Lessons to be Learned from the Wildfire Catastrophe of 2020 in the Pantanal Wetland

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ABSTRACT

South America's Pantanal is recognized as one of the largest wetlands in the world and a UNESCO World Heritage Site for its ecological significance (high biodiversity). The region experiences both seasonal wet/dry periods and pluriannual cycles of wet and dry years. Vegetation changes throughout the year as well as over the long-term with fires and floods being the major factors affecting vegetation patterns. In 2020 the Pantanal experienced an extraordinary high numbers of wildfires. An overview of the region's fire history is presented along with information on the 2020 wildfires, society's response, lessons learned, and suggestions on where to go from here.

INTRODUCTION

Recently, the Pantanal wetland was redlined on national and international media due to unprecedented wildfires in over 29% of the region with huge consequences for biodiversity, protected areas, and human lives (Einhorn 2020; Libonati et al. 2020). Understanding the causes of such a disaster, learning from the scientific and societal responses, and building an integrative fire management strategy are among the biggest challenges for the coming years. In this essay, we present a synthetic characterization of the Pantanal, focusing on the flood-fire dynamics. We summarize the information about the wildfires of 2020, and we present some societal responses that emerged during 2020. Finally, we call attention to the

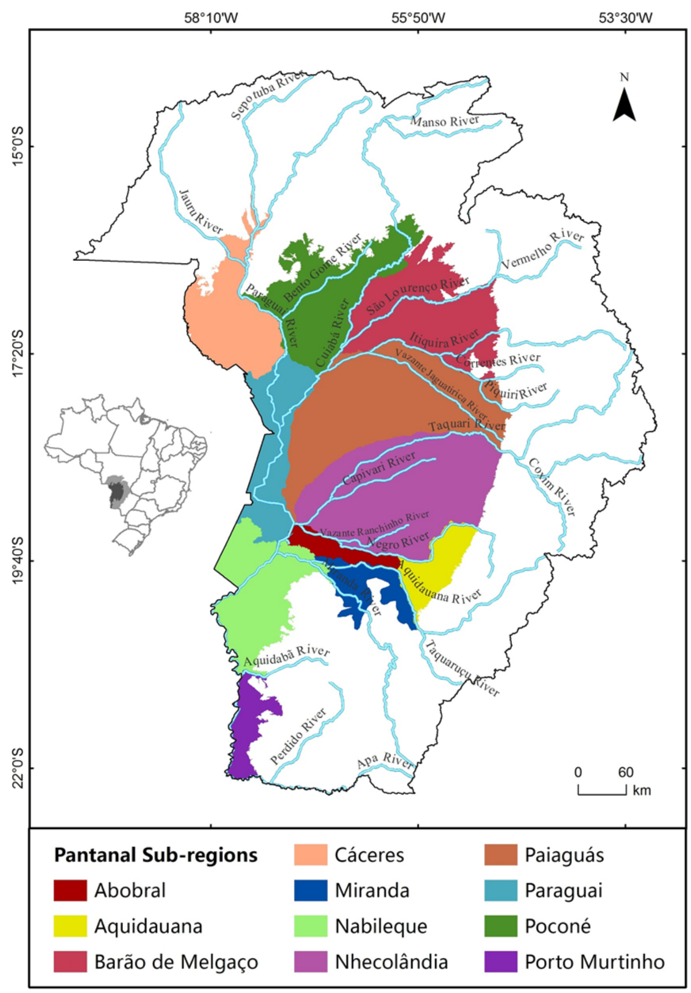

FIGURE 1. Brazilian Pantanal wetland inserted in the Upper Paraguay basin with 11 sub-regions according to Silva and Abdon (1998).

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need for integrated fire management considering the environmental particularities and possible social and ecological impacts of fire in this ecoregion. We believe that the learning lessons from the wildfires in the Pantanal can also be useful for preventing catastrophes in other wetlands around the world.

THE PANTANAL

The Pantanal is one of the biggest tropical continuous wetlands of the world with over 160,000 km^2 located in the heart of South America. Most of its area is located in Brazil (about 140,000 km^2) in the states of Mato Grosso do Sul (66.64%) and Mato Grosso (35.36%) with 15,000 km^2 in Bolivia and 5,000 km^2 in Paraguay (Silva and Abdon 1998; Junk and Nunes da Cunha 2012) (Figure 1). Its origin is related to the subsidence and uplifting of part of the Parana River basin that began between 60 and 35 million years ago and created the Paraguay River basin (Ab'Sáber 1988; Assine et al. 2016a)

The Pantanal is part of the Upper Paraguay River basin (Figure 1). The main rivers of this Basin are Paraguay, and its tributaries Jauru, Cabaçal, Sepotuba, Cuiabá, Taquari, Negro, and Miranda (Silva and Abdon 1998). While the Pantanal usually only includes the floodplain, some authors also include the residual hills of Urucum-Amolar as part of the system since they are very close to the floodplain and sometimes surrounded by the floodplain (Figure 2).

FIGURE 2. Caracará hill in the Pantanal National Park, the Paraguay River and the Amolar mountain range (in the back), near the border of Mato Grosso do Sul and Mato Grosso. (Photo by Geraldo Alves Damasceno Junior)

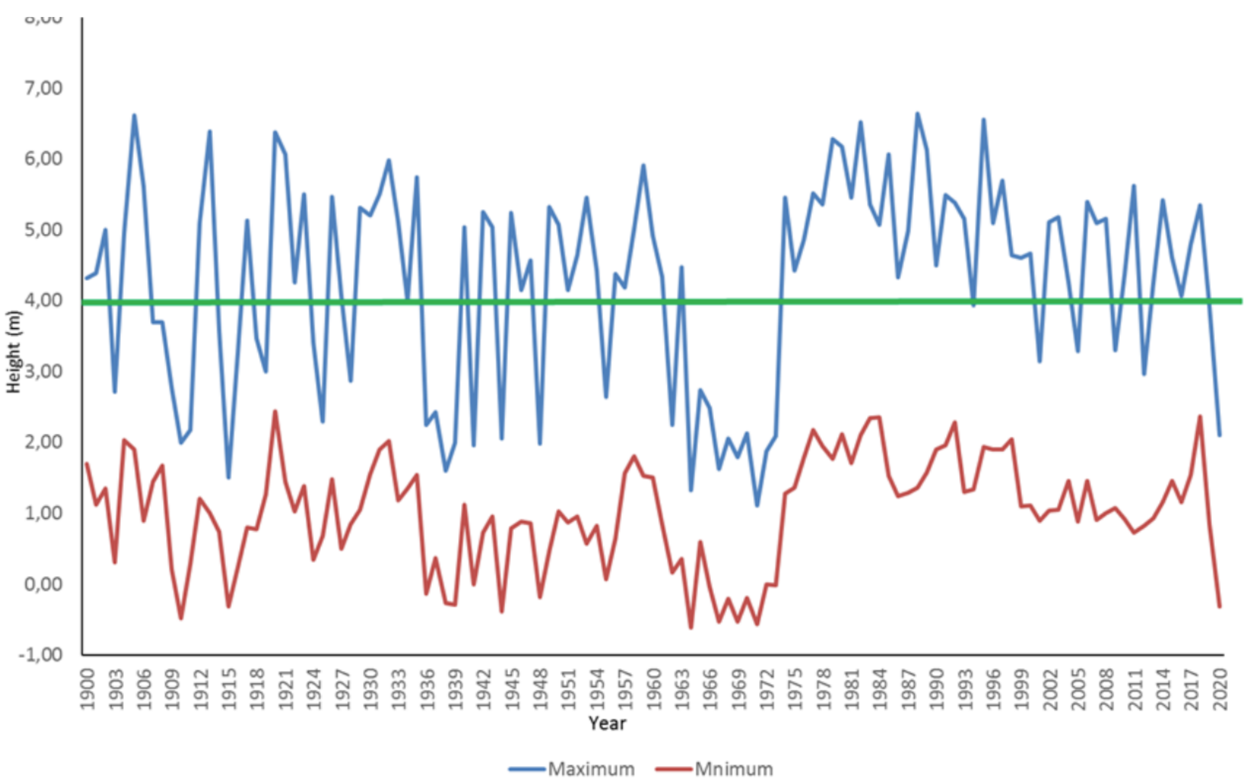

FIGURE 3. Maximum (blue line) and minimum (red line) levels (m) of the Paraguay River recorded in the Ladário hydrometric gauge from 1900 to 2020 (Source Brazilian Navy). The green line is the level at which the Paraguay River overflows.

The climate in Pantanal is the Awa type in Koeppen's classification, markedly seasonal, with a rainy season from October to March and the dry season from April to September. Annual rainfall in the Pantanal has an east-west reduction from about 1200 mm to about 1000 mm (Soriano 1997) and is higher in the upper watershed than in the floodplain.

The flooding regime of the Pantanal is mainly monomodal. There are three types of flooding. The first two are caused by the overflowing of the rivers (Hamilton et al. 1996). In the first, we have the peak of flooding soon after the peak of rain such as in the Miranda and Cuiabá Rivers. The second is the flooding in Paraguay River floodplain that has a peculiar characteristic due to its very flat slope with about 2 cm/km southwards (Assine et al. 2016b). Rainfall in the Paraguay River headwaters takes about three months to reach the middle of the Pantanal which is at the time in the dry season. Therefore, in the middle stretch, the Paraguay River flood occurs during the dry season and experiences its lowest levels during the rainy season; thus, unsynchronized from the rainfall. The third type of flooding occurs mainly in the Taquari fan subregions where without rivers, the combination of rainwater and water table rise during the rainy season produces the flooding. Besides this annual monomodal flood pulse, there is a pluriannual flooding regime. According to the data recorded by the Ladário hydrometric gauge, there are many sets of years with low levels of inundation (dry years) and sets of wet years when the levels of inundation are high (Figure 3).

The flooding pulse is considered the main driver of the Pantanal landscape (Junk et al. 2006; Pott et al. 2011), where the distribution of vegetation types obeys a topographical logic with deep-flooded areas occupied by aquatic vegetation and grasslands, with savanna vegetation in the middle, and *cerrado* or forest in higher areas. In this gradient, many types of macrohabitats are split by type of vegetation, soils, depth, and flooding duration (Nunes da Cunha and Junk 2015).

Considering these main drivers, we can say that vegetation of Pantanal can change over the year, with germination of aquatic plants from the seed bank during the flooded season and the germination of terrestrial species during the dry season (Bao et al. 2018; Souza et al. 2019). It can also change across the years with the pluriannual cycles of dry and wet years when certain types of vegetation can move in the landscape toward where the cycle is favorable. For example, in dry years there are species such as *Cereus bicolor* (Cactaceae) that can colonize flooded grasslands and *Vochysia divergens* (Vochysiaceae) that can advance and encroach the flooded grasslands in wet years (Figure 4).

In this intricate network of flooded and dry areas of the Pantanal, live human populations, which first occupied their territories hundreds of years ago. These populations of the indigenous and traditional communities have developed activities such as fishing, horticulture and cattle ranching, while they depend on the native vegetation for subsistence activities, like handicrafts, food, and medicine (Bortolotto and Amorozo 2012). In the large cattle ranches in the Brazilian Pantanal, there are rural workers and the owners.

FIGURE 4. Vochysia divergens (an evergreen trees with yellow flowers) shown in the Cuiabá River floodplain where it spreads during a sequence of wet years. (Photo by Fabio Edir S. Costa).

FIRE IN THE PANTANAL

The primary causes of fire in the Pantanal are weather phenomena such as lightning strikes and fires caused by human actions either by accident or intentionally to clean pastures on ranches (Libonati et al. 2020; Damasceno-Junior et al. in press). At the end of the dry season, when the clouds arrive in the region but without rain, lightning is more frequent.

The fire regime in Pantanal is strongly linked to the annual and pluriannual flood pulse. Fires occur mainly during the dry season – typically in August, September, and October (Figure 5) in areas where the flooding is synchronized with rain. The biomass produced during the flooding period becomes available as fuel to be burned during the dry season. Some areas burn every second year while others burn almost every year (Figure 6). In the case of the Paraguay River floodplain, wildfires can happen in two situations: 1) in years with low river level, in which the flood time is short or absent, exposing the biomass unavailable in years with regular flooding, and 2) when there are over 10 or 15 day-dry spells during the rainy season. Since during the rainy season the middle reach of the Paraguay River is always in lower levels (as noted above), this also exposes the accumulated biomass and necromass to occasional fires (Damasceno-Junior et al. in press). The

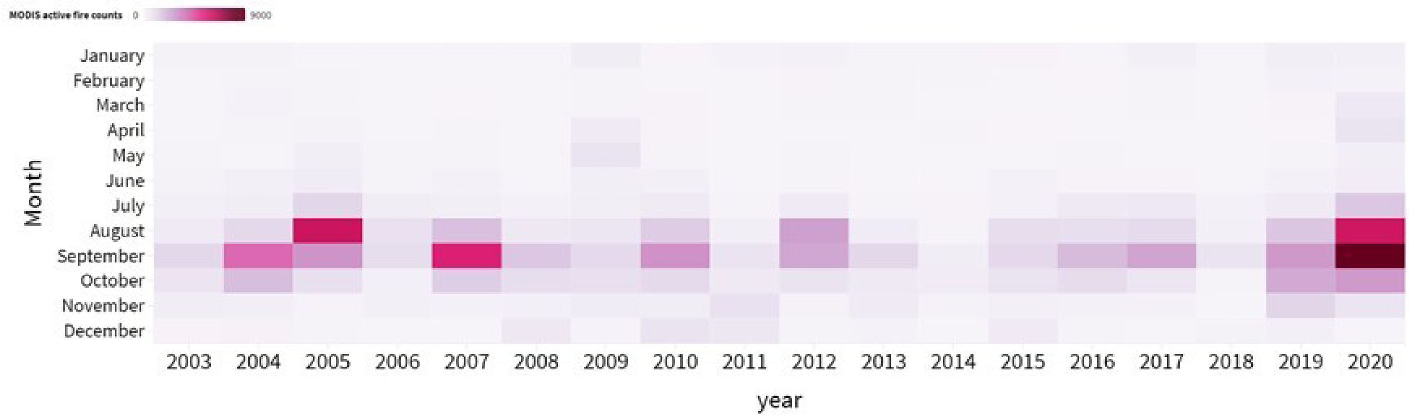

FIGURE 5. Heatmap showing monthly values of active fire counts from 2003 to 2020. Color intensity represents number of fires during the month as shown in the bar scale. (Data source: INPE 2020)

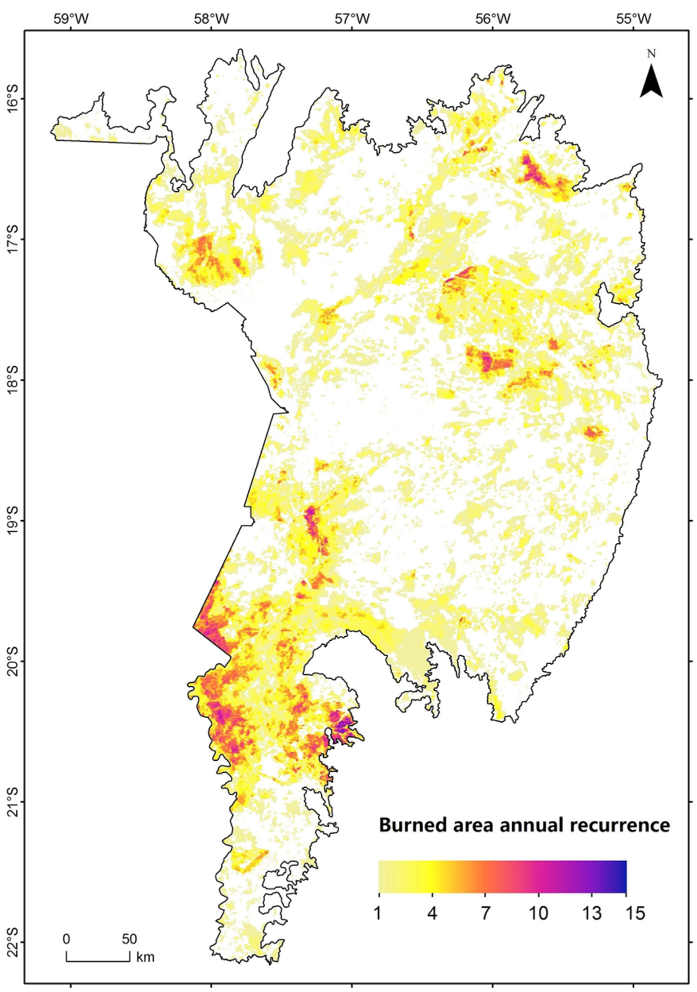

FIGURE 6. Annual recurrence of burned area from 2003 to 2019 in the Pantanal biome. Legend denotes the number of years with burned area recurrence. (Data source: MCD64A1 C6 burned area product derived from the MODIS sensors aboard the Terra and Aqua satellites, developed by the National Atmospheric Space Agency – NASA)

aggravating factor in 2020 was the burning of the dry histosol (that accumulated over wet decades) produced below-surface fire that was very difficult to control.

Fire plays a determinant role in shaping the Pantanal landscape. Combined with inundation, it can eliminate woody species tolerant to flooding that can colonize the grasslands during the wet years. On the other hand, flooding can also eliminate woody species promoted by fire in dry years (Manrique-Pineda et al. 2021). As a result, this action helps to maintain grasslands used as pasture by cattle ranchers.

The indigenous peoples have stories describing big fires that could have destroyed the Earth, and floods that would have terminated humanity in the past (Mindlin 2002). For the Terena ethnicity, a people originated from the Chaco Region, the fire has its origin in an ember put in the grassland by a hare (Oberg 1949).

Fire is part of mythical and seasonal events of the Pantanal and together with inundation acts powerfully on vegetation dynamics as noted above. Both fire and inundation have been receiving the attention of indigenous populations for centuries and more recently by landowners, rural workers, researchers, and other local human populations. Surprisingly, the use of fire as a management tool in the Pantanal has received little attention from researchers, despite Morelli et al. (2009) proposing that conservation units and indigenous territories in the Pantanal are significantly affected by fires of anthropic origin, particularly in the years of pronounced drought. Nevertheless, this is changing because the catastrophic fire events have been more frequent in late years, especially in 2020, with environmental, economic, social, and human health consequences (Observatório do Pantanal 2020).

People worldwide use controlled burning to dispose of residuals around their houses (Levis 2018), for hunting, for communication purposes (not recorded inside the Pantanal), in rituals, and to avoid uncontrollable fires (Mistry et al. 2016). The seasonally flooded grasslands in Pantanal have been used as pastures for cattle over two and a half centuries, which is the main economic activity in the region (Tomas et al. 2019). The traditional use of fire is to clean native grasslands of undesirable bushes and to promote resprouting of tough grasses before the rainy season (Silva et al. 1998; Soriano 2020). Under such management, both fire and cattle act together to reduce the biomass (fuel) in these grasslands. That combination can represent more fire frequency but less severity in each event. There are reports about catastrophic fires in conservation units, where cattle and fire were banned (Pott and Pott 2009). These aspects added to the high intensity of fires in 2020 and raised the discussion about the role played by cattle as "firefighter" helping to prevent wildfires in the Pantanal. There is no consensus about the limits of the use of cattle to prevent fires in different Pantanal environments among researchers. These aspects must be better investigated, including experimental studies that control fire frequency, intensity, and magnitude in association with different cattle management practices and densities.

Fires have also been associated with the phenomenon of change in water quality in the Pantanal known as "*dequada*" when oxygen depletes to levels that kill fish (Calheiros et al. 2000). The limits of the role played by fire and organic matter decomposition at flooding in this phenomenon are not yet well established.

THE BIG WILDFIRE OF 2020: AN OVERVIEW

We had a sequence of two years (2019 and 2020) with high levels of fire (Figures 7 and 8). The fires of 2020 can be considered the biggest cataclysmic fire event recorded in the Pantanal since the beginning of record-keeping. The recorded number of fire spots was much higher than previous years, and the annual average reached almost twice as many fire spots as the last year with the highest average number of fire spots - 2005 (Figure 7). They were caused mainly by a combination of factors. The first is occurrence of the

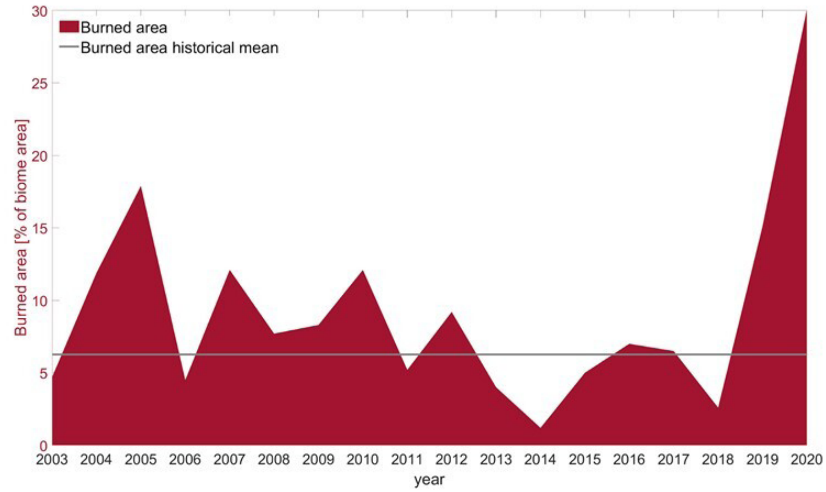

FIGURE 7. Average percentage of the Pantanal area burned in each year from 2003 to 2020 according to satellite-derived burned area products from NASA (MCD64 C6; Giglio et al 2018), ESA (FIRE-CCI; Lizundia-Loyola et al. 2020), INPE/LASA (AQM1KM; Libonati et al. 2015) and LASA-UFRJ (ALARMES – Pinto et al. 2020). Mean value for the period is depicted in the gray line.

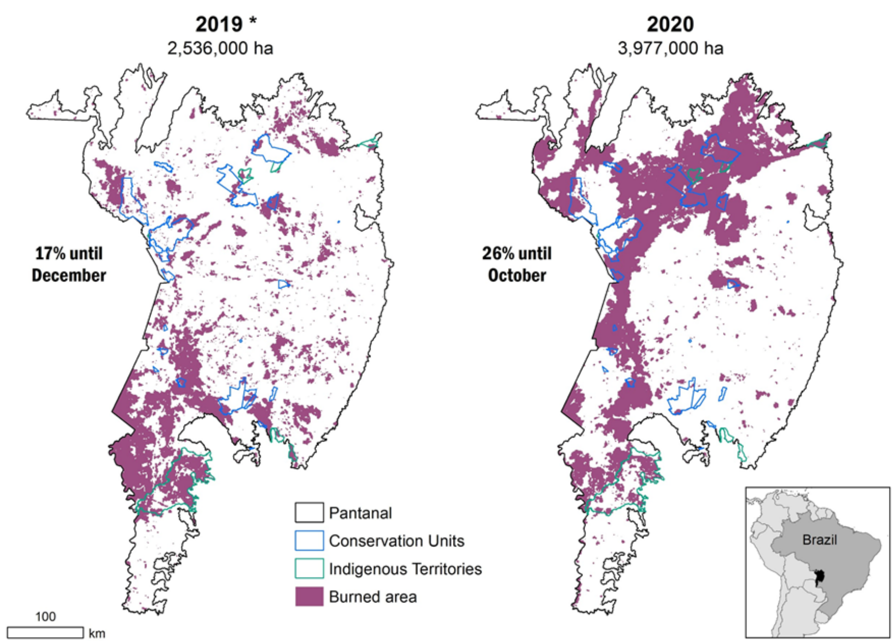

FIGURE 8. Comparison between the burned area (magenta) in 2019 (left panel) and 2020 (right panel), highlighting the conservation units (blue polygons) and indigenous territories (green) within the Pantanal biome (black polygon). The subpanel indicates the geographical location of the biome within Brazil, South America. (Data source: Laboratory for Environmental Satellite Applications of the Federal University of Rio de Janeiro. https://lasa.ufrj.br/news/burned-area-pantanal-2020/)

7th biggest drought in 120 years, and the worst in the last 47 years (Figure 3). Consequently, there was no flooding in many areas of the Pantanal, which exposed a tremendous amount of biomass as fuel, mainly the histosols (organic soils), that are wet and not available to fire in "normal" years. Despite the use of fire being forbidden in the Pantanal during the dry season, some people typically used to burn vegetation, and for many reasons continued this practice, seemingly unaware of the risk. There was no alarm system to prevent the spread of initial foci and, as a result, we had these generalized fire events in the Pantanal. The air humidity was around 10%, the temperature above 35º C, and the wind over 40 km/h accelerated the fire spread. Usual firebreaks would not stop the fire because it spread underneath via the histosol, that can only be extinguished by heavy rain. The glowing debris even jumped over the 200 m wide Paraguay River. Further aggravating was the difficult accessibility to the burning spots and fire lines, through the entangled vegetation, carrying little useful equipment in the face of the magnitude of the flames and the area. It was impossible to put bulldozers or people to build firebreaks ahead to fight fire with fire.

It is relevant to consider that the climate condition in 2020 was comparable to the 14 years of drier years between 1960 and 1975 (see Figure 3). It is likely that fire raged over the wetland during those years, and the impacts were also substantial. So, the Pantanal we know today is at least partially a result of that period, and this led to a necessary conclusion: the 2020 disaster did not destroy the Pantanal, and is not the end of the well-known richness and productivity of its ecosystems. The problem we need to address properly is that catastrophic disasters such as the 2020 Wildfire should not be allowed to happen again, in order to permit the ecosystems to recover themselves in the following years. Deep degradation is expected if repeated fire events occur in the same areas for many years as this may lead to a loss of ecosystem resilience and reduced biodiversity. Thus, preventing wildfire is an essential strategy to contribute to the conservation of the Pantanal.

FIGURE 9. Firefighters struggling through the marsh to reach a burning area in the Pantanal. (Photo by Alexandre Matos Pereira)

GAPS OF KNOWLEDGE AND CHALLENGES

During the huge fires experienced in the Pantanal during 2020, we could identify many areas of concern ranging from scientific knowledge gaps to challenges in terms of fire prevention, control, and emergency response.

The first challenge we identified was the scant information available on fire dynamics in tropical wetlands. Previous knowledge came from studies in savanna and forest areas. The interaction between flood and fire is scarcely known in tropical areas, particularly in the Pantanal. In terms of fire management, there are few studies about the effect of fire on biodiversity, ecological services, human health, infrastructure, and so on.

Secondly, in terms of monitoring and alert systems, there was poor integration of information between the states of Mato Grosso and Mato Grosso do Sul (the Pantanal is shared between these two Brazilian states). The water that inundates the most fire-prone areas in Mato Grosso do Sul comes from Mato Grosso. A safety alarm system must warn when rainfall is below "normal" in the headwaters of Mato Grosso. It is also relevant to build a system integrating Brazil, Paraguay, and Bolivia that share similar environments. Even between the two Brazilian states - Mato Grosso and Mato Grosso do Sul - integration and communication is still not a common practice. The first political initiative to establish the Pantanal as a management unit for Mato Grosso do Sul (MS) and Mato Grosso (MT), happened just recently on October 15, 2016, during an event held by Instituto SOS Pantanal, called Sustainability and Tourism in Pantanal. Then, the governments of both states, with the consent of the Ministry of the Environment, signed a document with unified commitments and actions towards the wetlands, known as "Caiman Letter''. However, even with this initiative, we identified a lack of adequate warnings, communication, and use of preventive information by the local communities and institutions. Thus, the integration of these two Brazilian states in terms of fire management in Pantanal is still a challenge. Within the framework of joint public policies, the Integrated Fire Prevention and Fighting Management Plan made by those two states are similar, and the result of joint debates. However, to achieve an effective and efficient predictive and alert model, much work still needs to be done. Nonetheless, with the magnitude of fire events in the years 2019 and

2020, the fire brigades of MT and MS and the brigades of IBAMA (PreviFogo) acted together, combating the fires in the Pantanal. That can be a beginning of joint action and a basis for the construction of a joint plan to prevent and combat wildfires.

In terms of combat and emergency actions, we could see a massive mobilization of organizations such as IBAMA, ICMBio, Police, Army, Firefighters, private fire brigades, and volunteers (Figure 9). More than 300 people were involved in fighting fires throughout 2020. The fire-fighting began in March and April, atypical months for operations to combat wildfires in the Pantanal. Even though the federal environmental agency IBAMA did not have teams hired for the usual non-critical period, it mobilized resources and made fighting possible together with the firefighters, as well employing helicopters to contain the advance of flames. For the second semester, mainly between July and October, the most mandatory months for the occurrence of forest fires, government agencies such as IBAMA and ICMBio, hired fire brigades to fight fires (Figure 10). Approximately US$ 250,000.00 is invested, including salaries, equipment, and tools that allow 90 brigade members to work throughout the second semester, carrying out work not only on combat but also on fire prevention and management.

Despite all the efforts and investments made to train, hire, and manage these teams, fighting wildfires in the Pantanal requires structure or organization/communication. Currently, even with the involvement of all these agencies, there is no provision of adequate inputs for displacement, communication and maintenance teams in the field. Considering all these characteristics, the operational costs of combat are extremely high. The costs incurred by IBAMA during 90 days of combat were practically the same amount spent to maintain the 90 brigades for 6 months. The cost of a helicopter alone can represent about 80% of the total operating cost. Hence, instead of focusing mostly on combat, adequate allocation of financial and other resources to wildfire prevention and management would be preferable, while at the same time, enhancing socioeconomic and ecological benefits (Garcia et al. in press).

People living in the rural area of the Pantanal, subject to floods, droughts and fire, are still on the margins of decision-making. They could contribute with their traditional knowledge about the role of fire in the management of pastures, native fields, and riparian forests, for example. It is therefore necessary to establish a communication channel with the people who live in the place, to understand their point of view and their knowledge. One way to do this is through participatory research, involving and engaging local people in the search for sustainable solutions.

FIGURE 10. Agents of the National Center for the Prevention and Fighting of Forest Fires (PrevFogo) fighting against fire in different regions of Brazilian Pantanal in the second half of 2020. (Photos by Alexandre Matos Pereira).

GOVERNMENT AND CIVIL MOBILIZATION, RECIPROCITY, AND SOLIDARITY

Collective actions promoted by civil society actors in Brazil were fundamental to improve the actions against fires. The fires in the Pantanal caused a national commotion. Several people looked for NGOs active in the region to contribute financial resources and volunteers to fight the fires, to contribute to the rescue of fauna and to help the populations impacted by the fire. NGOs received thousands of messages of solidarity. Some campaigns were launched to collect financial resources that allowed several civil society organizations to help in an emergency to fight the fire, to rescue the fauna and to distribute food to impacted communities. Initiatives such as Impulsa Pantanal (Mupan / Wetlands International), Movimento Pantanal Chama (SOS Pantanal / Luan Santana), Brigade Alto Pantanal (IHP), and ECOA (Ecologia e Ação) among others created brigade programs in the most impacted areas.

The campaign's result was significant due to the support from celebrities such as Gisele Bündchen, Luan Santana, and other artists from Brazil. There were also donations from enterprises and individual persons to these NGOs. The amount collected allowed them to make an emergency contribution and establish a fire prevention plan through the creation of Rural Volunteer Brigades - Brigades Pantaneiras and a recovery program.

For the fauna there were initiatives such as SOS animals of Pantanal MS and "É o Bicho" in MT that received more than 30 ton of fruits and vegetables and distributed in selected points inside the Pantanal to feed the fauna during the critical periods of fire and drought. There was also a program called GRETAP under the coordination of the Catholic University (UCDB) that took care of animals found alive but injured by fire or smoke.

National and international media covered the wildfires in an unprecedented way, in almost real-time. Searching in Google by using "Fire in the Pantanal" only in 2020 we found 3,940 news articles in Portuguese and 484 in English. Moreover, more than 3,400 videos on this theme were published on social networks and journalistic websites. Artists also had a fundamental role in getting financial support. Just as one example, the Live #OPantanalChama received over 957,519 visualizations raising funds for fauna care, fire brigades, and restoration of the Pantanal.

Despite the many positive examples of governmental and civil mobilization, there remains an evident lack of strategic planning and coordination/integration among actors.

SCIENTIFIC COMMUNITY MOBILIZATION

The rapid sharing of information across the scientific community has allowed researchers to characterize and monitor wildfires in almost real-time. Research groups such as LASA and INPE provided maps and information to the media. Federal Universities of Mato Grosso do Sul, and Mato Grosso organized lives to share scientific information about fires to the public.

As a response to the catastrophe, two ecological projects were articulated: the PELD-CNPq and MCTI projects. The PELD project was built from a call by the Brazilian government (CNPq - National Council for Scientific and Technological Development) to establish long-duration projects in ecology (PELD in Portuguese). In this project, a group of researchers from Mato Grosso do Sul in partnership with other states such as Rio de Janeiro and São Paulo and also researchers from Paraguay established a group called Wetland Fire Study Nucleus (NEFAU in Portuguese - WFSN in English). The main objective of this project is to evaluate the role played by the interaction of fire and flood in ecological processes of the Pantanal. It is a medium-duration project for 4 years. The project also will investigate the effect of prescribed fire in the most fire-prone areas located mainly in the Paraguay River floodplain. The Science, Technology, and Innovation Ministry (MCTI) initiated another project involving researchers from many states of Brazil to conduct emergency research actions. This initiative was focused on the development of systems of alert, experiments of prescribed fire, and studies about wildfires at a landscape scale.

PERSPECTIVES FOR THE NEXT YEARS

The biggest lesson from the Wildfire of 2020 was that we were not prepared for it. Building an effective forecasting capacity and persuasively communicating information on high-consequence risks to everybody potentially affected is a critical step for the next few years (Libonati et al. 2020). This warning system, followed by an efficient protocol of proactive measures, is essential to avoid negative impacts on biodiversity, the local community, and the socio-economy. Hence, it is necessary to build a culture of resilience and sustainability, whereby proper fire management prevents fire from becoming a degradation element, but one that is a particular element of the ecosystem that can be considered as part of a restoration strategy (Garcia et al. in press). Furthermore, the integration of traditional knowledge of indigenous peoples and residents, and the technical and scientific findings arising from short and long-term monitoring will lead to improved decisions in the processes involving conservation and use of natural resources associated with fire in the Pantanal.

To avoid and mitigate both natural and unnatural calamities in the future, we also need to develop strategic and operational planning processes in a participative way - an integrated program of fire management for the Pantanal. Integrated fire management may include several fire prevention and fighting actions, such as the use of prescribed burns, which aims to contain/eliminate the accumulation of dry biomass. For these actions, environmental managers need to consider the phenological calendar of useful and/or fire-sensitive plants, the reproductive period of animals and the location of human dwellings. In addition to these issues, linked to man and other components of biota, fire management will need to consider the physical factors of the environment, such as climate and the flood pulse characteristic of the Pantanal.

In summary, the need for and improvements in long-term and participatory research, co-production of knowledge about fire management, mobilization, citizen engagement, cooperation between institutions, solidarity and dialogues are key issues and lessons that we identified during the catastrophic fires in the Pantanal during 2020. Moreover, a better understanding of the interaction between fires, floods and people is a critical topic that should be addressed in the future studies to inform fire management strategies not only in the Pantanal but worldwide. ■

REFERENCES

Ab'Sáber, A.N. 1988. O Pantanal Mato-Grossense e a Teoria dos Refúgios. *Rev Bras Geogr* 50: 1–28.

Assine, M.L., H.A. Macedo, J.C. Stevaux, I. Bergier, C.R. Padovani, and A. Silva 2016a. Avulsive rivers in the hydrology of the Pantanal wetland. In: Bergier, I. and Assine, M.L. Dynamics of the Pantanal Wetland in South America. Springer Verlag, Berlin Heidelberg, Germany. pp. 83 – 110.

Assine, M.L., E.R. Merino, F.N. Pupim, L.V. Warren, R.L. Guerreiro, and M.M. McGlue. 2016b. Geology and geomorphology of the Pantanal basin. In: Bergier, I. and Assine, M.L. Dynamics of the Pantanal Wetland in South America. Springer Verlag, Berlin Heidelberg, Germany. pp. 23 – 50.

Bao, F., T. Elsey-Quirk, M.A. de Assis, and A. Pott. 2018. Seed bank of seasonally flooded grassland: experimental simulation of flood and post-flood. *Aquat Ecol* 52: 93–105 . https://doi.org/10.1007/s10452-017-9647-y

Bortolotto, I.M., and M.C. de Mello Amorozo 2012. Aspectos históricos e estratégias de subsistência nas comunidades localizadas ao longo do rio Paraguai em Corumbá-MS. In: Moretti, E.C., and A. Banducci-Junior (eds.). *Pantanal: Territorialidades, Culturas e Diversidade*. UFMS, Campo Grande, pp 1–283

Calheiros, D.F., A.F. Seidl, and C.J.A. Ferreira. 2000. Participatory research methods in environmental science: Local and scientific knowledge of a limnological phenomenon in the Pantanal wetland of Brazil. *J Appl Ecol* 37: 684–696. https://doi.org/10.1046/j.1365-2664.2000.00524.x

Damasceno-Junior, G.A., A.M.M. Pereira, J. Oldeland, P. Parolin, and A. Pott In press. Fire, Flood and Pantanal vegetation. In: Damasceno-Junior G.A., and A. Pott (eds.). Flora and Vegetation of Pantanal wetland. Springer International Publishing, Berlin, Germany.

Einhorn, C., M.M. Arréllaga, B. Migliozzi, and S. Reinhard. 2020. The World's Largest Tropical Wetland Has Become an Inferno. The New York Times. Oct. 13, 2020. Available at: https://www.nytimes.com/interactive/2020/10/13/climate/pantanal-brazil-fires.html

Garcia, L.C., J.K. Szabo, F.O. Roque, A.M.M. Pereira, C. Nunes da Cunha, G.A. Damasceno-Junior, R.G. Morato, W.M. Tomas, R. Libonati, and D.B. Ribeiro. In Press. Record-breaking wildfires threaten the Pantanal, the world's largest tropical wetland. *Journal of Environmental Management*.

Giglio, L, L. Boschetti, D.P. Roy, M.L. Humber, and C.O. Justice. 2018. The Collection 6 MODIS burned area mapping algorithm and product. *Remote Sens. Environ.* 217: 72–85. https://doi.org/10.1016/j.rse.2018.08.005.

Hamilton, S.K., S.J. Sippel, and J.M. Melack 1996. Inundation patterns in the Pantanal Wetland of South America determined from passive microwave remote sensing. *Arch für Hydrobiol* 137: 1–23.

INPE. 2020. Banco de Dados de queimadas. http://queimadas.dgi.inpe.br/queimadas/bdqueimadas/ accessed in December 2020.

Junk, W., and C. Nunes da Cunha 2012. Pasture clearing from invasive woody plants in the Pantanal: a tool for sustainable management or environmental destruction? *Wetl Ecol Manag* 20: 111–122. https://doi.org/10.1007/s11273-011-9246-y

Junk, W.J., C. Nunes da Cunha, K.M. Wantzen, P. Petermann, C. Strüssmann, M.I. Marques, and J. Adis. 2006. Biodiversity and its conservation in the Pantanal of Mato Grosso, Brazil. *Aquat Sci* 68: 278–309. https://doi.org/10.1007/s00027-006-0851-4

Libonati, R., C.C. da Camara, A.W. Setzer, F. Morelli, and A.E. Melchiori. 2015. An algorithm for burned area detection in the Brazilian Cerrado using 4 Mm MODIS imagery. *Remote Sensing* 7 (11): 15782–15803. doi:10.3390/rs71115782.

Libonati, R, C.C. da Camara, L.F. Peres, L.A.F. Carvalho, and L.C. Garcia. 2020. Rescue Brazil's burning Pantanal wetlands. *Nature* 588: 217–220. https://www.nature.com/articles/d41586-020-03464-1

Lizundia-Loiola, J., G. Otón, R. Ramo, and E. Chuvieco 2020. A spatio-temporal active-fire clustering approach for global burned area mapping at 250 M from MODIS data. *Remote Sensing of Environment* 236: 111493. doi:10.1016/j.rse.2019.111493.

Manrique-Pineda, D.A., E.B. de Souza, A.C. Paranhos Filho, C.C.C. Encina, and G.A. Damasceno-Junior. 2021. Fire, flood and monodominance of *Tabebuia aurea* in Pantanal. *For Ecol Manage* 479: 118599. https://doi.org/10.1016/j.foreco.2020.118599

Mindlin, B. 2002. O fogo e as chamas dos mitos. *Estud Avançados* 16: 149–169. https://doi.org/10.1590/s0103-40142002000100009

Mistry, J., B.A. Bilbao, and A. Berardi 2016. Community owned solutions for fire management in tropical ecosystems: case studies from indigenous communities of South America. *Philos Trans R Soc B Biol Sci* 371. https://doi.org/10.1098/rstb.2015.0174

Morelli F., A. Setzer, and S.C. Jesus. 2009. Focos de queimadas nas unidades de conservação e terras indígenas do Pantanal, 2000-2008. *Geografia* 34: 681-695.

Nunes da Cunha, C., and W.J. Junk. 2015. A classificação dos macrohabitats do Pantanal Mato-grossense. In: Nunes da Cunha, C., M.T.P. Fernandez, and W.J. Junk (eds.). *Classificação e Delineamento das Áreas Úmidas Brasileiras e de seus Macrohabitats*. EdUFMT, Cuiabá. pp 77–122

Oberg, K. 1949. *Terena and the Caduveo of Southern Mato Grosso, Brazil*. United States Government Printing Office, Washington, DC.

Observatorio do Pantanal. 2020. Incêndios voltam a consumir a região do Pantanal. Observatório do Pantanal, Available in: https://observatoriopantanal.org/2020/04/20/incendios-voltam-a-assolar-a-regiao-do-pantanal/#https://observatoriopantanal.org/pt-br/#!/about_section. Access in: May, 2020.

Pinto, M.M., R. Libonati, R.M. Trigo, I.F. Trigo, and C.C. da Camara. 2020. A deep learning approach for mapping and dating burned areas using temporal sequences of satellite images. *ISPRS J. Photogramm. Remote Sens.* 160: 260–274. https://doi.org/10.1016/j.isprsjprs.2019.12.014.

Pott, A., A. Oliveira, G.A. Damasceno-Junior, and J.V. Silva. 2011. Plant diversity of the Pantanal wetland. *Brazilian J Biol* 71: 265–273. https://doi.org/10.1590/S1519-69842011000200005

Pott, V.J., and A. Pott. 2009. Vegetação do Pantanal: fitogeografia e dinâmica Arnildo. In: Anais 2º Simpósio de Geotecnologias no Pantanal. Embrapa Informática Agropecuária/INPE, Corumbá. Pp. 1065–1076.

Silva, M.D., R. Mauro, A. Pott, A. Boock, V.J. Pott, and M. Ribeiro 1998. Una sabana tropical inundable: el Pantanal arcilloso, propuesta de modelos de estados y transiciones. *Ecotropicos* 10: 87-98.

Silva, J.S.V., and, M. de M. Abdon. 1998. Delimitação do Pantanal brasileiro e suas sub.regiões. *Pesqui Agropecuária Bras* 33: 1703–1711.

Soriano, B.M.A. 1997. *Caracterização climática de Corumbá*. Boletim de Pesquisa, 11, Embrapa-CPAP, Corumbá. 25 p.

Soriano, B.M.A., E.L.C. Cardoso, W.M. Tomas, S. Santos, S.M. Crispim, and L. Pellegrin. 2020. Uso do fogo para o manejo da vegetação no Pantanal. Documentos, 164, Embrapa Pantanal, Corumbá. 17 p.

Souza, E.B. de, G.A. Damasceno-Junior, and A. Pott. 2019. Soil seed bank in Pantanal riparian forest: persistence, abundance, functional diversity and composition. *Oecologia Aust* 23: 891–903.

Tomas, W.M., F.O. Roque, R.G. Morato, P.E. Medici, R.M. Chiaravalloti, F.R. Tortato, J.M.F. Penha, et al. 2019. Sustainability agenda for the Pantanal Wetland: perspectives on a collaborative interface for science, policy, and decision-making. *Trop. Conserv. Sci.* 12. https://doi.org/10.1177/1940082919872634