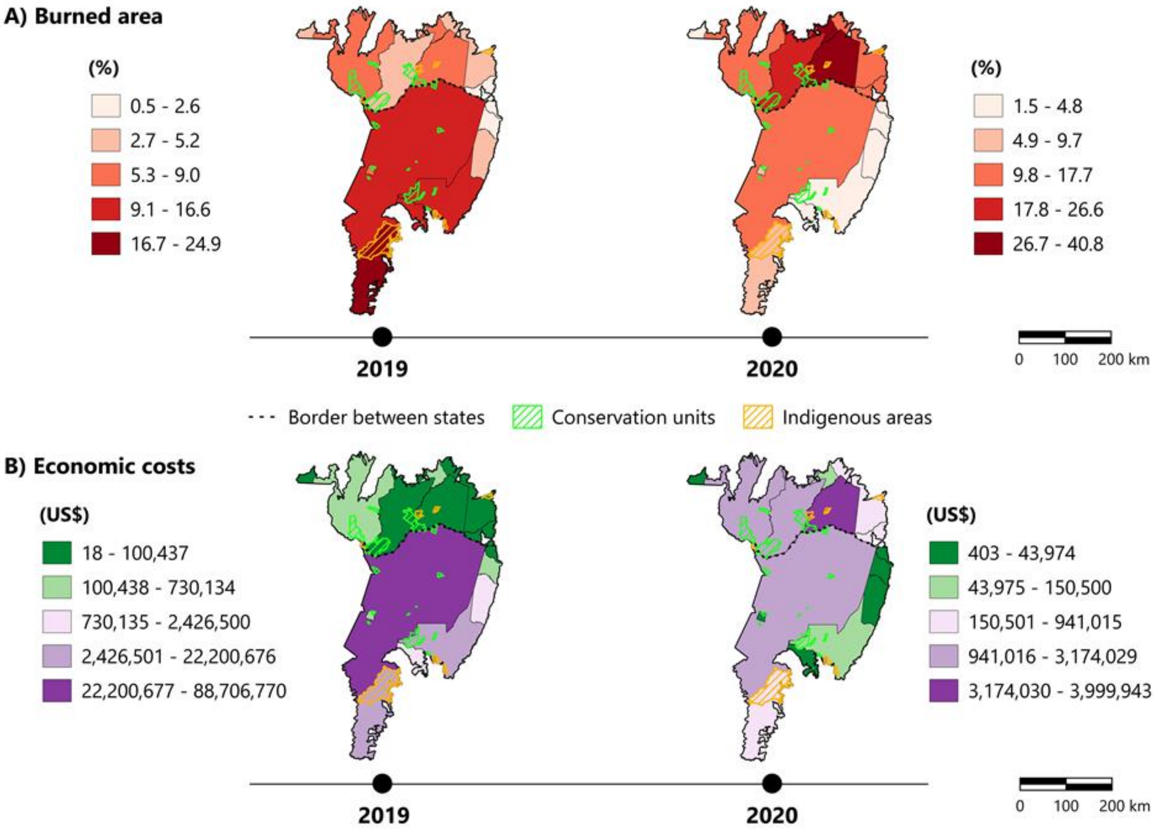

Figure 3. Pantanal Biome municipalities burned areas by relative burnt area (%) and economic costs in dollars for 2019 and 2020.

Source: Estimates using impact values simulated by the model and total annual data of burned area (in km²).

In 2019, for every square kilometer of burned area, there was a loss of ~10 thousand dollars (40.4 thousand reais) in GDP in MS and ~0.5 thousand dollars (2.2 reais) in GDP in MT. However, the pattern was reversed in 2020, with MT experiencing a loss of ~1.8 thousand dollars (10.8 thousand reais) in GDP, and MS losing ~0.5 thousand dollars (2.7 thousand reais) in GDP per square kilometer of burned area (Table 2). The other columns of the table (Value-added and Income) follow the same interpretation. These estimates provide an approximation of the marginal economic costs of burned areas in each state.

Table 2. Economic costs in the Gross Domestic Product (GDP), Value Added (VA) and Income of the Pantanal 2019 and 2020 wildfires per km^2 of burned area of the Mato Grosso do Sul (MS) and Mato Grosso (MT) states. Values are presented in USD considering the exchange rate accumulated by the Organization for Economic Cooperation and Development (OECD) for each 2019 and 2020 years.

State	2019			2020		
	GDP	VA	Income	GDP	VA	Income
MS	10,270.1	8,660.1	2,755.3	526.3	467.7	294.9
MT	578.1	480.7	167.7	2,101.6	1,766.8	908.3

4. Discussion

The wildfires in the Pantanal are experiencing a concerning increase in scale and frequency. Recent research has explored various impacts associated with these wildfires, including animal deaths, human health issues, and reduced resources available to fauna (Berlinck et al. 2021, Garcia et al. 2021, Marques et al. 2021, Tomas et al. 2021, Correa et al. 2022, Kumar et al., 2022). However, there remains a need for a clearer understanding of how these wildfires negatively affect economies and human communities, not only for those directly impacted but also considering tele-coupling processes and connected economies. Such information is crucial for public officials, community leaders, and local citizens to comprehend the broader impacts of wildfires on economies and society, allowing them to incorporate these dimensions into strategies aimed at mitigating future catastrophes. Our study reveals that the 2019 and 2020 Pantanal wildfires had a substantial monetary net effect, amounting up to $200 million dollars. Yet, this value is likely an underestimation due to the limitations mentioned in the "Caveats about the results" section and the unreliability of available data in their current state.

The costs of wildfires are not uniformly distributed in time and space across states. Our findings indicate that in 2019, the State of Mato Grosso Sul was more affected, while in 2020, it was the State of Mato Grosso; and both years impacted the economies of other states such as São Paulo and Paraná. The dynamics of fire are heterogeneous and interconnected with broader wildfire and economic dynamics, calling for inter-state integrated management programs, even beyond the areas directly affected by the wildfires. This tele-coupling extends beyond economic values in agriculture and tourism sectors, as demonstrated in this study, and encompasses large-scale environmental relationships, such as particle flow with public health consequences in distant states (Li et al. 2023).

It is evident that emergency costs and their influence extend far beyond the burn site and are much higher than prevention costs. Therefore, investments in integrated fire management are essential to avoid successive waves of economic impact similar to those described in this study and have proven to be highly effective in reducing wildfires (Oliveira et al. 2022).

The area affected by wildfires has been experiencing a concerning upward trend, with larger and more destructive fires (IPCC, 2022). Consequently, the costs associated with firefighting efforts have escalated over the years (Suppression Costs | National Interagency Fire Center, n.d.). One effective strategy to reduce the extent and severity of wildfires is Integrated Fire Management (IFM), which can help prevent successive waves of economic impacts, as demonstrated in various studies in Brazil Oliveira et al. (2022). For instance, research in federal protected areas has shown that IFM can lead to reduced burned areas, decreased conflicts, and better protection of fire-sensitive environments (Berlinck et al., 2021).

Similarly, Oliveira et al. (2022) found that the implementation of IFM, particularly through Indigenous Brigades, significantly reduced wildfire occurrence in the Kadiwéu Indigenous Land, with the occurrence of fire being influenced more by community practices rather than weather conditions. Moreover, studies in central Brazil have highlighted those prescribed burns, made possible by legislative changes, have contributed to reducing large fires, the number of fire scars, fire intensity, and greenhouse gas emissions (Santos et al., 2021).

Despite significant research and data collection efforts, the results presented in our study still lack certain details that warrant further investigation. For example, valuing the ecosystem services that the biome fails to generate due to extensive burning remains a challenge. Additionally, crucial information regarding the losses of animals, landscapes, gas emissions, changes in water cycles, and other ecological aspects lacks clear monetary translations and has not been considered here. Silvestro et al. (2021) demonstrated that suppression costs in the 2019 Mediterranean megafires accounted for only 16% of the estimated ecosystem services affected during the event, indicating that relying solely on suppression costs as an indicator of wildfire economic losses is reductive.

The wildfires and the resulting damage are considered as an exogenous variable, but this perspective may be limited, as the increase in wildfires could be somewhat related to the expansion of productive activity. Certain effects that could mitigate the negative impacts of wildfires were not considered. For instance, the actual investment value in constructing bridges to replace the burned ones could generate some positive short-term effects, which would to some extent offset the negative estimates made. However, due to the available data, it is not feasible to precisely quantify these positive and negative effects.

Another important consideration is that the Pantanal is a fire-dependent ecosystem, where some level of fire is necessary to regulate ecosystem services and prevent larger wildfires (Damasceno-Junior et al., 2021). Nonetheless, there is no consensus on the "desired" amount or frequency of these burns, making it difficult to estimate the extent of "excessive" fires in a specific year.

The effects analyzed here are based on a comparative statistic exercise, which means that other variations in the economic situation were not taken into account, and the results are valid only for the year in which they were calculated. Making projections for subsequent years is not possible due to seasonal variations in the burned area by municipality, as well as fluctuations in prices and quantities.

The accuracy of financial loss calculations related to wildfires in the S2ID websystem is questionable. Discrepancies exist between the recorded burned area and the registered financial losses, and the methodology used to calculate these losses is not transparent. Furthermore, information on the amounts spent by state governments on firefighting efforts is not publicly available, and the values presented in our study were obtained from government representatives in technical events and interviews, lacking detailed expenses or the source of the budget. Similarly, third sector expenses were based on reports from several organizations, but collective registration of firefighting expenses among members of the "Observatório Pantanal" (Pantanal Observatory) is lacking, leading to potential underestimation of the data.

Other significant sectors, such as tourism, which plays a crucial role in the Pantanal's economy, are also not adequately measured, and there is no national system to assess private sector losses under natural disasters. The Pantanal is a significant tourism destination, particularly for flagship animals and fishing activities, and studies on tourism sector losses are yet to be fully explored.

Despite the limitations and challenges in datasets, our study clearly demonstrates that the impacts of Pantanal wildfires extend beyond the regional scale, affecting numerous Brazilian states, particularly Mato Grosso do Sul, Mato Grosso, and São Paulo. A national research agenda focusing on developing mechanisms to quantify financial losses from natural disasters could lead to a more accurate analysis of impacts. Integrating structural impact techniques, such as input-output models, with ecological impacts can provide valuable insights for policymakers, researchers, and society not only in the Pantanal but globally. By incorporating high-quality information into the decision-making process of economic agents, optimization of decisions is possible, ultimately contributing to greater conservation and sustainable development.

Acknowledgments

This research was funded by the Project Rede Pantanal from the Ministry of Science, Technology and Innovations of Brazil (FINEP Grant No. 01.20.0201.00). We thank LASA/UFRJ for contributing data on burnt areas in the Pantanal. MCScur and AVNunes thanks FINEP for the research scholarship, process number 1382771. LOAnderson thanks the Productivity scholarship, National Council for Scientific and Technological Development (CNPq), process number 314473/2020-3. LCGarcia thanks to L'Oreal-UNESCO-the Brazilian Academy of Sciences (ABC) for the “For Women in Science” award. RLibonati thanks the Productivity scholarship from the National Council for Scientific and Technological Development (CNPq), process number 311487/2021-1 and from FAPERJ (Grant E-26/200.329/2023). DBRibeiro thanks National Council for Scientific and Technological Development (CNPq) Grant E- 33/2018; process 441948/2018-9). AVNunes was supported by the National Council for Scientific and Technological Development (CNPq) (grant number 150102/2023-2).

References

Abram, N.J. et al. 2021. Connections of climate change and variability to large and extreme forest fires in southeast Australia. Commun Earth Environ 2, 8. https://doi.org/10.1038/s43247-020-00065-8

ANA (Agência Nacional de Águas e Saneamento Básico). 2020. Estatística pesqueira. Relatório de Andamento 06: Diagnóstico de Ictiofauna, Ictioplâncton e Pesca na RH Paraguai. Elaboração de Estudos de Avaliação dos Efeitos da Implantação de Empreendimento Hidrelétricos na Região. 110p. https://www.ana.gov.br/

Berlinck, C.N. et al. 2021. The Pantanal is on fire and only a sustainable agenda can save the largest wetland in the world. Brazilian Journal of Biology 82: e244200. https://doi.org/10.1590/1519-6984.244200

Botzen, W.W. et al. 2019. The economic impacts of natural disasters: A review of models and empirical studies. Review of Environmental Economics and Policy. 13:2, 167-188. https://doi.org/10.1093/reep/rez004

Bowman, D.M. et al. 2019a. Human–environmental drivers and impacts of the globally extreme 2017 Chilean fires. AMBIO 48, 350–362. https://doi.org/10.1007/s13280-018-1084-1

Bowman, D.M. et al. 2019b. Fire caused demographic attrition of the Tasmanian palaeoendemic conifer *Athrotaxis cupressoides*. Austral Ecol. 44, 1322–1339. https://doi.org/10.1111/aec.12789

Brando, P. et al. 2020. Amazon wildfires: Scenes from a foreseeable disaster. Flora, 151609. https://doi.org/10.1016/j.flora.2020.151609

Cohen, O. et al. 2022. Long-term health impacts of wildfire exposure: A retrospective study exploring hospitalization dynamics following the 2016 wave of fires in Israel. International Journal of Environmental Research and Public Health 19:5012 https://doi.org/10.3390/ijerph19095012

Correa, D.B. et al. 2022. Increased burned area in the Pantanal over the past two decades. Science of the total environment 835:15386 https://doi.org/10.1016/j.scitotenv.2022.155386

Damasceno-Junior, G. A., Oliveira Roque, F., Garcia, L. C., Ribeiro, D. B., Tomas, W. M., Scremin-Dias, E., Dias, F. A., Libonati, R., Rodrigues, J. A., Santos, F. L. M., Pereira, A. de M. M., Souza, E. B. de, Reis, L. K., Oliveira, M. da R., Souza, A. H. de A., Manrique-Pineda, D. A., Ferreira, B. H. dos S., Bortolotto, I. M., & Pott, A. 2021. Lessons to be Learned from the Wildfire Catastrophe of 2020 in the Pantanal Wetland. Wetland Science and Pratice, 38: 107–115.

Garcia, L.C. et al. 2021. Record-breaking wildfires in the world's largest continuous tropical wetland: Integrative fire management is urgently needed for both biodiversity and humans. Journal of Environmental Management 293, 112870. https://doi.org/10.1016/j.jenvman.2021.112870

Haddad, E.A., et al. 2017. Matriz interestadual de insumo-produto para o Brasil: uma aplicação do método IIOAS. Revista Brasileira de Estudos Regionais e Urbanos, 11(4), 424-446.

Hanes, C.C. et al. 2018. Fire-regime changes in Canada over the last half century. Can. J. For. Res. 49, 256–269. https://doi.org/10.1139/cjfr-2018-0293

Higa, L., et al. 2022. Active fire mapping on Brazilian Pantanal based on deep learning and CBERS 04A Imagery. Remote Sensing 14:688. https://doi.org/10.3390/rs14030688

IPCC. 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

IBGE. 2019. Biomas do Brasil 1:250 000. Online at. https://www.ibge.gov.br/geociencias/informacoes-ambientais/estudos-ambientais/15842-biomas.html

IBGE. 2022. Malha Municipal. Online at https://www.ibge.gov.br/geociencias/organizacao-do-territorio/malhas-territoriais/15774-malhas.html

Kim, Y.S. et al. 2021. Economic drivers of global fire activity: A critical review using the DPSIR framework. Forest Policy and Economics, 131, 102563. https://doi.org/10.1016/j.forpol.2021.102563

Kumar, S. et al. 2022. Changes in land use enhance the sensitivity of tropical ecosystems to fire-climate extremes. Scientific reports 12:964. https://doi.org/10.1038/s41598-022-05130-0

Leontief, W.W., 1936. Quantitative input and output relations in the economic systems of the United States. The review of economic statistics, 105-125.

Li, X. et al. 2023. Aggravated multi-source air pollution exposure caused by open fires in China. Journal of Cleaner Production 394: 136402. https://doi.org/10.1016/j.jclepro.2023.136402

Libonati, R. et al. 2020. Rescue Brazil's burning Pantanal wetlands. Nature 588:217-219 https://doi.org/10.1038/d41586-020-03464-1

Libonati, R. et al. 2022. Assessing the role of compound drought and heatwave events on unprecedented 2020 wildfires in the Pantanal. Environmental Research Letters, 17(1), 015005. https://doi.org/10.1088/1748-9326/ac462e

Marengo, J.A. et al. 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

Marques, J.F. et al. 2021. Fires dynamics in the Pantanal: Impacts of anthropogenic activities and climate change. Journal of Environmental Management 299:113586 (M.L. Calijuri). https://doi.org/10.1016/j.jenvman.2021.113586

Martins, P.I., et al. 2022. Prioritising areas for wildfire prevention and post-fire restoration in the Brazilian Pantanal. Ecological Engineering 176: 106517 https://doi.org/10.1016/j.ecoleng.2021.106517

Menezes, L.S. et al. 2022. Lightning patterns in the Pantanal: Untangling natural and anthropogenic-induced wildfires. Science of the total environment 820:153021 https://doi.org/10.1016/j.scitotenv.2022.153021

Oliveira, M. R. et al. 2022. Indigenous brigades change the spatial patterns of wildfires, and the influence of climate on fire regimes. Journal of Applied Ecology, 59(5), 1279–1290. https://doi.org/10.1111/1365-2664.14139

Otrachshenko, V., Nunes, L.C. 2022. Fire takes no vacation: impact of fires on tourism. Environment and Development Economics 27:86–101 https://doi.org/10.1017/S1355770X21000012

Pausas JG, Millán MM. 2019. Greening and Browning in a Climate Change Hotspot: The Mediterranean Basin, BioScience 69:143–151, https://doi.org/10.1093/biosci/biy157

Pausas, J. G., Keeley, J.E. 2021. Wildfires and global change. Frontiers in Ecology and the Environment, 19(7), 387–395. https://doi.org/10.1002/fee.2359

Pivello, V.R. et al. 2021. Understanding Brazil's catastrophic fires: Causes, consequences and policy needed to prevent future tragedies. Perspectives in Ecology and Conservation, 19(3), 233-255. https://doi.org/10.1016/j.pecon.2021.06.005

Pott, A., Pott, V. J. 2021. Flora of the Pantanal. In G. A. Damasceno-Junior & A. Pott (Eds.), Flora and Vegetation of the Pantanal Wetland (pp. 39–228). Springer Nature Switzerland. https://doi.org/10.1007/978-3-030-83375-6_3

Reid, C.E. et al. 2016. Critical Review of Health Impacts of Wildfire Smoke Exposure. Environmental Health Perspectives 124:9 CID: https://doi.org/10.1289/ehp.1409277

Santos, F.L.M. et al. Prescribed Burning Reduces Large, High-Intensity Wildfires and Emissions in the Brazilian Savanna. Fire 2021, 4, 56. https://doi.org/10.3390/fire4030056

Seidl, A. F., et al. 2001. Cattle ranching and deforestation in the Brazilian Pantanal. Ecological Economics, 36(3), 413-425. https://doi.org/10.1016/S0921-8009(00)00238-X

SEMAGRO. 2022. Report on Mining in Mato Grosso do Sul CFEM. Campo Grande: SEMAGRO. Online at: http://www.semadesc.ms.gov.br/wp-content/uploads/2023/01/Relatorio_CFEM_2022.pdf

Shrestha, R.K., et al. 2002. Value of recreational fishing in the Brazilian Pantanal: a travel cost analysis using count data models. Ecological economics, 42(1-2), 289-299. https://doi.org/10.1016/S0921-8009(02)00106-4

Silvestro, R., et al. 2021. The Footprint of Wildfires on Mediterranean Forest Ecosystem Services in Vesuvius National Park. Fire, 4, 95. https://doi.org/10.3390/fire4040095

Souza, E.B. de. et al. 2021. Composition and Distribution of Woody and Palm Vegetation in the Pantanal Wetland (pp. 443–469). https://doi.org/10.1007/978-3-030-83375-6_9

Stephenson, C. et al. 2013. Estimating the economic, social and environmental impacts of wildfires in Australia. Environmental Hazards, 12(2), 93–111. https://doi.org/10.1080/17477891.2012.703490

Tomas, W.M. et al. 2019. Sustainability Agenda for the Pantanal Wetland: Perspectives on a Collaborative Interface for Science, Policy, and Decision-Making. Tropical Conservation Science Volume 12 https://doi.org/10.1177/1940082919872634

Tomas, W.M. et al. Distance sampling surveys reveal 17 million vertebrates directly killed by the 2020's wildfires in the Pantanal, Brazil. Sci Rep 11, 23547 (2021). https://doi.org/10.1038/s41598-021-02844-5

Wang D, et al. 2021. Economic footprint of California wildfires in 2018. Nat Sustain 4, 252–260. https://doi.org/10.1038/s41893-020-00646-7

Williams, A.P. et al. 2019. Observed impacts of anthropogenic climate change on wildfire in California. Earths Future 7, 892–910. https://doi.org/10.1029/2019EF001210

Wagenbrenner, J.W., et al. 2021. Post-wildfire hydrologic recovery in Mediterranean climates: A systematic review and case study to identify current knowledge and opportunities. Journal of Hydrology, 602, 126772. https://doi.org/10.1016/j.jhydrol.2021.126772