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Prioritising areas for wildfire prevention and post-fire restoration in the Brazilian Pantanal

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ABSTRACT

In 2020, fires in the Pantanal, the world's largest continuous tropical wetland, made global news. The flames destroyed almost one-third of the biome. Furthermore, 43% of the affected area was burnt for the first time in 20 or even more years. As the combination of extreme drought and anthropogenic actions that caused these extreme wildfires is still prevalent, scientifically informed actions are necessary to prevent catastrophic fires in the future. Fire prevention, as well as restoration need to be spatially prioritised, as it is unfeasible to plan actions for the whole extent (150,355 km^2) of the Brazilian Pantanal. In this study, we identified areas of high fire risk based on meteorological fire risk tendency for 1980–2020, fire intensity, last year with fire, the recurrence of fires for 2003–2020, and remaining areas of natural forest vegetation around watercourses. These native remnants include unburnt areas that can serve as refuges for fire-sensitive species and are important for fire prevention. We identified 246 km^2 with high fire risk, i.e., high probability of megafires, with vegetation types that support fire-sensitive plant species. We found that while 179 km^2 had high or medium natural regeneration potential, 66 km^2 had low potential and needed active restoration. Over 3120 km^2 have been severely degraded by recent fires. About 93% of these areas have high or medium potential for natural regeneration, where the suggested actions are passive restoration and Integrated Fire Management. We estimated the cost of post-fire restoration for areas with high and medium potential for natural regeneration to be around 123 million USD. In areas with low regeneration potential (219 km^2), we suggest active restoration. The cost to restore these areas using transplanted seedlings or enrichment planting is estimated between 28 and 151 million USD.

1. Introduction

In 2020, the world's largest continuous tropical wetland suffered one of the most severe tragedies in its history, with almost one third of its area burned (Libonati et al., 2020; Libonati et al., 2022). Besides, ~43% of the areas affected by fires in the Pantanal in 2020 had not been burnt in the previous two decades (Garcia et al., 2021). The 2020 fires affected at least 17 million native vertebrates (Tomas et al., 2021), 4 billion invertebrates (Berlinck et al., 2020) and uncountable plants. These uncontrolled fires occurred because of a combination of prolonged drought and anthropogenic activities, including electrical problems, garbage burning, honey collecting, and fires lit accidentally or to remove shrubs and stimulate the grass growth (Libonati et al., 2020). Agency budget reductions and other aspects of the current Brazilian political landscape have placed constraints on firefighters, exacerbating an insufficient fire prevention strategy (Garcia et al., 2021; Leal-Filho et al., 2021). In 2020, the Paraguay River also experienced its lowest flood level since 1973 and a fire corridor was able to form in its flood zone (Garcia et al., 2021). Fires are known to reach extreme proportions in years with low flood levels (Arruda et al., 2016), the biomass produced since the last flooding remains available as fuel (Garcia et al., 2021). With natural or human-originated ignition, the large amount of combustible dry plant

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material that can accumulate in fire-prone ecosystems, such as the Pantanal (Hardesty et al., 2005; Pivello et al., 2021). These conditions can lead to megafires, which are wildfires that result in 500–1000 ha (depending on the definition) of area burned, with many negative impacts on the environment and local communities (Pivello et al., 2021).

The Pantanal extends to three countries, Brazil, Bolivia, and Paraguay and is characterised by floods and droughts occurring in well-defined seasons marked by the flood pulse. This biome supports over 2000 plant, 271 fish, 57 amphibian, 131 reptile, over 580 bird, and at least 174 mammal species (Tomas et al., 2019). These numbers represent described species, but new taxa are still being discovered, as many parts of the Pantanal are difficult to access and remain poorly known floristically (Sousa-Baena et al., 2013). Because of this amazing biodiversity, the Pantanal is considered a Biosphere Reserve by UNESCO, Reserva Particular do Patrimônio Natural in Brazil, and Reserva Natural Privada, classified as Strict Nature Reserve in Paraguay (Soriano et al., 2020; Tomas et al., 2019).

Predictions for future climate scenarios for the Pantanal include rising temperatures, changes in precipitation and alterations in seasonal and interannual weather extremes, with more droughts, heat waves, and floods (Marengo et al., 2015; Thielen et al., 2020; Thielen et al., 2021). Because of the reduced rainfall, the Pantanal has been losing water and is experiencing more severe droughts than in the past (Marengo et al., 2015). The water deficit is expected to increase, given the 5–7 °C average annual temperature increase and the 30% reduction in rainfall predicted by the end of the 21st century (Marengo et al., 2015; Lázaro et al., 2020). These conditions facilitate the occurrence of extreme fire events and pose a serious threat for conservation. More restoration actions will be necessary in areas with fire-sensitive vegetation. However, severe climate is also predicted to make restoration more challenging (Holmgren and Scheffer, 2001; Leroux and Whitten, 2014), due to increased costs and decreased success. Moreover, the hydrographic basin of the Pantanal has been suffering rapid native vegetation conversion, which is also expected to further increase (Guerra et al., 2020a). For ecological actions, it is important to treat the Upper Paraguay River Basin as a management unit (Roque et al., 2016). As the rivers of the Pantanal originate in the highlands of the Cerrado surrounding the Pantanal (Bergier, 2013), the conversion of these areas has affected the ecohydrological dynamics of the Upper Paraguay River Basin (Bergier, 2013). With worsening climatic conditions, megafires will remain on the horizon, unless strong public policies are implemented (Libonati et al., 2020; Garcia et al., 2021). As of 2021, the drought continues (Thielen et al., 2021) and stakeholders need to collaborate to prevent extreme fires and to restore fire-sensitive vegetation. However, with limited resources, we need to prioritise actions and identify priority areas for management, protection, and restoration (Garcia et al., 2021).

Future scenarios studies have identified areas that will be strongly affected by land use changes. For instance, the Upper Paraguay River Basin has been predicted to lose a large area of vegetation by 2050 (Guerra et al., 2020a). The area between the plateau and lowland is known as the "Arc of Vegetation Loss" of the Pantanal, given its similarity to the "Amazon Arc of Deforestation" (Guerra et al., 2020a). In these areas, the current rate of deforestation is faster than in other parts of the biome (Guerra et al., 2020a). The main cause of land use conversion in the Pantanal is the intensification of the traditional extensive cattle ranching, replacing native pasture with exotic grasses (Tomas et al., 2019). Based on these illegally converted areas, the recovery target in the Pantanal is 50,000 ha according to PLANAVEG, Brazil's national plan for native vegetation recovery (Brasil, 2017), which includes a legal mandate for restoration (Brancalion et al., 2016). However, in this study, we focus on areas affected by wildfires, excluding degraded areas caused by land conversion. In Brazil, restoration usually occurs in degraded areas with no native vegetation, in order to comply with the environmental laws. As our interest is beyond the legal requirements (i.e., we do not consider cleared vegetation that should be revegetated), we focus on existing natural forest remnants with fire-sensitive native plant species that could be degraded by fire.

In spite of this, native vegetation restoration is less studied in the Pantanal compared to other Brazilian biomes, representing a significant knowledge gap (Guerra et al., 2020b). Our study is the first attempt to prioritise areas that are in need of restoration after fire degradation in this biome. These data are essential for informed decision-making, nevertheless urgent decisions are currently made in the absence of this information. These choices include allocating financial resources for the restoration of highly degraded areas and for the fire management of currently unburnt areas. We also need to consider the temporal scale of fire management and identify priorities for urgent and long-term actions.

Fire occurs naturally in many ecosystems, affecting vegetation composition, structure, and distribution (Pausas and Keeley, 2014; Oliveira et al., 2014; Arruda et al., 2016; Kohagura et al., 2020; Silva et al., 2021). However, fire-adapted environments can contain fire-sensitive species and can provide refuge for fauna after fire events (Pivello et al., 2021). As fire-sensitive species are not adapted to fires, habitats where these species occur need to be protected, as extreme droughts have increased both the probability and the intensity of forest fires (Pivello et al., 2021; Wintle et al., 2020; Silva et al., 2021). While most plant species of the open vegetation communities of the Pantanal are fire tolerant, some that are associated with watercourses are sensitive to high-intensity and frequent wildfires (Pivello et al., 2021; Pott and Pott, 1994, 2004; Pott et al., 2011). For instance, riparian and gallery forests are both vulnerable to wildfires in tropical savannas systems (Flores et al., 2020; Pivello et al., 2021). In gallery forests, the canopy is connected between the two sides of the river, while in riparian forests the canopies do not join. These forest types are found along water bodies in grassland or savanna ecosystems and may contain fire-sensitive plant species (Soriano et al., 2020; Pivello et al., 2021). If these forests repeatedly experience severe fires, their fire-sensitive species will be seriously affected and will need human intervention to recover. Areas that have not been burned for decades also need special attention, as they can serve as refuges for fire-sensitive species (Garcia et al., 2021).

In this study, we identify priority areas considering the cost-effectiveness of actions, selecting areas of high fire risk for fire prevention, where dry biomass has accumulated and consider climate trends that promote the spread of fires. We also identify areas that support fire-sensitive plant species, such as forest remnants associated with watercourses and areas, where the 2020 fire caused severe degradation and need to be prioritised for restoration.

Since restoration is understudied in the Pantanal (Guerra et al., 2020b), restoration techniques also need to be tested on a case-by-case basis. We distinguish areas with different levels of resilience that need different restoration strategies. In general, passive restoration, including natural regeneration, is recommended in areas that will naturally return to the reference ecosystem when the factor causing degradation (in this case, fire) is no longer present (i.e., these areas have medium or high resilience). On the other hand, degraded areas with a low resilience, besides the use of Integrated Fire Management (IFM) strategies, will need active restoration to recover their ecological functions and interactions. Integrated Fire Management includes prevention and suppression strategies and techniques, such as prescribed fires, as well as suppression of undesired fires (Pivello et al., 2021). This approach considers social, economic, cultural and ecological factors in order to minimise damage and maximise benefits of fires to the environment and local people (Rego et al., 2010), and is effective strategy for transitional zone of savanna and wetland (Oliveira et al. n.d.). Active restoration techniques, such as fire-sensitive species enrichment through planting native seedlings, transplanting seedling, direct seeding, and topsoil transposition are more expensive than passive restoration techniques, because they need more intervention and human care.

The practical approach of this study provides a tool to aid fire prevention and restoration planning. The priority areas identified by this study have already been used by the State Public Prosecutor's Office of Mato Grosso do Sul to identify farms with a high fire risk. The potentially affected landowners were inducted about ways to avoid fires on their proprieties. This practical regional approach contains a rigorous and compelling prioritisation protocol. Before implementation by policy makers, the methodology was validated during an online workshop with Brazilian fire management experts, who were also familiar with Pantanal vegetation. Other key contribution of this study is to highlight fire-sensitive areas with no legal obligation to restore. These areas should be prioritised as their restoration will bring large benefits to the ecosystem, while represent a smart use of finite public resources and environmental compensations.

2. Materials and methods

2.1. Datasets

In this study, we focus on the Brazilian Pantanal, located in the Upper Paraguay River Basin (IBGE, 2013). We obtained maps of the areas that were burned each month from the 6th collection of the MODIS Monthly Burned Area Product (MCD64A1) (Giglio et al., 2009, 2018). Daily fire radiative power data were obtained from the MODIS sensor (MCD14ML), with a 1-km spatial resolution, which allows quantifying the intensity of each event (Laurent et al., 2019). These two MODIS products were extracted for 2003–2020. We also used the Fire Weather Index for 1960–2020, based on the Canadian Forest Fire Weather Index (FWI) System (Dee et al., 2011; Haiden et al., 2016), obtained from the ERA5 reanalysis of the ECMWF (Van Wagner, 1987). The Fire Weather Index is based on effects of three fuel moisture values (Fine Fuel Moisture Code, Duff Moisture Code, and Drought Code) and the effect of wind on fire behaviour represented by three other components (Van Wagner, 1987; Alexander and De Groot, 1988). The Daily Fire Weather Index is based on meteorological variables including temperature and air relative humidity at the surface, wind speed at 10 m, and accumulated precipitation (Van Wagner, 1987). These variables have a 25-km resolution and were obtained for the dry seasons (June–October) of 1980–2020.

We obtained vegetation information from the Collection 5 of the MapBiomas Program (https://mapbiomas.org). This dataset has a 30-m spatial resolution and covers 1985–2019 (Souza et al., 2020). We also used a 250-m resilience map of the Pantanal (Pott et al., 2018), which is based on percentage of native vegetation (forest or non-forest), agriculture or pasture, areas with a slope of over 15%, average distance between native vegetation fragments (forest or non-forest), average Agricultural Production Historical Use Index, recent (10 years) deforestation, and pasture primary productivity. We also used the fuel load map of IBAMA (2021) based on Landsat imagery between February 1 and April 5, 2021. Finally, we used projections of vegetation loss considering land use changes in 2050 with a 250-m spatial resolution based on the study of Guerra et al. (2020a).

2.2. Methodology

The resources available for nature conservation in general are scarce (Murdoch et al., 2007). Consequently, prioritisation protocols are valuable, especially when large areas need to be monitored and managed with insufficient resources (Game et al., 2013). In these cases, the resources need to be used in a way to gain the maximum ecological benefits. The criteria we used for prioritisation in this study were based on several assumptions:

(a) Natural forest remnants contain fire-sensitive plant species that decline after repeated intensive fire events (Pivello et al., 2021).

(b) Areas with high historical tendency of fire in the last four decades (i.e., period with available data) will continue to experience high risk (Van Wagner, 1987; Tedim et al., 2018).

(c) Recently burned areas have low levels of dry biomass to burn, while areas that had not been burnt in the last two decades could have accumulated large amounts of biomass that can serve as fuel (Pivello et al., 2021).

d) Areas with high fires recurrence have a higher probability to burn than other areas, which can threaten their fire-sensitive species (Libonati et al., 2021).

We analysed fire risk based on areas with high potential to burn in the Pantanal using the following variables:

I. Fire Weather Index trend, which indicates the difficulty to control fire based on meteorological parameters, classified as low (<0.28), moderate (0.28–0.36), or high (0.36<) positive increase (Supplementary material, Fig. 1a),
II. Recurrence of fire, classified as low (1–5 years), medium (6–10 years), or high (more than 10 years) (Supplementary material, Fig. 1b),
III. Median fire intensity (Daily Fire Radiative Power), classified as low (<80 MW), medium (80–240 MW), or high (240 < MW). We calculated the Median fire intensity averages for a 5-km grid (Supplementary material, Fig. 1c),
IV. Time since the last fire event, classified as recent (2015–2020), intermediate (2009–2014), and distant past (2003–2008) (Supplementary material, Fig. 1d),
V. To identify fire-sensitive vegetation, we selected forest remnants within 30 m from watercourses (NWA, 2015), using the MapBiomas forest vegetation map (Souza et al., 2020).

We intersected the vegetation shape file with the resilience map of the Pantanal (i.e., the natural regeneration potential) (Pott et al., 2018), in order to classify areas as low, medium, or high potential for restoration. We classified remnant areas with a low natural regeneration potential as high priority. Finally, we compared current land use with potential land use in 2050 to obtain areas threatened by land conversion (Guerra et al., 2020a).

Our recommended actions were based on two strategies, fire prevention and damage mitigation (Fig. 1). For fire prevention, we identified areas of high fire risk, where the climatic conditions that facilitate extreme fire coincide with potential biomass accumulation. To identify these areas, we used the results of the previous step (i.e., historical tendency of fire, time since the last fire, and fire recurrence) and overlayed them with the conditions that increase fire risk: (i) high fire risk based on meteorological factors, (ii) a long time since the last fire resulting in fuel accumulation, and (iii) areas with low fire recurrence that potentially still host fire-sensitive species. After finding areas with high potential to burn, we overlaid these areas with forest vegetation associated with watercourses that potentially host fire-sensitive species.

For damage mitigation, we prioritised fire-degraded areas for restoration. We only considered areas that have suffered the highest damage to vegetation, based on the areas that (a) have been affected by high-, and medium-intensity fires since 2003, (b) burned since 2015, and (c) had high and medium fire recurrence since 2003. We overlaid these fire-degraded areas with the extent of riparian forests and the layer for natural regeneration potential to identify priority targets areas for restoration.

To estimate the cost to restore areas degraded by fire, we searched for published values for the Pantanal and surrounding areas (Antoniazzi et al., 2016; Benini and Adeodato, 2017; Imasul, 2016; Reis et al., 2021). As the Pantanal is enormous and the costs of logistics have a large effect on the total cost, these values should not be considered final and they should be updated based on new information when they become available. The type and extent of degradation also strongly affects restoration cost. This region has many different phytophysiognomies that demand different techniques, which will affect the cost. The involvement of different stakeholders can also change the cost. For instance, the restoration will be cheaper when implemented by the landowner compared to a hired company, because of taxes and wages.

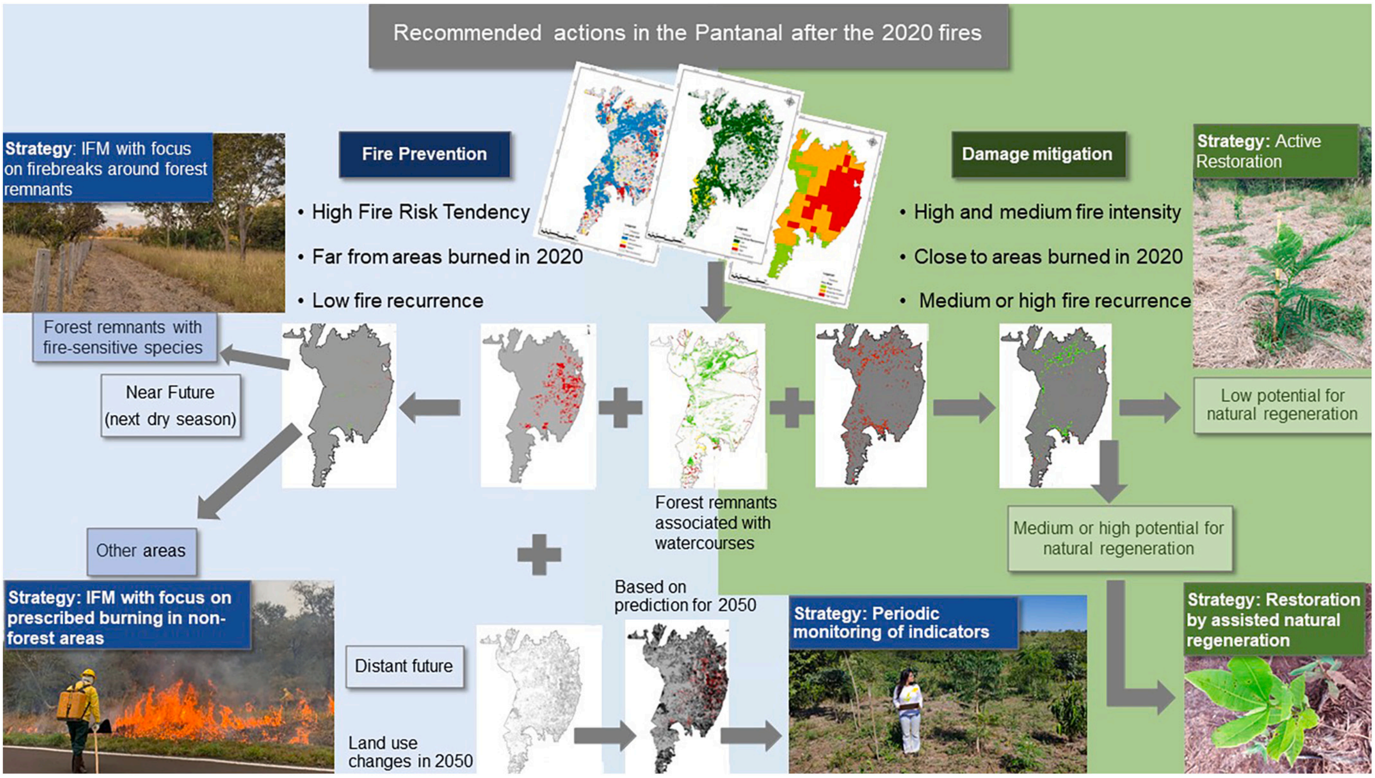

Fig. 1. Assumptions and variables used in the decision-making process to prioritise areas and actions and to inform fire-prevention and damage-mitigation strategies in the Brazilian Pantanal.

The availability of seed supplier and seed networks will also affect the price range. Here we used a simple estimate, recognising the limited nature of the currently available information. As the cost per hectare will depend on the strategy, to facilitate comprehension, we separated areas in need of passive and active restoration. We converted values in BRL into USD at the rate of the year of the data collection and corrected the value using the Consumer Price Index (White, 1999). We averaged per hectare costs reported in different publications for each of the three recommended techniques and multiplied this value by the number of hectares to obtain a final cost for the entire study area (Supplementary material, Table 1).

Fire prevention costs have not been reported for the Pantanal. Since the conditions in the Pantanal are similar to those in the Cerrado and 93% of the Brazilian Pantanal falls within private rural properties (Tomas et al., 2019), we adopted the 0.19 USD per hectare per year cost estimated by the “Aliança da Terra” program for private properties in the Cerrado (Oliveira et al., 2021). This cost of fire management programs includes six months of fire management, training, and capacity building (Oliveira et al., 2021).

3. Results

We identified 529,450 ha with a large amount of accumulated biomass that have a risk of extreme wildfires (Fig. 2b). These areas coincide with areas of dry vegetation and land use conversion in 2050 (Fig. 2c,d).

Considering the large size of the resulting area, we refined our prioritisation, selecting native remnants near watercourses that potentially contain fire-sensitive species. Hence, we mapped 24,580 ha with vegetation types that support fire-sensitive plant species and have a high probability of megafires based on climatic variables (Fig. 3). In these areas, 16,220 ha, 1722 ha and 6638 ha presented high, medium, low natural regeneration potential, respectively (Supplementary material, Table 2).

A large area was highly affected and degraded by recent fires. About 315,429 ha contained native riparian forest remnants with fire-sensitive species (Fig. 4).

Our analyses identified that around 90% of these areas (290,678 ha, Supplementary material, Table 2) present high potential for natural regeneration. We also identified 2854 ha with medium potential for natural regeneration and 21,898 ha with low potential. Most priority areas for fire prevention (Fig. 3–99,3%) and damage mitigation (Fig. 4–86%) are outside of protected areas and indigenous territories.

Considering their high and medium potential for natural regeneration, the cost to restore these areas relying on natural regeneration would be a one-off cost of around 122,990,391 USD (Supplementary material, Table 1). In the 21,898 ha identified as having low potential for natural regeneration, active restoration using transplanting seedling or enrichment planting is estimated to be 28,003,576-151,328,101 USD. The investment necessary to implement fire prevention in the 529,450 ha identified as having high fire risk based on the high amount of dry biomass is around 100,595,00 USD. If we only consider priority areas that include sensitive species (22,857 ha), the value is around 4343 USD annually.

4. Discussion

This study provides a prioritisation scheme considering the prevention of wildfires and damage mitigation through post-fire restoration. Our results can inform regional public policies to prevent the occurrence of megafires and advise ecological restoration of degraded areas by national and international organisations that want to repair the damage caused by past fires. Our data show that areas of high fire risk (high potential to spread fire) overlap with areas that are predicted to undergo land conversion in the future (Guerra et al., 2020a). These areas are near the Pantanal-Cerrado border known as the Arc of Deforestation (Guerra et al., 2020a). Based on historical data from 2001 to 2019, the size of burned area and the fire intensity have been moderate on the Cerrado

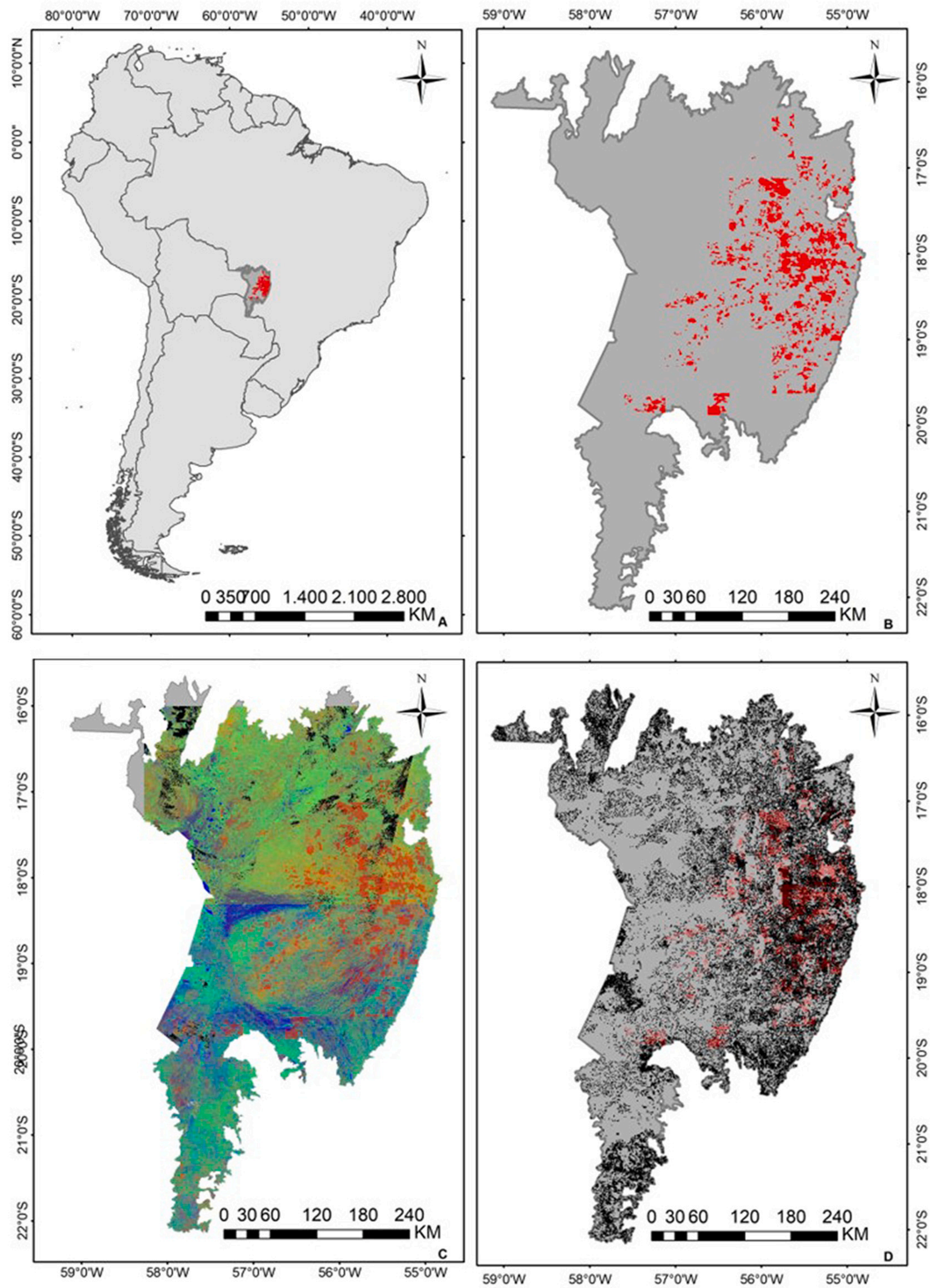

Fig. 2. (A) The location of Brazilian part of the Pantanal (dark grey), (A,B) areas of high fire risk (red), (C) areas of high fire risk marked on the fuel load map of IBAMA (2021) with dry vegetation (red), green vegetation (green) and clouds or water (blue). (D) Areas of current high fire risk (red) and considering land conversion scenarios for 2050 (black) (Guerra et al., 2020a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

side in the highlands of the Upper Paraguay River Basin, with large fire scars (Silva et al., 2021). Fire events are the major cause of forest disturbance in the tropics, occurring more frequently because of climate change (Ooi et al., 2014; FAO, 2020; Libonati et al., 2021). The synergistic effect of climate change and inadequate environmental governance have resulted in large wildfires in the Brazilian Pantanal (Leal-Filho et al., 2021; Libonati et al., 2020; Mega, 2020). Unfavourable climatic conditions continue and extreme events, such as intense droughts keep occurring (Marengo et al., 2021). In the long-term (over 30 years), prediction and studying different scenarios can help to structure plans and strategies and to make better choices. Fires, together with floods, have been historically shaping the landscapes of the Pantanal (Damasceno-Junior et al., 2021; Oliveira et al., 2014; Arruda et al., 2016). However, recent droughts and land-use changes have led to

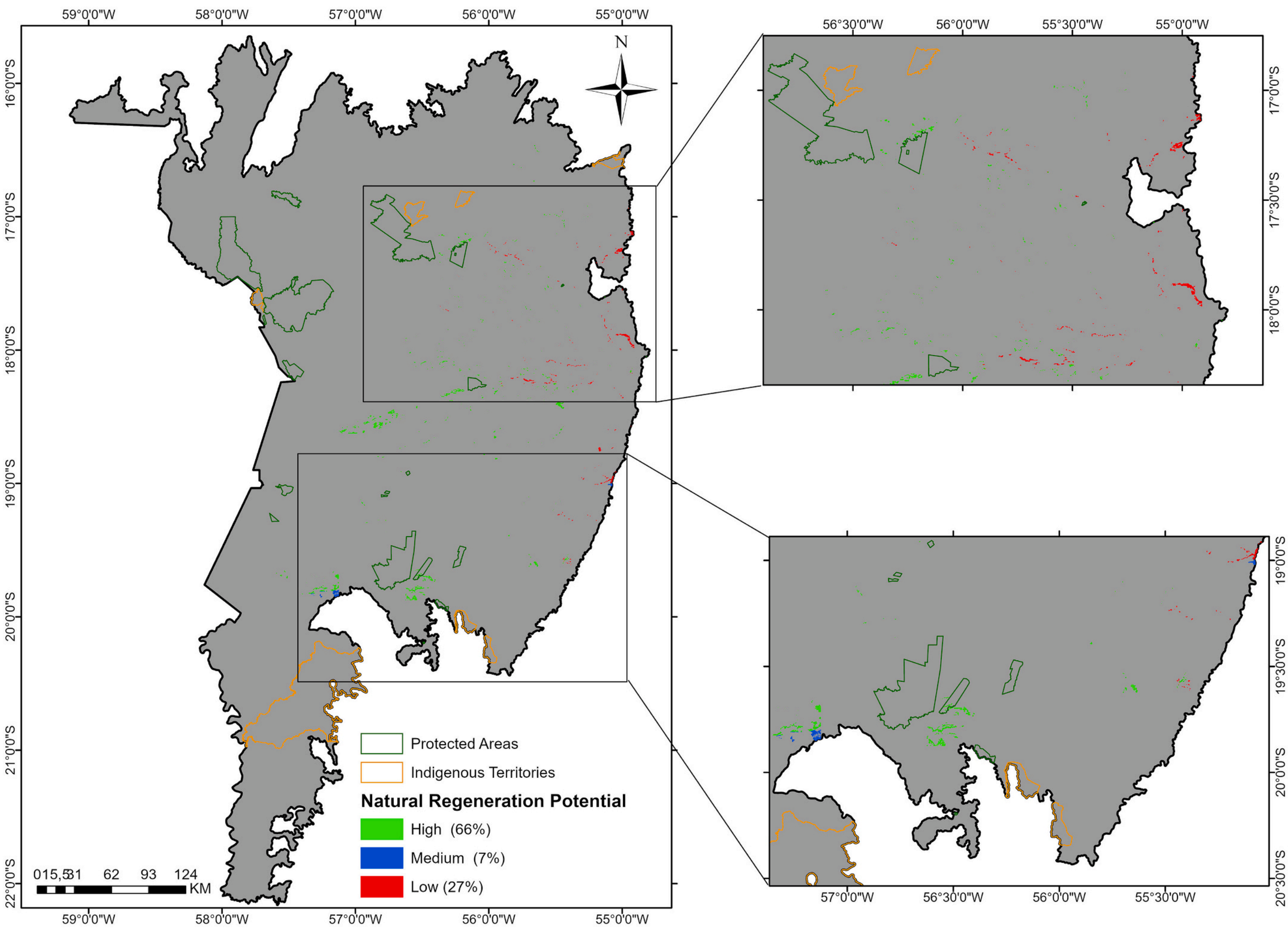

Fig. 3. Priority areas for fire prevention in the Brazilian Pantanal, showing Protected Areas (dark green) and Indigenous Territories (orange) along with forest vegetation associated with watercourses patches of low (red), medium (blue), and high (bright green) natural regeneration potential. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

larger areas getting affected by fires (Libonati et al., 2020). For instance, in 2020, 43% of the area affected had not been previously burnt in the last two decades (Garcia et al., 2022).

Regarding fire prevention, different vegetation types need different fire management strategies. Integrated Fire Management has been suggested as a tool to prevent extreme fires in the Pantanal (Berlinck et al., 2020; Damasceno-Junior et al., 2021; Garcia et al., 2021; Oliveira et al. n.d.). We suggest prescribed burning in grasslands or pastures located around the priority areas identified in our study, two to three years after the last fire event, depending on the recovery of the vegetation structure (Fig. 1). Prescribed burning should be conducted during the wet season, early during the short dry periods, or immediately after the rainy season, when the vegetation is still green and moist and the rains can control the fire (Garcia et al., 2021). Prescribed burning, particularly when informed by traditional knowledge, acts as micro-disturbance (Mistry et al., 2005; Flores et al., 2020). These smaller fires help to restore landscape heterogeneity and can effectively reduce fuel load by decreasing flammability and consequently, reduce the spread of wildfires (Mistry et al., 2005; Garcia et al., 2021; Santos et al., 2021; de Andrade et al., 2021). On the other hand, fires need to be prevented in riparian and gallery forests, as these vegetation types can host fire-sensitive species. We recommend creating firebreaks ("aceiros") in the first year after the last fire in the immediate area around the forest remnants that we identified as a priority and use prescribed burning in the surrounding non-forest vegetation types to decrease accumulated biomass (Fig. 1).

The cost of fire prevention is lower than fire suppression (Oliveira et al., 2021). The cost estimated by our study seems relatively low, as it only includes maintenance costs of equipment and vehicles, as well as communication and training costs, but it does nor include the income of firefighters and brigade chiefs, nor equipment, vehicles, and fuel costs (Oliveira et al., 2021). Our calculations are valid for situations when the landowners are conducting fire prevention using their own material and workforce. Future studies should consider all of these costs, including hiring new fire brigades and management taxes to obtain a more realistic estimate.

Regarding damage mitigation, passive and active restoration strategies can be used to mitigate the loss of biodiversity and ecosystem function (Williams-Linera et al., 2021). While it takes longer considering the recovery trajectory, passive restoration can still be a viable option when human and financial resources are scarce (Williams-Linera et al., 2021). However, depending on the resilience of the site, recovery may never occur, therefore, it is important to analyse the regeneration progress of the site. Even in fire-prone ecosystems, active restoration strategies may be necessary in areas that have been degraded by the fires, particularly in forest remnants with fire-sensitive species (Pivello et al., 2021).

Fire affects vegetation structure, species abundance, and richness, leading to fire-resistant species gaining dominance in the community (Zaidan and Carreira, 2008; Kohagura et al., 2020; Arruda et al., 2016;

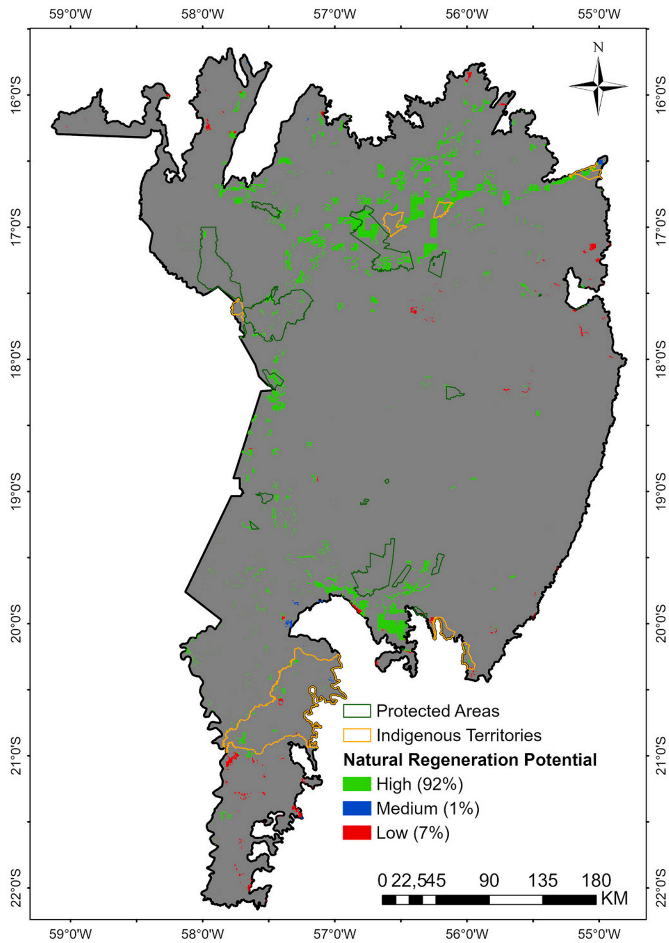

Fig. 4. Priority areas for damage mitigation: post-fire restoration in the Pantanal based on recently burnt areas (2015–2020) and forest vegetation associated with watercourses classified by natural regeneration potential (low (red), medium (blue) and high (bright green)). Protected Areas and Indigenous Territories are indicated in dark green and orange, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Bicalho et al., 2015). Fire generally affects plant germination in a negative way, but it can be positive for some species, which become dominant after fires, changing the community structure (Ferreira et al., 2021; Soares et al., 2021). Fire impacts are harder on fire-sensitive species, such as *Alchornea castaneifolia*, *Bactris glaucescens,* and *Genipa americana* (Pott and Pott, 1994; Pott and Pott, 2004; Damasceno-Junior et al., 2021), impacting monodominant stands that are also affected by floods (Manrique-Pineda et al., 2021). Fire also damages the canopy of moist forests, such as gallery and riparian forests (Flores et al., 2020). Recurrent and intensive fires reduce the populations of key species, such as *G. americana* (Pott and Pott, 2004), which is an important food resource for animals, a species of socio-cultural importance for Indigenous people (Libonati et al., 2020) and a potential raw material for a new kind of sustainable plastic (Santos et al., 2017). Hence, fires in areas with fire-sensitive species can lead to losses of key species populations.

Transplantation of naturally regenerating seedlings, focusing on the most abundant species of native remnants has a great potential as a restoration tool in the Pantanal, as it uses acclimatised individuals and preserves local and endemic genotypes (Reis et al., 2021). Since individual seedlings can be protected using fencing from herbivory by large mammals (Reis et al., 2021), it can be used as enrichment by planting the seedlings in a fire-degraded forest. In this case, we recommend using fire-sensitive species for planting. Seedling survival can be high even under extreme flooding, and this strategy is cost effective, being 61% cheaper than conventional planting of saplings and presents a viable option considering the limited availability of regional nurseries (Reis et al., 2021). However, this technique has just been tested in high-resilience forests in the Pantanal (Garcia et al., 2022) and still needs to be evaluated under potentially low natural regeneration. As there is no perfect technique for all areas, decisions should be made on a case-by-case basis.

The extreme fires in 2020 encouraged new measures to be implemented in order to avoid catastrophic fires in the future. For example, the Integrated Fire Management Decree publication N° 15,654/2021 published by the Mato Grosso do Sul State Government recognised fire use as a part of the ecological process, useful fire-prevention and fire-mitigation practices by indigenous people and traditional communities, and the importance of biomass reduction in agricultural systems. This Decree suggests ways to prevent extreme fires, integrating the government, civil society, landowners, and private sector through Integrated Fire Management Plans, the State Program of Fire Brigades, and the Interinstitutional Committee for Prevention and Combat of Forest Fires. This Decree established a permanent information system about wildfire, including monitoring and management, integrating all sectors of society and prioritised the investments in research on Integrated Fire Management. It also recommended IFM techniques and suggested that the process of hiring firefighters needed to be simplified. Our research endorses these measures, suggesting higher uptake. Nevertheless, the Decree fails in some aspects, for instance suggesting the replacement of native grassland with exotic species and promoting fire suppression instead of the use of prescribed burns (Garcia et al., 2021). As the Decree contains many positive recommendations for the use of fire as a management tool by landholders, we recommend revising this latter part (Decree N° 15,654/2021, article 38, item VI). Mato Grosso do Sul State also declared a "state of environmental emergency" (Decree "E" N° 26, of April 29, 2021) before the height of the fire season that facilitated the purchase of assets and services necessary for fire prevention. At the national scale, a new law (#11,276/2018) has been recently approved by the Chamber of Deputies and is currently under consideration by the National Congress.

The Federal Policy and State Public Prosecutor's Office are also acting to identify areas, where the first fires started in 2020, investigating possible anthropogenic reasons in order to prevent reoccurrence. Increased scientific research, connecting civil society organisations involved in fire prevention (for instance creating new fire brigades) and restoration, and engaging and educating society about the consequences of fires predicted a better year for 2021 compared to 2020. Nevertheless, some problems continued. In 2021, firefighters only got contracted in July, which is considered late and the Environmental Ministry announced further budget cuts for resources (Garcia et al., 2021). When the resources are less than what is necessary, actions need to be prioritised to support efficient strategies. Science-based decisions can help to focus actions on regions with the highest risk in the short-term. Science has an important role to respond to urgent demands from society, creating fast and cost-effective solutions. Multidisciplinary approaches are also becoming increasingly important to handle fire crises in the Pantanal (Libonati et al., 2020).

Our research focused on areas, where fire can cause the most damage based on high fire risk and the presence of fire-sensitive species. For these 22,857 ha, we did not consider the environmental liability of the farms (i.e., farms that lack native vegetation have a legal obligation to restore areas that add up to 50,000 ha for the whole Pantanal). Hence, in this study, we only considered areas that have native vegetation remnants, focussing on the restoration needs of the Pantanal beyond the 50,000 ha covered by legally mandated restoration and we did not tested overlap among these layers to seach for areas with overlapping. We also estimated the cost of restoration according to the level of degradation. It is extremely unlikely that such large-scale restoration can occur, but it is important to have the costs of restoration estimated to be able to prioritise post-fire restoration and fire prevention. In our study, while the cost per hectare of active restoration was higher, the area in need of passive restoration was considerably larger than the area for active restoration, resulting in a higher total value for passive restoration for the entire Pantanal. We also need to disseminate information to the community about the extent of the damage and raise awareness about the importance of fire prevention. Practical results will only be achieved if the recommendations of this study reach the interest of landholders, managers, decision makers, and the public. Our maps clearly show that most priority areas for fire prevention and damage mitigation are outside of protected areas and indigenous territories, so landowners will need to help.

In this study, we provided science-based recommendations that have already been accepted by the State Public Prosecutor's Office to alert landholders about the urgent actions, encouraging them to implement Integrated Fire Management and restoration efforts to enhance the recovery of the Pantanal after fire. Investment in fire prevention can reduce 50% of the burned areas (Oliveira et al., 2021). Hence, we suggest focusing investments in priority areas identified in this research to avoid this tragedy happening again. Priority areas should be restored according to their natural regeneration potential and available resources, evaluated on a case-by-case basis.

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Credit Author Statement

PIM and LBCB collected and analysed the data and wrote the first draft. JKS refined and edited drafts of the text and the figures. LCG and RL conceived the ideas, and designed the methodology, and coordinated the manuscript. All authors contributed to organisation and writing of the manuscript, contributed critically to the drafts and gave final approval for publication.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2021.106517.

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