



# Joining forces to fight wildfires: Science and management in a protected area of Pantanal, Brazil

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## ABSTRACT

In 2020, the world's largest continuous stretch of wetlands, the Pantanal in South America, recorded its most catastrophic fire season of the last two decades, resulting in severe economic, ecological and health consequences. Regional environmental institutions and communities are taking measures to protect their unique ecosystem, as is the case of the Reserva Particular do Patrimônio Natural (RPPN) Sesc Pantanal, a national protected area. The reserve was severely affected by the 2020 wildfires and is now en route to recover and intensify prevention strategies. Here, we employ a state-of-the-art satellite-derived burned area dataset and a global climate reanalysis product to map and assess the incidence and vulnerability of this reserve to its most concerning disturbance: wildfires. We validated the remote-sensed burned area product and found that the product successfully maps the years with higher fire activity. Then, we studied historical occurrences of burned areas within the reserve. The results show large burned areas are uncommon, and highlight the year 2020 as an outlier, when around 65 % of the reserve was burned. Climate trends over the last four decades show increasing temperatures and wind speed, and decreasing relative humidity and precipitation. Fire weather is thus steadily rising, bearing favourable conditions for fire activity over the most critical months of the year. This study provides useful information for fire management decisions within the largest privately held natural reserve in Brazil, and further allows the assessment of the applicability and limitations of large-scale and state-of-the-art products to inform decision-making within protected areas.

## 1. Introduction

Pantanal is the largest continuous stretch of wetlands in the world, characterised by an ever-changing boundary between land and water, where many regions change seasonally from terrestrial to aquatic systems (Alho and Silva, 2012). In Brazilian territory, the Pantanal biome covers the Brazilian states of Mato Grosso do Sul and Mato Grosso, and it is surrounded by the Cerrado and Amazon biomes, where spring-fed rivers and headwaters are located (Guerra et al., 2020). The Pantanal captures water from the surrounding plateaus during the rainy season, and then drains it slowly to the lower sections of the Paraguay river, creating a complex drainage network (Ivory et al., 2019). Its landscape consists of a mosaic of floodable and non-floodable grasslands, forests,

open woodlands, and temporary or permanent aquatic macrohabitats (Cunha et al., 2021; Tomas et al., 2019). This allows for high biodiversity (Tomas et al., 2019). In 2000, the “Pantanal Conservation Area” was inscribed on UNESCO's World Heritage list (UNESCO, 2024), and around 25,156,000 ha were deemed as an UNESCO Biosphere Reserve (UNESCO, n.d.). These sites are home to nearly 3 million people, and the Pantanal Biosphere Reserve is one of the largest biosphere reserves in the world (UNESCO, 2023).

Pantanal is also considered a fire-dependent biome, where fire influences species type, abundance, and ecological functioning and processes (Pivello et al., 2021). Fire promotes seed germination for some species (Pott and Pott, 2004) and, along with the flood pulse, it allows the existence of several monodominant vegetation types

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(Manrique-Pineda et al., 2021; Pott et al., 2011). Accordingly, both fire and flood act as ecological filters that, among other factors, shape the structure of plant communities in tropical wetlands and floodable savannas, in such a way that this neotropical savanna wetland system is resilient as long as its natural patterns and periodicities of flooding and burning are maintained (Arruda et al., 2016; Oliveira et al., 2014). Lightning strikes may sometimes originate fire in the Pantanal region, however this natural source is infrequent and more likely to happen during the summer period, from December to February (Menezes et al., 2022). The vast majority of fires in Pantanal are associated with anthropogenic ignitions (Menezes et al., 2022).

In 2020, severe wildfires threatened the delicate balance of Pantanal's wetlands. Around a third of the biome was burned (Libonati et al., 2020), killing at least 17 million vertebrates (Tomas et al., 2021). The severity of these wildfires has been linked to several environmental and socioeconomic factors, including: severe drought; location of the fire corridor in the Paraguay River flood zone; firefighters' constraints; insufficient wildfire prevention strategies; and budget reductions in public environmental agencies (Garcia et al., 2021). More than a third of these wildfires occurred in areas previously unburnt or where burning is not usual (Barbosa et al., 2022; Garcia et al., 2021; Libonati et al., 2022), and mostly over natural vegetation (Correa et al., 2022). They particularly affected forested regions, contributing the most (47 %) to the total carbon loss of the 2020 Pantanal wildfires (Barbosa et al., 2022).

The 2020 wildfires have also been shown to be closely linked with atypical meteorological conditions (Libonati et al., 2022; Marques et al., 2021), particularly a prolonged and severe drought (Marengo et al., 2021; Thielen et al., 2020). Fire danger levels in 2020 reached unseen values over the last 40 years and large burned areas occurred simultaneously with compounded drought and heatwave events (Libonati et al., 2022). Climate change has been occurring fast in the Pantanal, with temperatures rising steadily over the last four decades (Libonati et al., 2022; Marques et al., 2021), along with increased evapotranspiration rates (Marques et al., 2021). Soil moisture has been decreasing (Marques et al., 2021) and the number of days without precipitation has substantially increased, while the water mass during the drought season decreases (Geirinhas et al., 2023; Lázaro et al., 2020). The extent of wildfires in Pantanal has been linked to the occurrence of heatwaves (Silva et al., 2022) that are rising together with extreme hot conditions (Libonati et al., 2022; Marengo et al., 2021). Expected future changes in climate might provide even more favourable conditions for wildfires to occur (Ribeiro et al., 2022; Marengo et al., 2016).

In light of ongoing and future climate change, and motivated by the events of 2020, the academic community has been making efforts to further understand and characterise historical fire and climate patterns in Pantanal. Likewise, protected areas within the biome are already being adapted and measures are being taken to prevent such events from happening again. Over the last decades, most protected areas in Pantanal followed a zero-fire policy due to the perceived negative consequences of any type of fire on the native vegetation. However, the wildfires of 2020 put the effectiveness of the zero-fire policy into question (Garcia et al., 2021). Part of the answer might lie in the neighbouring biome, the Cerrado, where a broad approach dedicated to the use of fire to manage rural and traditional territories was introduced in some protected areas in 2014, known as Integrated Fire Management (IFM) (Schmidt et al., 2016). The successful results generated with the IFM implementation led the federal public authorities, responsible for Brazilian protected areas, to expand and recommend this approach to other areas with recurrent fire issues (Schmidt et al., 2018). The IFM aims to change harmful fire regimes (frequent, high intensity wildfires that burn large areas in the peak of the dry season) to the ones that benefit at the same time environmental conservation and socioeconomic needs, by accounting for cultural and scientific knowledge and technical experience (Myers, 2006).

However, the lack of long-term reliable data in Pantanal hinders these assessments and the ensuing decision-making. There are very few

long-term meteorological stations in Pantanal, and these are mainly located in the southernmost regions (Hofmann et al., 2010). This provides an opportunity to explore reanalysis products which provide observation-based estimates of meteorological fields, around the globe, with a common spatial and temporal resolution. Similarly, the systematic quantification of burned areas is only possible due to recent advances in remote sensing techniques and burned area mapping by satellite information.

Although satellite-derived products provide a means to obtain spatially and temporally consistent burned area data, their applicability and usefulness in fire management highly depend on the time and spatial scales at which these products operate. Quick and real-time management decisions rely on near-real time estimates that, until a few years ago (ALARMES, n.d.), could only be provided for Pantanal through active fire products (e.g. FIRMS). On the other hand, long-term fire dynamics can be easily assessed through satellite-derived burned area products. Although great strides have been made over the last decades to improve satellite-derived burned area estimates, the automatic detection of burned areas remains complex due to the wide spatial and spectral diversity of burned patches (Bastarrika et al., 2011). In general, most satellite-derived burned area products develop algorithms to reduce false alarms (commission errors) while increasing the detection of burned patches (omission errors). Balancing and reducing commission and omission errors becomes challenging as strict detection criteria may lead to lower commission errors but may fail to detect fires, while the opposite would occur with less strict detection criteria (Boschetti et al., 2004). Accordingly, global products often employ algorithms that consider a wide range of burning conditions and thus have distinct commission and omission errors in different landscapes (Rodrigues et al., 2019). On the other hand, algorithms that are developed for a specific site or ecosystem may provide more accurate estimates, albeit at the expense of applicability in other regions (Campagnolo et al., 2021).

Here, we employed a burned area product specifically developed for Brazilian biomes and a state-of-the-art global reanalysis dataset to study fire and climate within a privately held natural reserve in Pantanal: the Reserva Particular do Patrimônio Natural (RPPN) Sesc Pantanal. First, we validated the satellite-derived burned area dataset to the study region. Then, we used the validated data to evaluate historical fire activity within the reserve and further evaluated climate trends to understand current and future vulnerability to climate change. Lastly, these results were interpreted in light of past and current fire management within the RPPN Sesc Pantanal, along with ongoing and future challenges.

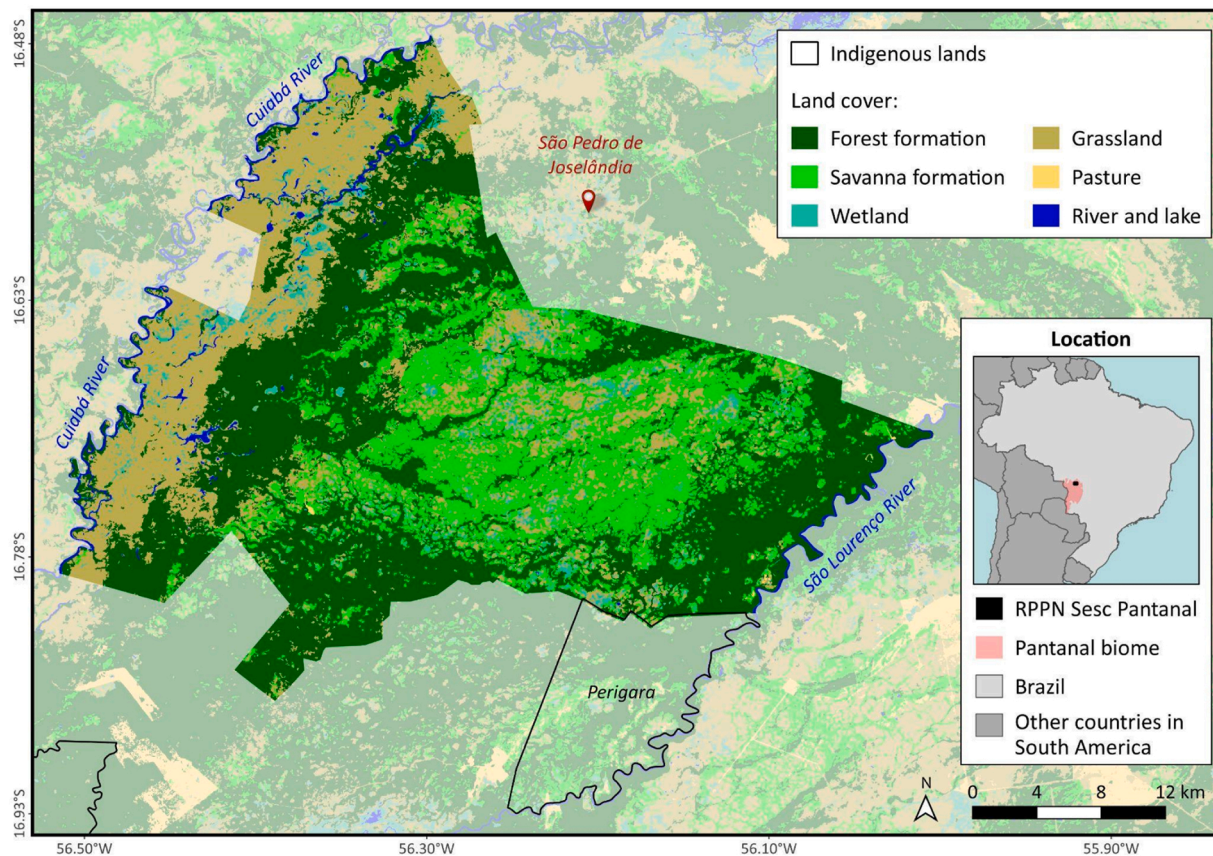
## 2. Data and methods

### 2.1. Study area

Located in northern Pantanal, the RPPN Sesc Pantanal is managed by the Serviço Social do Comércio (Sesc, a Commercial Service Institution), covering slightly less than 108,000 ha. Created on July 4<sup>th</sup>, 1997, in the municipality of Barão de Melgaço, in Mato Grosso state, this reserve has been dedicated to preserving and restoring its biodiversity and ecosystems over the last 20 years. The maintenance of the RPPN Sesc Pantanal ensures the availability of water and its quality and supports high levels of biodiversity. Since 2000 it has been included as part of Pantanal's Biosphere Reserve and 3 years later it became a Ramsar site adhering to its Convention on Wetlands, an intergovernmental treaty signed in 1971 that provides the framework for the conservation and the wise use of wetlands and their resources (Ramsar, 2023).

The western and eastern parts of the reserve are bordered by the Cuiabá and São Lourenço rivers respectively, and the southern region shares a border with the Indigenous Land of Perigara (Fig. 1). The surroundings of the RPPN Sesc Pantanal are mostly occupied by cattle ranches and the district of São Pedro de Joselândia with a population of around 2000 people dispersed in rural properties.

Hofmann et al. (2010) provided an extensive characterization of



**Fig. 1.** Map of the RPPN Sesc Pantanal with land cover information for 2021 (MapBiomas, 2023), along with its location within the Brazilian Pantanal (pink) and Brazil/South America (light/dark grey) in the lower right panel.

climate within the RPPN Sesc Pantanal. According to the Köppen climate classification, they defined climate in the reserve as “Aw” (Tropical savanna climate with dry-winter characteristics), marked by a pronounced dry season in the winter. Rainfall occurs during the summer, with annual totals varying between 1000 and 1600 mm. The reserve’s territory is periodically flooded in almost its entirety during the rainy season (December to April), due to the accumulation of rainfall in the region and on headwaters of rivers within the Alto Paraguai basin. It also features very high temperatures with monthly means above 22 °C and an average annual temperature of around 26.5 °C.

The reserve has a wide variety of vegetation types and has recently been described with 13 macrohabitats (Cunha et al., 2021), including both fire-sensitive and fire-dependent formations (Pivello, 2011). All the environments within the reserve are preserved and free of anthropogenic disturbance for more than 20 years (Brandão et al., 2011).

## 2.2. Datasets and pre-processing

Burned area data was obtained from the AQM-LS V1 product (Pereira et al., 2021) covering the 2000–2021 period. The AQM-LS product is a joint effort of LASA/UFRJ and Instituto Federal de Educação, Ciência e Tecnologia do Sul de Minas (IFSULDEMINAS). Derived from multi-temporal composite satellite imagery, namely Landsat missions, at 30 m spatial resolution, this algorithm also uses machine learning and active fire data to map yearly burned areas. Here, we employed one of the first versions of the AQM-LS extended to the Pantanal biome.

For validation, Landsat imagery from the U.S. Geological Survey was accessed from Google Earth Engine (GEE). All imagery was collected for Level 2, Collection 2, and Tier 1, for Landsat missions 5, 7, and 8, spanning from 2000 to 2021.

Land cover information was obtained from the MapBiomas

Collection 7 product (MapBiomas, 2023). MapBiomas Collection 7 mapped 27 classes of land use and land cover annually over all Brazilian biomes from 1985 to 2021. It relies on a random forest algorithm applied to Landsat satellite imagery, with a spatial resolution of 30 m (Souza et al., 2020). We used the 2000–2021 period, to match the range of the burned area satellite-derived product. Moreover, for the purposes of this study, all pixels within the “River, Lake and Ocean” class (ID 33) were removed.

To evaluate the current climate, we studied climatic variables often used in fire danger assessment to represent distinct components of fire occurrence, frequency, and behaviour, namely: temperature, precipitation, relative humidity, and wind speeds (IPCC, 2022; UNEP, 2022). To do so, we used ERA5, the state-of-the-art reanalysis product from the European Centre for Medium-Range Weather Forecasts (ECMWF; Hersbach et al., 2020). ERA5 runs from 1959 to the present, with hourly output, and describes the Earth in a regular  $0.25^\circ \times 0.25^\circ$  grid which corresponds to, approximately,  $25 \text{ km} \times 25 \text{ km}$ . For this analysis we used the following meteorological parameters taken at 16:00 UTC (which corresponds to 12:00 local standard time, as per methods used in the Canadian Forest Fire Weather Index system; Van Wagner, 1987) from 1980 to 2021: 2-metre temperature, 2-metre dew point temperature, and the u and v components of 10-metre wind. Hourly fields of total precipitation were also downloaded and accumulated into daily totals. Surface and dew-point temperatures are used to estimate relative humidity by means of the August–Roche–Magnus formula (Lawrence, 2005). Finally, wind u and v components were also converted to wind speed (ECMWF, 2024). Amongst several reanalysis products, ERA5 has shown increased accuracy in simulating wind speeds in Brazil (Siefert et al., 2022). Data for all variables was masked to the shapefile of the RPPN Sesc Pantanal, and all grid points that touched the reserve’s polygon were used.



ERA5's fire danger product based on the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987), was also employed (Vitulo et al., 2020). The FWI system uses daily values of temperature, relative humidity, wind speed and daily precipitation to estimate seven indices that describe different components/constraints of fire. Here, we used the Daily Severity Rating (DSR), a numerical representation of the difficulty of controlling fires computed using the FWI index, that more accurately reflects the expected effort required for fire suppression. The FWI system is a highly adaptable fire danger index system, widely used to characterise meteorological fire danger worldwide (e.g. Quilcaille et al., 2023; IPCC, 2022; Jain et al., 2022; Abatzoglou et al., 2019). Both FWI and DSR have been used to study fire in Brazilian biomes (Li et al., 2021; Silva et al., 2019), including Pantanal (Libonati et al., 2020, 2022; Martins et al., 2022). Similarly to meteorological fields from the ERA5 reanalysis, DSR data was also masked to the shapefile of the RPPN Sesc Pantanal, including all grid points that touched the polygon.

### 2.3. Validation of the burned area product

To validate the AQM-LS product within our study area, we visually inspected multitemporal Landsat imagery using Geographic Information System (GIS) technology, particularly QGIS version 3.22.6 with GEE plugin integration. Visual inspection is often employed in validation studies (e.g. Bowman et al., 2003), algorithm development (e.g. Pinto et al., 2021, Daldegan et al., 2014), and operational purposes (Bastarrika et al., 2011). For each year, we compared the yearly AQM-LS burned area map with Landsat imagery from January 1 to December 31 in colour composition (red, green and blue; RGB). The combination of the reflectance spectral bands of short-wave infrared (SWIR, in Red), near-infrared (NIR, Green), and red (Blue), allowed the visual identification of vegetation fire scars by contrasting fire events (shades of red) with the unburned vegetation (shades of green). This colour composition has been shown to allow an easy interpretation of burned areas (Pinto et al., 2021, Pereira et al., 1999). By overlaying the AQM-LS burned area map with the Landsat imagery in RGB, we investigated the spatial and temporal agreement/discordance between these products. Commission errors (i.e. false alarms) were manually removed from the raw AQM-LS mapping, henceforth referred to as the validated version (AQM-LS<sub>val</sub>).

### 2.4. Analysis of burned land cover

To assess the land cover types that corresponded to burned areas in AQM-LS<sub>val</sub>, we simply overlapped and intercompared pixel to pixel these products in the same raster format, as they have the same spatial (30 m) and temporal (yearly) resolution. We then assigned the correspondent land cover classification to each burned pixel in the AQM-LS<sub>val</sub> product.

### 2.5. Statistical analysis

To evaluate interannual climate patterns we focused on the period from July to October, when most wildfires occur in Pantanal (Damasceno-Junior et al., 2021). Averages were computed in the case of temperature, relative humidity, wind speed, and the fire danger index (DSR), and precipitation was aggregated over these months. Climate extremes were evaluated through the 90<sup>th</sup> percentile of temperature, wind speed, and DSR, and the 10<sup>th</sup> percentile for relative humidity.

Trends in burned area and climate variables were evaluated using the non-parametric Theil-Sen regression (Sen, 1968; Theil, 1950), a robust estimator insensitive to outliers with a breakdown point of about 29.3 % compared to simple linear regression. The statistical significance of the trends was evaluated by the two-tailed Mann-Kendall non-parametric test at the 5 % significance level (Kendall, 1975; Mann, 1945).

Lastly, the relationship between interannual burned area and the fire danger index was estimated through simple linear regression, and

goodness of fit evaluated by the coefficient of determination ( $R^2$ ).

## 3. Results

### 3.1. Validation of the burned area product

We found that there are considerable differences between the raw AQM-LS product and Landsat imagery. The AQM-LS algorithm showed commission errors for almost all years of the time series, leading to an overestimation of burned areas within the RPPN Sesc Pantanal (Fig. 2).

Years with higher burned areas were found to be properly mapped (Table S1), in which the difference between the validated (AQM-LS<sub>val</sub>) and raw AQM-LS products range from 0 % to 9 % (2003, 2005, 2010, 2019, and 2020). On the other hand, differences reached 100 % in four years (2000, 2001, 2009, and 2018), in which all mapped burned areas were commission errors, and another six years had commission errors above 94 % (2004, 2006, 2011, 2013, 2014, and 2021). Nevertheless, these high relative differences between the raw and validated products correspond to small burned areas, ranging from 100 to 2900 ha. Only the year 2000 was particularly anomalous as the AQM-LS product assigned 12330 ha of burned areas, where there were none.

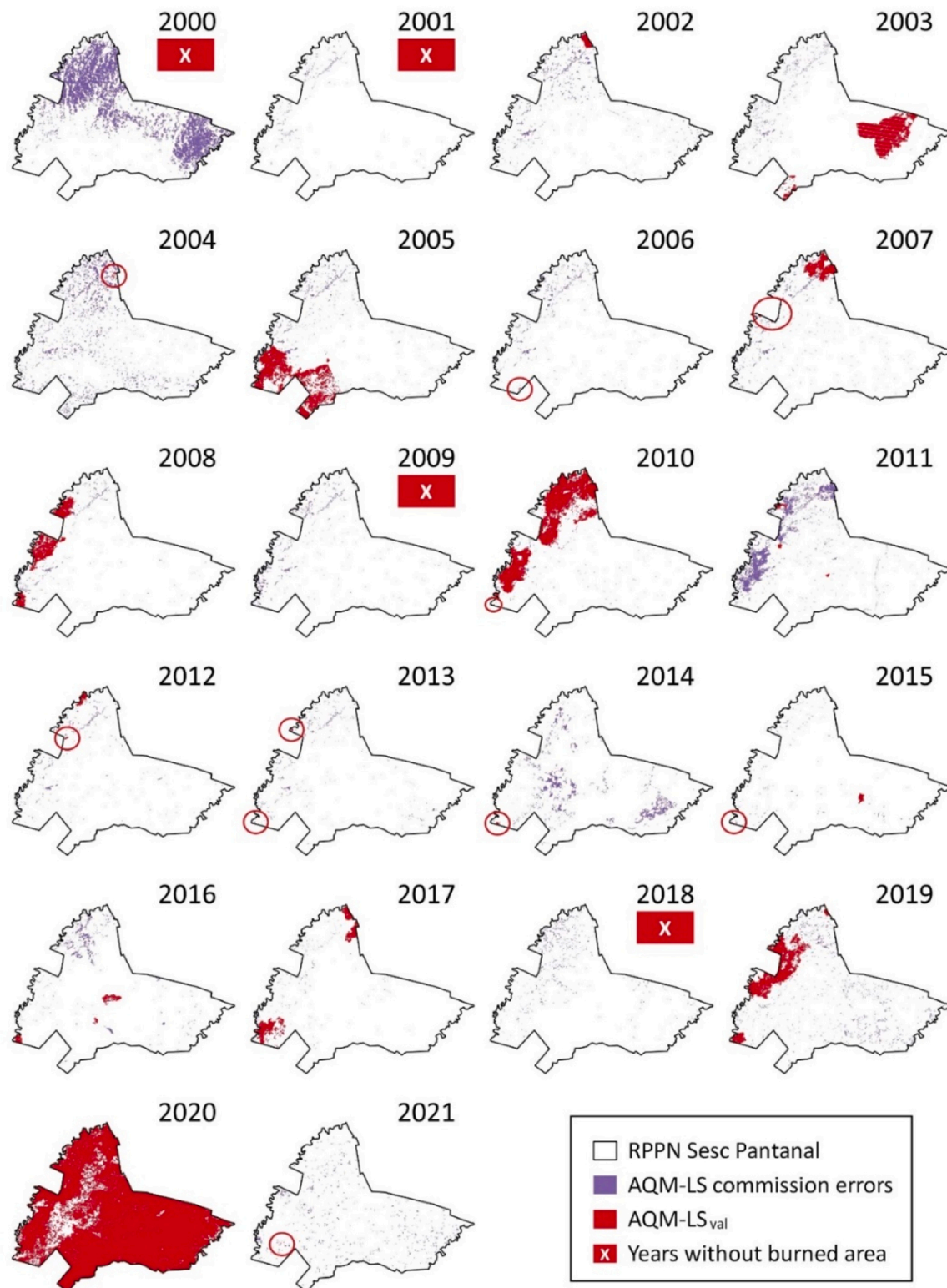
Commission errors were often due to misclassification of clouds, water bodies, seasonally flooded areas, and paths (Figure S1). It is also worth noting the case of 2003 (Figure S2), where there are clear missing gaps in data, both in the AQM-LS mapping and in Landsat imagery used for the visual validation, due to the failure of the Scan Line Corrector in Landsat-7 from June 1<sup>st</sup> 2003 onwards (USGS, n.d.).

### 3.2. Historical fire characterization

Using AQM-LS<sub>val</sub>, we characterised historical fire activity within the RPPN Sesc Pantanal. As in the entirety of the Pantanal biome (Libonati et al., 2022), 2020 recorded severe wildfire events, with more than 70000 ha of burned area (around 65 % of the reserve's area), severely contrasting with the previous years (2000–2019) when there was an average of 1685 ha burned per year (Fig. 3a). Unlike previous years, the wildfires advanced towards the centre of the reserve and 70 % of the total burned area in 2020 had not been burned before (over the 2000–2019 period).

Before 2020, only in 2010, the reserve burned over 10000 ha, and the most extreme events were found to be those burning above 2004 ha (the 75<sup>th</sup> percentile). Over 22 years of data, no burned area trend was found. Most areas were hit only once (69 % of the total burned area), most of which occurred in 2020 (Fig. 3b). A smaller percentage of areas burned two (20 %) or three (9 %) times over the 2000–2021 period, and only 2 % burned more than four times. Around 33 % of the reserve seems never to have burned over the last 22 years.

Recurring burned areas are located in the western region (Fig. 3b), near the Cuiabá river and on the frontier with adjacent territories. These regions are classified as grasslands by the MapBiomass product in 2021 (Fig. 1), but it is worth noting that the MapBiomass product alternatively considers this region as grasslands and wetlands (depending on the year). Accordingly, when analysing burned areas by land cover type throughout 2000–2019 (Fig. 4), most burned areas occurred in grasslands and wetland formations corresponding to this western region. Wetlands and grasslands corresponded to approximately 50.8 % and 27.3 % of the total burned areas over this period, followed by savannas and forests (12.9 and 8.4 %, respectively). The year of 2020, however, changed this pattern: most burned areas occurred in forested areas (37.4 %), followed by grasslands (29.7 %) and savanna formations (27.2 %). The years of 2005 and 2010 also burned a larger portion of forest, with 1165 (22.6 % of the total annual burned area) and 632 ha (5.8 %), respectively. Lastly, in 2003, a large stretch of burned savanna, around 2966 ha (58.3 %), exceeded the areas burned of grasslands, with slightly more than 1802 ha (35.4 %).

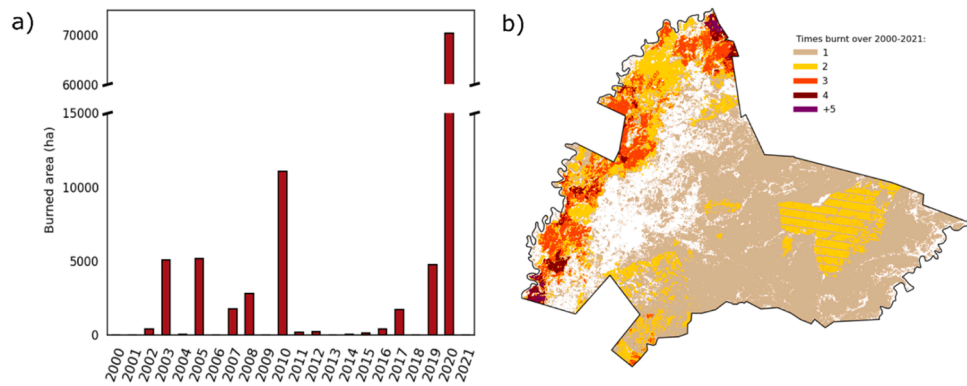


**Fig. 2.** Year to year mapping of burned areas by the AQM-LS product from 2000 to 2021. Commission errors are shown in purple, and hits (AQM-LS<sub>val</sub>) are shown in red. Years with a white X in red background highlight years where the validation found no burned areas, and the red circles highlight very small burned areas.

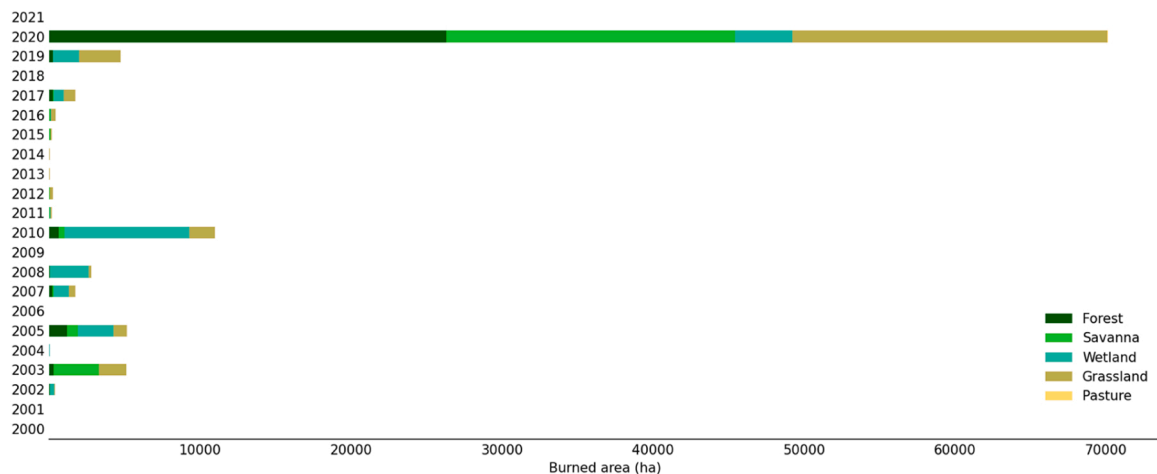
### 3.3. Climate

Regional climate within the RPPN Sesc Pantanal was characterised using reanalysis data. Considering the average over the last 40 years, higher temperatures were found from August to October, preceded by the lowest temperature values from May to July (Fig. 5a). There was

little variation in absolute temperatures, with temperatures ranging from 30–31 °C during the austral summer months (henceforth defined as December, January and February) and 29–32 °C in austral winter (henceforth defined as June, July and August). Conversely, relative humidity had higher variability (Fig. 5b): lower values from July to September ranging from 43 % to 48 %, and summer months from 68 %



**Fig. 3.** a) Interannual variability of burned area from 2000–2021 as estimated by the validated AQM-LS product (AQM-LS<sub>val</sub>). b) The number of times a pixel was burnt over the time series (2000–2021).



**Fig. 4.** Land cover types of burned areas using the validated AQM-LS product (AQM-LS<sub>val</sub>) from 2000 to 2021.

to 71 %. The reserve also showed a marked rainfall seasonality (Fig. 5c), with a dry season from April to October, reaching minimum rainfall values from June to August (below 16 mm/month). Summer months represented, on average, 51 % of total annual precipitation, and the average annual precipitation over the last 40 years was around 1459 mm. Finally, the months with the highest wind speeds occurred from July to September with 9.2–9.5 km/h (Fig. 5d).

However, we found that seasonal patterns seem to be changing (Fig. 5). Although the seasonality of temperature does not appear to be altered, its magnitude is higher the closer it is to the 21<sup>st</sup> century (Fig. 5a). Values from 2020–2021 were well above those of the previous decade (2010–2019), and when looking at seasonal cycles per year (Figure S3), both years achieved unprecedented temperature values in September and 2020 continued with record values up to November. Similarly, relative humidity values from the 1980–1999 period were systematically higher than the following 20 years (2000–2020), particularly from the months of August to October (Fig. 5b). Both 2020 and 2021 achieved unseen lower relative humidity values from August to September, and 2020 reached minimum values over most of the months (Figure S3).

The later months of the dry season show decreasing precipitation over the last decades, with 2020–2021 having remarkably less rainfall in September and October than the climatological mean (Fig. 5c). Although wind speed patterns were not as easily interpreted, it is worth pointing out that wind speeds during the 2020–2021 period were also systematically higher than the climatological mean for months May to August (Fig. 5d).

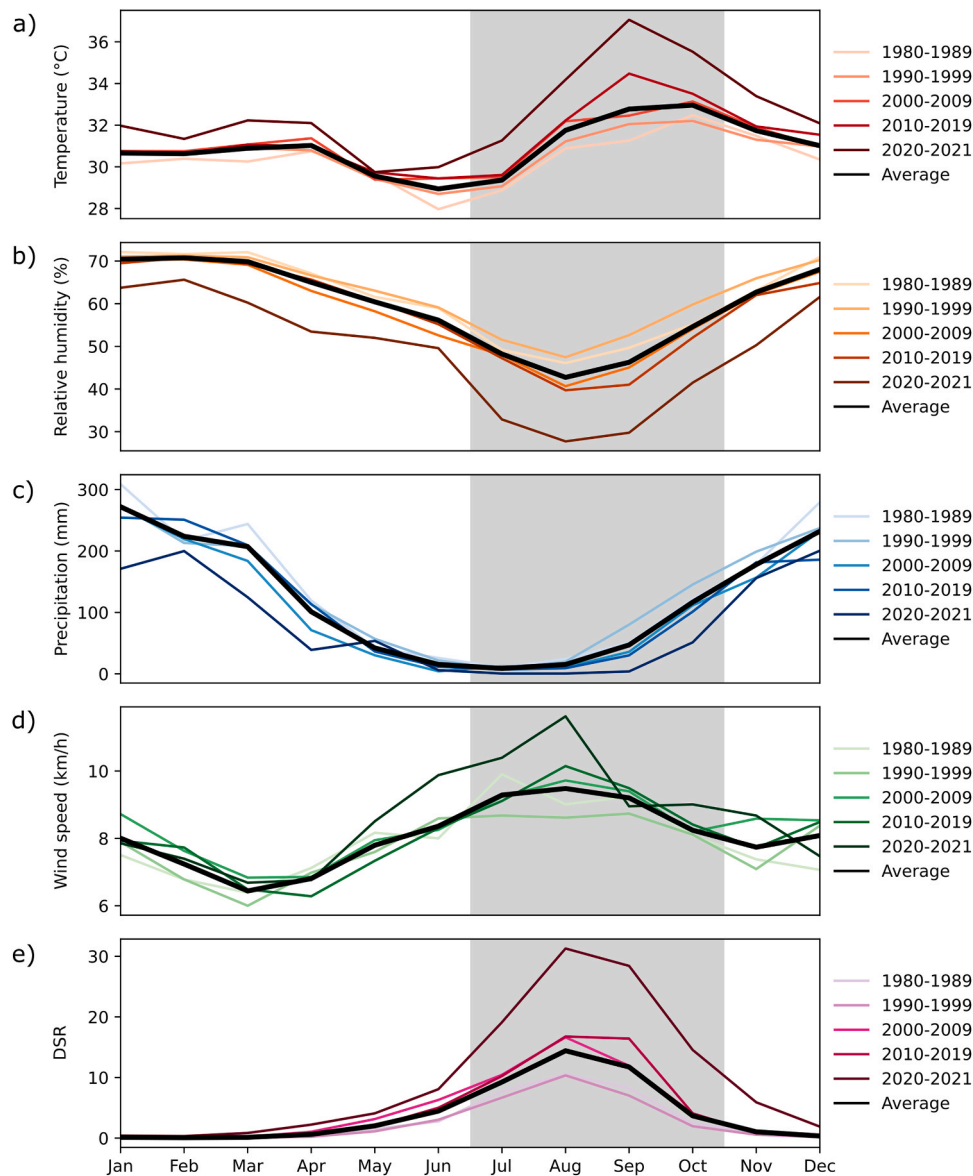
The 4-month period from July to September coincides with yearly

maximum temperatures and wind speed, lowest values of relative humidity, and the end of the dry season. Accordingly, fire danger achieved higher values from July to September, and reached its maximum in August. Consistent with climatic trends, the DSR was found to be systematically increasing over the last decades, and the 2020–2021 period achieved much higher values than the climatological mean (Fig. 5e).

Moreover, meteorological conditions favourable to fire seem to be increasing since 1980, particularly in the critical months from July to September (Fig. 6). Average temperatures and wind speeds were found to be steadily rising (at a rate of 0.76 °C and 0.18 km/h per decade; Figs. 6a and 6d), while relative humidity and precipitation showed decreasing trends (lowering 2.74 % and 33.1 mm per decade, respectively; Figs. 6b and 6c). Accordingly, DSR was also substantially increasing at a rate of 22.8 per decade (Fig. 6e). The year of 2020 showed unprecedented fire danger values over the time series, when DSR reached a maximum of 25. In contrast, there was a slight decrease in DSR values during 2021 (21).

The average of annual precipitation has also been decreasing at an alarming rate of –99.7 mm/decade (Figure S4). The average value for the last 10 years (2012–2021), around 1297 mm, was significantly lower than the climatological mean (1459 mm). Even when looking at the wet season, particularly the summer months, responsible for most of the yearly rainfall, there was also a decreasing trend of –47.3 mm/decade.

Temperature extremes seem to be increasing more than average, at a rate of 0.76 °C per decade (Fig. 6a). The 10 % lowest relative humidity values also showed a decreasing trend in the July–October period, at a rate of 2.67 % per decade (Fig. 6b). Lastly, wind speed showed no



**Fig. 5.** Seasonal cycles of: a) surface temperature ( $^{\circ}\text{C}$ , red); b) relative humidity (%; orange); c) precipitation (mm, blue); d) wind speed (km/h, green); and e) fire danger index Daily Severity Rating (DSR) (dimensionless, purple). Lighter to darker colours represent a decadal mean from 1980–1989 to 2010–2019, and the average for the last 2 years (2020–2021). Black lines are the average over the time series, from 1980 to 2021. Grey shaded areas represent the months from July to October.

significant trends for extreme values (Fig. 6d).

There seems to be little correlation between the fire danger index and burned area. A simple linear regression model using averaged values of DSR from July to October as predictor of interannual burned areas (AQM-LS<sub>val</sub>) resulted in a coefficient of determination of 0.48 (Figure S5).

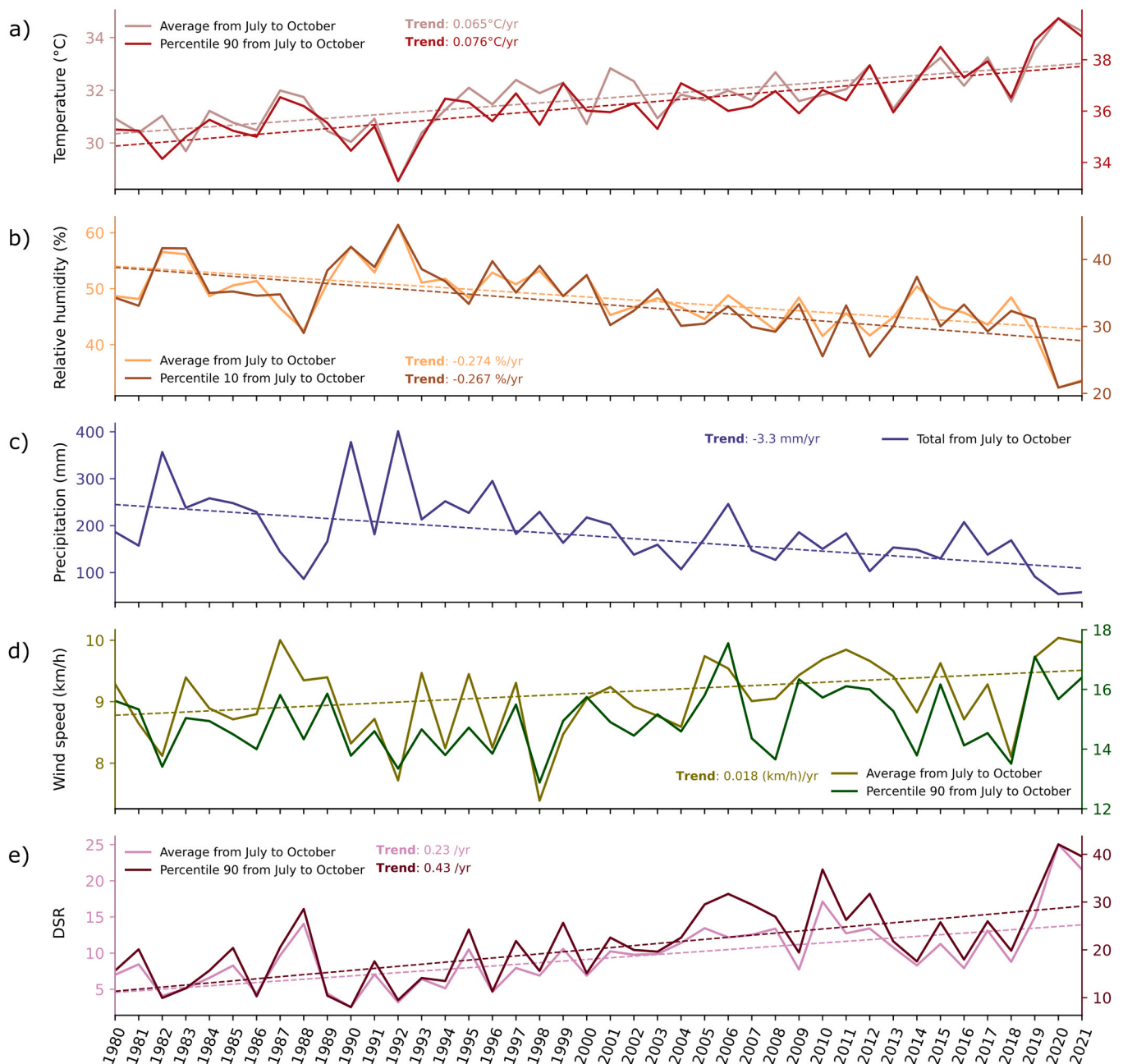
#### 4. Discussion

##### 4.1. Using remote sensed burned areas to study fire activity

We found that the AQM-LS algorithm sometimes failed to distinguish between burned and unburned areas within the RPPN Sesc Pantanal, and often assigned wrong classifications. This led to an overestimation of burned areas, which is most conspicuous in years that, according to visual inspection, showed little to no fire activity. On the other hand, years with large burned areas were well-mapped by the AQM-LS product. Compared to other remote sensed burned area products derived

from Landsat imagery that rely on change detection approaches based on pairs of images, the AQM-LS product has significantly reduced omission errors (Pereira et al., 2021). Nevertheless, in contrast with the automatic detection by the AQM-LS product and visual inspection, the RPPN Sesc Pantanal managers and firefighters report that almost the entirety of the reserve burned in 2020. The AQM-LS marked a large stretch of forested regions as unburned, known as the fire-sensitive “Cambarazal” (Sesc, 2023), where lower temperatures and higher relative humidity usually hinder the occurrence and spread of fires (Hofmann et al., 2010). It is not surprising that fires in forested regions are largely undetected, as it is widely known that satellite-derived burned area products have difficulty in detecting understory fires, as the tree canopy obscures the burning underneath (Morton et al., 2013). It is also worth noting that mapping burned areas in the tropics presents a greater challenge as the ephemeral character of the signal is easily scattered by the wind, rain, or hidden by re-growth (Pereira et al., 2021; Pereira, 2003).





**Fig. 6.** Interannual variability from 1980 to 2021 for: a) temperature (°C, reds); b) relative humidity (%), oranges); c) precipitation (mm, blue); d) wind speed (km/h, greens); and e) fire danger index DSR (adimensional, purples). Darker shades represent the extremes, evaluated as percentiles 90 for temperature, wind speed and DSR; and percentile 10 for relative humidity. Dashed lines represent significant trends (below the 5 % confidence level), and the trend slope is shown on the graph with the corresponding colour. Non-significant trends are not shown.

#### 4.2. Understanding fire patterns

The AQM-LS<sub>val</sub> product provided a reliable 20-year history of fire dynamics within the reserve. In general, large fires are not common within the reserve. Apart from 2020, only 2003, 2005, 2010 and 2019, burned considerable areas. Amongst these, the years of 2005 and 2010 were marked by reduced rainfall during the austral summer due to an anomalous northward position of the Atlantic Intertropical Convergence Zone (ITCZ; Marengo et al., 2021), which may have led to drier, and thus more susceptible to burning, biomass during the austral winter.

Burned area estimates from the last two decades showed how extreme and unprecedented the 2020 wildfires were, with six times more burned area than the previous record year (2010). Records from the RPPN Sesc Pantanal management detail that these wildfires began in

a rural area at the northern border on August 2<sup>nd</sup>, but soon there were multiple ignition sources and fire-lines coming from different directions towards the reserve. The fire-fighting efforts focused on infrastructure and the main roads that worked as firebreaks and fire-free corridors for animals to escape. Despite all efforts, it was estimated that thousands of vertebrates were killed (Crawshaw et al., 2020). Most of the area burned in 2020 had not burned over the last two decades, which, associated with non-existent fuel management actions, allowed the accumulation of biomass susceptible to burning.

In general, higher fire incidence was found near the reserve's limits, particularly along the northern and western border. This region is marked in the land cover product as wetlands and grasslands, but it represents the main flooded areas within the reserve, consisting of three macrohabitats (Sesc, 2023): clean and natural field ("Campo limpo



natural” in portuguese); flooded shrubland (“Arbustais inundados”); and riparian forest (“Floresta ribeirinha do rio Cuiabá”). As a RPPN, no anthropogenic fire is allowed within its limits and, accordingly, the wildfires that affect the reserve often start in the surrounding regions and move towards the RPPN’s area. It is common for rural populations in this region to use fire to stimulate pasture regrowth, clean areas, burn the garbage, for slash and burn agriculture, hunt (indigenous hunting) and celebrate (cultural celebrations or rituals) (Ibama, 2018; Sesc, 2023). Mainly these fires are conducted as controlled burns, but sometimes they are carried out without due care, under risky fire weather and environmental conditions, and without safety measures, facilitating its spread and generating wildfires. Apart from the natural fires, other anthropogenic sources have been reported for the RPPN’s region, such as electrical wiring ruptures (due to poor maintenance), vehicle accidents, and burning to clean the vegetation on the side of the road (Sesc, 2023). The combination of these anthropogenic fire sources, fuel loads available in large extensions with extremely dry periods, significantly increases the risk of wildfires.

#### 4.3. Fire in the context of a changing climate

A state-of-the-art reanalysis product allowed an assessment of historical trends in meteorological variables and fire weather. Although there is no in-situ data to compare or validate ERA5’s estimates, we found that precipitation estimates are in agreement with a previous study in the RPPN (Hofmann et al., 2010), and in line with the surrounding regions (Ivory et al., 2019; Marengo et al., 2015).

Over the last decades, monthly fire danger has been systematically increasing, particularly from July to September. Along with October, these months are considered Pantanal’s fire season, where the vast majority of fires occur (Damasceno-Junior et al., 2021; Libonati et al., 2022). Compared with September, October showed a considerable decrease in fire danger due to increased rainfall and relative humidity. Nevertheless, concurrent with high temperatures and wind speeds, fuel loads are extremely dry by the end of the dry season and highly susceptible to burning, which may lead to large burned areas in September and October, as seen in the case of the 2020 Pantanal fires (Libonati et al., 2022). Additionally, the dry season seems to be expanding, with systematically lower rainfall values for September and October over the last 22 years. Associated with increased temperatures and decreased relative humidity, fire weather conditions last longer every year, in line with reports from the RPPN Sesc Pantanal management team.

In par with Pantanal, the reserve is experiencing changes in climate patterns, with increasing conditions favourable to wildfire occurrence over the last four decades. These climate change trends in Pantanal, and by extent the reserve, will likely persist in the future (Llopart et al., 2020; Marengo et al., 2015), associated with higher frequency and extent of extreme events such as heatwaves or droughts (Ribeiro et al., 2022; Reboita et al., 2021; Silva et al., 2022; Thielen et al., 2020). However, climate may not be the main driver of fire within the RPPN, as a fire danger index explained slightly less than 50 % of interannual burned areas. A relevant example is the case of the year 2021, when fire danger was very high, including a record in temperatures for September and in relative humidity in July, but there were virtually no burned areas. This is to be expected as fire in the reserve is mainly anthropogenic (Neves, 2015) and, although favourable meteorological conditions are a necessary condition for large wildfires to occur, they alone are not sufficient. Along with climate, several other factors might weigh in the occurrence and spread of fire, such as fuel amount and conditions, ignition sources, and fire management.

#### 4.4. Implications for fire management

Before the creation of the reserve in 1997, the area of the reserve was used for cattle breeding and controlled burns were commonly applied (Brandão et al., 2011). In its central area (Fig. 1), a savanna-like

formation called “Campos de murundu”, where the cattle grazed, had the largest areas burned every other year in September and October (corresponding to less than 5 % of the reserve’s area, except for 1993 when almost 20 % was burned) (Sesc, 2023). However, after the creation of the RPPN no controlled burn was carried out, as the RPPN Sesc Pantanal followed a zero-fire policy. Preventive measures focused only on environmental education, social mobilisation, and capacity building. Throughout protected areas in Brazil, it has been shown that since its implementation, the zero-fire policy has increased large wildfire events, as the unmanaged vegetation expressively built-up fuel loads (Moura et al., 2019).

After the 2020 Pantanal wildfires, the need to change fire management and policy in the biome became readily apparent. Strategies and initiatives were quickly introduced, such as the creation of many community, volunteer and private fire brigades, and the development of management plans like the IFM. In 2021, the first experimental prescribed burns were applied in three small areas in the reserve to help managers better understand fire behaviour and severity. Associated with increased research efforts, such as the present study, this knowledge expansion combined with fire management needs, led to the decision to implement the IFM approach in the reserve. As well as continuing the RPPN’s previous preventive efforts, the IFM requires continued work on maintaining firebreaks, implementing prescribed burns, suppression of wildfires, and collaborative work with the reserve’s neighbours, interested organisations and researchers (Sesc, 2023). Accordingly, joint efforts were made with the collaboration of community leaders, scientists, the Military Fire Department and other civil society organisations (SOS Pantanal, Mupan, and Funatura) to build capacity in the surrounding communities, instal modern fire monitoring equipment to detect ignition sources, recover fire sensitive forests that were burned in 2020, and invest in fire-related research in the reserve (Sesc, 2023).

It is expected that the implementation of IFM within the reserve will change several aspects of its fire regime, particularly through prescribed burns that aim to control fuel loads prior to the critical wildfire season. As prescribed burns are undertaken in strategic and fire-adapted areas at the beginning of the dry or rainy season, the frequency and seasonality of fires will change, while the occurrence and extent of wildfires are expected to decrease (Ribeiro and Pereira, 2023; Santos et al., 2021). These changes in fire activity will require a continuous assessment of its effect within the reserve’s 13 macrohabitats. Understanding the optimal frequency, timing, and extent of prescribed burns, the amount and seasonality of fine fuels that need managing, and impacts on biodiversity, are some of the key research questions to be addressed.

## 5. Conclusions

This study provides an historical characterization of fire and climate within the largest privately held protected area in northern Pantanal: the RPPN Sesc Pantanal. We validated a Brazilian burned area product, and found large commission errors, mainly due to clouds, water bodies, flooded areas, and roads, leading to overestimating burned areas within the reserve. On the other hand, the automatic algorithm properly mapped years with large burned areas, albeit with omission errors in 2020. The validated dataset allowed a better assessment of fire activity in the reserve over the last two decades. We found that large burned areas are not common within the reserve, and most burned areas occurred in its western region near the Cuiabá river. Most of these burned areas were due to wildfires that started outside of the confines of the reserve but spread inwards, severely damaging its ecosystems. The most extreme year within the time series was 2020, in par with the rest of the Pantanal biome, where most of the reserve burned and forested regions were particularly affected.

We also showed that changes in climate are occurring within the reserve, mirroring trends for the Pantanal biome. Fire weather conditions seem to have lasted longer every year and steadily increased over the last 40 years. These trends reinforce the importance of developing an

integrated adaptive fire management in the reserve that preserves the microclimate, the environment, and its biodiversity to avoid extreme wildfires, such as those observed in 2020. An appropriate IFM for the region is only possible through interaction between various actors (firefighters, local agents, surrounding communities), adequate investment in firefighting equipment and infrastructure, environmental education to reduce ignition sources and reinforce the ecological value of the reserve, and local knowledge of the areas that are most vulnerable to fire for an efficient environmental management.

Finally, we found that, while satellite-derived burned area and reanalysis products provide useful information relevant to decision-making in the RPPN Sesc Pantanal, combining these products with local knowledge and expertise is crucial. Remote sensed burned area products have developed rapidly over the last decades due to better instruments and algorithms, but still show limitation. In particular, for smaller areas, such as protected areas, where a high spatial resolution is required, these products still show high commission errors, *per* our case in the RPPN Sesc Pantanal, and require visual interpretation by a skilled interpreter to yield accurate and precise results. On the other hand, reanalysis products also allow the assessment of climate where in-situ measurements and long-term datasets are not available or reliable.

This study provides tailored information for fire management decisions within the RPPN Sesc Pantanal, using methods that may be easily replicated and employed to study other protected areas worldwide. Our findings further highlight the role of fire management policies in wildfire occurrence and prevention, and align with recent studies for the Pantanal (Ribeiro and Pereira, 2023; Garcia et al., 2021) and worldwide (UNEP, 2022; Stoof and Kettridge, 2022; Rego et al., 2021) on the introduction of an integrated fire management approach as a possible solution.

#### CRediT authorship contribution statement

**Patrícia S. Silva:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Julia A. Rodrigues:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Joana Nogueira:** Writing – original draft, Methodology, Conceptualization. **Livia C. Moura:** Writing – original draft, Conceptualization. **Alexandre Enout:** Writing – original draft, Conceptualization. **Cristina Cuibália:** Writing – original draft, Conceptualization. **Carlos C. DaCamara:** Conceptualization. **Allan A. Pereira:** Software, Data curation. **Renata Libonati:** Writing – original draft, Supervision, Methodology, Conceptualization.

#### 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.

#### Data Availability

Data will be made available on request.

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#### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.envsci.2024.103818](https://doi.org/10.1016/j.envsci.2024.103818).

#### References

- Abatzoglou, J.T., Williams, A.P., Barbero, R., 2019. Global emergence of anthropogenic climate change in fire weather indices. *Geophys. Res. Lett.* 46, 326–336. <https://doi.org/10.1029/2018GL080959>.
- ALARMES [WWW Document], n.d. URL (<https://alarmes.lasa.ufjf.br/>) (accessed 4.15.24).
- Alho, C.J.R., Silva, J.S.V., 2012. Effects of severe floods and droughts on wildlife of the pantanal wetland (Brazil)—a review. *Anim* 2012 Vol. 2, 591–610. <https://doi.org/10.3390/ANI2040591>.
- Arruda, W.D.S., Oldeland, J., Paranhos Filho, A.C., Pott, A., Cunha, N.L., Ishii, I.H., Damasceno, G.A., 2016. Inundation and fire shape the structure of riparian forests in the pantanal, Brazil. *PLoS One* 11, e0156825. <https://doi.org/10.1371/JOURNAL.PONE.0156825>.
- Barbosa, M.L., Haddad, I., da Silva Nascimento, A.L., Máximo da Silva, G., Moura da Veiga, R., Hoffmann, T.B., Rosane de Souza, A., Dalagnol, R., Susin Streher, A., Souza Pereira, F.R., Oliveira e Cruz de Aragão, L.E., Oighenstein Anderson, L., 2022. Compound impact of land use and extreme climate on the 2020 fire record of the Brazilian Pantanal. *Glob. Ecol. Biogeogr.* 00, 1–16. <https://doi.org/10.1111/GEB.13563>.
- Bastarrika, A., Chuvieco, E., Martín, M.P., 2011. Mapping burned areas from Landsat TM/ETM+ data with a two-phase algorithm: balancing omission and commission errors. *Remote Sens. Environ.* 115, 1003–1012. <https://doi.org/10.1016/j.rse.2010.12.005>.
- Boschetti, L., Flasse, S.P., Brivio, P.A., 2004. Analysis of the conflict between omission and commission in low spatial resolution dichotomic thematic products: the Pareto Boundary. *Remote Sens. Environ.* 91, 280–292. <https://doi.org/10.1016/j.rse.2004.02.015>.
- Bowman, D.M.J.S., Zhang, Y., Walsh, A., Williams, R.J., 2003. Experimental comparison of four remote sensing techniques to map tropical savanna fire-scars using Landsat-TM imagery. *Int. J. Wildl. Fire* 12, 341. <https://doi.org/10.1071/WF03030>.
- Brandão, L.G., Antas, P. de T.Z., Oliveira, L.F.B. de, Pádua, M.T.J., Pereira, N. da C., Valutky, W.W., 2011. Plano de Manejo da Reserva Particular do Patrimônio Natural do SESC Pantanal (2nd ed.).
- Campagnolo, M.L., Libonati, R., Rodrigues, J.A., Pereira, J.M.C., 2021. A comprehensive characterization of MODIS daily burned area mapping accuracy across fire sizes in tropical savannas. *Remote Sens. Environ.* 252, 112115. <https://doi.org/10.1016/j.rse.2020.112115>.
- Correa, D.B., Alcântara, E., Libonati, R., Massi, K.G., Park, E., 2022. Increased burned area in the Pantanal over the past two decades. *Sci. Total Environ.* 835, 155386. <https://doi.org/10.1016/j.scitotenv.2022.155386>.
- Crawshaw, D., Oliveira, G.S., Cordeiro, J.L.P., Kindel, A., Rangel, B.Z., Trierveiler, F., Oliveira, L.F.B., 2020. Relatório Parcial Ações Emergenciais Pós-fogo RPPN Sesc Pantanal Parte I.
- Cunha, C.N. da, Bergier, I., Tomas, W.M., Damasceno-Junior, G.A., Santos, S.A., Assunção, V.A., Sartori, A.L.B., Pott, A., de Arruda, E.C., da Silva Garcia, A., Nicola, R.D., Junk, W.J., 2021. Hydrology and Vegetation Base for Classification of Macrohabitats of the Brazilian Pantanal for Policy-Making and Management 365–391. [https://doi.org/10.1007/978-3-030-83375-6\\_7](https://doi.org/10.1007/978-3-030-83375-6_7).
- Daldegan, G., de Carvalho, O., Guimarães, R., Gomes, R., Ribeiro, F., McManus, C., 2014. Spatial patterns of fire recurrence using remote sensing and GIS in the Brazilian Savanna: serra do tombador nature reserve, Brazil. *Remote Sens* 6, 9873–9894. <https://doi.org/10.3390/rs6109873>.
- Damasceno-Junior, G.A., Roque, F., de O., 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. *Wetl. Sci. Pract.* 38, 107–115.
- European Centre for Medium-Range Weather Forecasts (ECMWF), 2024. ERA5: How to calculate wind speed and wind direction from u and v components of the wind? [WWW Document]. URL (<https://confluence.ecmwf.int/pages/viewpage.action?pageId=133262398>) (accessed 6.4.24).
- Garcia, L.C., Szabo, J.K., de Oliveira Roque, F., de Matos Martins Pereira, A., Nunes da Cunha, C., Damasceno-Júnior, G.A., Morato, R.G., Tomas, W.M., Libonati, R., Ribeiro, D.B., 2021. Record-breaking wildfires in the world's largest continuous tropical wetland: Integrative fire management is urgently needed for both biodiversity and humans. *J. Environ. Manag.* 293, 112870. <https://doi.org/10.1016/J.JENVMAN.2021.112870>.
- Geirinhas, J.L., Russo, A.C., Libonati, R., Miralles, D.G., Ramos, A.M., Gimeno, L., Trigo, R.M., 2023. Combined large-scale tropical and subtropical forcing on the severe 2019–2022 drought in South America. *npj Clim. Atmos. Sci.* 6, 185. <https://doi.org/10.1038/s41612-023-00510-3>.
- Guerra, A., Roque, F. de O., Garcia, L.C., Ochoa-Quintero, J.M., Oliveira, P.T.S. de, Guariento, R.D., Rosa, I.M.D., 2020. Drivers and projections of vegetation loss in the Pantanal and surrounding ecosystems. *Land Use Policy* 91, 104388. <https://doi.org/10.1016/j.landusepol.2019.104388>.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S.,

- Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.N., 2020. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* 146, 1999–2049. <https://doi.org/10.1002/qj.3803>.
- Hofmann, G.S., Hasenack, H., Oliveira, L.F.B., Cordeiro, L.J.P., 2010. O clima na Reserva Particular do Patrimônio Natural SESC Pantanal. *Serviço Social do Comércio*.
- Ibama, 2018. Relatório da Compilação dos Resgates do Conhecimento Tradicional Sobre o Uso do Fogo Em Terras Indígenas Brasileiras.
- IPCC, 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability, Summary for Policymakers*. Cambridge University Press, Cambridge, UK and New York, USA.
- Ivory, S.J., McGlue, M.M., Spera, S., Silva, A., Bergier, I., 2019. Vegetation, rainfall, and pulsing hydrology in the Pantanal, the world's largest tropical wetland. *Environ. Res. Lett.* 14, 124017 <https://doi.org/10.1088/1748-9326/AB4FFE>.
- Jain, P., Castellanos-Acuna, D., Coogan, S.C.P., Abatzoglou, J.T., Flannigan, M.D., 2022. Observed increases in extreme fire weather driven by atmospheric humidity and temperature. *Nat. Clim. Chang.* 12, 63–70. <https://doi.org/10.1038/s41558-021-01224-1>.
- Kendall, M.G., 1975. *Rank correlation methods*, 4th ed. Griffin, London.
- Lawrence, M.G., 2005. The relationship between relative humidity and the dewpoint temperature in moist air: a simple conversion and applications. *Bull. Am. Meteorol. Soc.* 86, 225–234. <https://doi.org/10.1175/BAMS-86-2-225>.
- Lázaro, W.L., Oliveira-Júnior, E.S., Silva, C.J. da, Castrillon, S.K.I., Muniz, C.C., 2020. Climate change reflected in one of the largest wetlands in the world: an overview of the Northern Pantanal water regime. *Acta Limnol. Bras.* 32, 1–8. <https://doi.org/10.1590/S2179-975X7619>.
- Li, S., Sparrow, S.N., Otto, F.E.L., Rifai, S.W., Oliveras, I., Krikken, F., Anderson, L.O., Malhi, Y., Wallom, D., 2021. Anthropogenic climate change contribution to wildfire-prone weather conditions in the Cerrado and Arc of deforestation. *Environ. Res. Lett.* 16, 094051 <https://doi.org/10.1088/1748-9326/AC1E3A>.
- Libonati, R., DaCamara, C.C., Peres, L.F., Sander de Carvalho, L.A., Garcia, L.C., 2020. Rescue Brazil's burning Pantanal wetlands. *Nat* 2021 588, 217–219. <https://doi.org/10.1038/d41586-020-03464-1>.
- Libonati, R., Geirinhas, J. o L., Silva, P.S., Russo, A., Rodrigues, J.A., Belém, L.B.C., Nogueira, J., Roque, F.O., Dacamara, C.C., Nunes, A.M.B., Marengo, J.A., Trigo, R. M., 2022. Assessing the role of compound drought and heatwave events on unprecedented 2020 wildfires in the Pantanal. *Environ. Res. Lett.* 17, 015005 <https://doi.org/10.1088/1748-9326/AC462E>.
- Llopart, M., Simões Reboita, M., Porfírio da Rocha, R., 2020. Assessment of multi-model climate projections of water resources over South America CORDEX domain. *Clim. Dyn.* 54, 99–116. <https://doi.org/10.1007/s00382-019-04990-z>.
- Mann, H.B., 1945. Nonparametric tests against trend. *Econometrica* 13, 245. <https://doi.org/10.2307/1907187>.
- Manrique-Pineda, D.A., de Souza, E.B., Paranhos Filho, A.C., Cáceres Encina, C.C., Damasceno-Junior, G.A., 2021. Fire, flood and monodominance of *Tabeuia aurea* in Pantanal. *Ecol. Manag.* 479, 118599 <https://doi.org/10.1016/j.foreco.2020.118599>.
- MapBiomas, 2023. MapBiomas Project- Collection 7 of the Annual Series of Land Use and Land Cover Maps of Brazil [WWW Document]. URL (<https://brasil.mapbiomas.org/>) (accessed 2.3.23).
- Marengo, J.A., Alves, L.M., Torres, R.R., 2016. Regional climate change scenarios in the Brazilian Pantanal watershed. *Clim. Res.* 68, 201–213. <https://doi.org/10.3354/CRO1324>.
- Marengo, J.A., Cunha, A.P., Cuatras, L.A., Deusdará Leal, K.R., Broedel, E., Seluchi, M.E., Michelin, C.M., De Praga Baão, C.F., Chuchón Ángulo, E., Almeida, E.K., Kazmierczak, M.L., Mateus, N.P.A., Silva, R.C., Bender, F., 2021. Extreme drought in the Brazilian pantanal in 2019–2020: characterization, causes, and impacts. *Front. Water* 0, 13. <https://doi.org/10.3389/FRWA.2021.639204>.
- Marengo, J.A., Oliveira, G.S., Alves, L.M., 2015. Climate Change Scenarios in the Pantanal. *Handb. Environ. Chem.* 37, 227–238. <https://doi.org/10.1007/978-2015-357>.
- Marques, J.F., Alves, M.B., Silveira, C.F., Amaral e Silva, A., Silva, T.A., dos Santos, V.J., Calijuri, M.L., 2021. Fires dynamics in the Pantanal: Impacts of anthropogenic activities and climate change. *J. Environ. Manag.* 299, 113586 <https://doi.org/10.1016/j.jenvman.2021.113586>.
- Martins, P.I., Belém, L.B.C., Szabo, J.K., Libonati, R., Garcia, L.C., 2022. Prioritising areas for wildfire prevention and post-fire restoration in the Brazilian Pantanal. *Ecol. Eng.* 176, 106517 <https://doi.org/10.1016/j.ecoleng.2021.106517>.
- Menezes, L.S., de Oliveira, A.M., Santos, F.L.M., Russo, A., de Souza, R.A.F., Roque, F.O., Libonati, R., 2022. Lightning patterns in the Pantanal: untangling natural and anthropogenic-induced wildfires. *Sci. Total Environ.* 820, 153021 <https://doi.org/10.1016/j.scitotenv.2022.153021>.
- Morton, D.C., Le Page, Y., DeFries, R., Collatz, G.J., Hurr, G.C., 2013. Understorey fire frequency and the fate of burned forests in southern Amazonia. *Philos. Trans. R. Soc. B Biol. Sci.* 368 <https://doi.org/10.1098/RSTB.2012.0163>.
- Moura, L.C., Scariot, A.O., Schmidt, I.B., Beatty, R., Russell-Smith, J., 2019. The legacy of colonial fire management policies on traditional livelihoods and ecological sustainability in savannas: Impacts, consequences, new directions. *J. Environ. Manag.* 232, 600–606. <https://doi.org/10.1016/j.jenvman.2018.11.057>.
- Myers, R.L., 2006. *Living with Fire—Sustaining Ecosystems & Livelihoods Through Integrated Fire Management*.
- Neves, C.C.R.P., 2015. *Vulnerabilidade da paisagem pantaneira: estudo de caso da Reserva Particular do Patrimônio Natural Sesc Pantanal e entorno*. Universidade de São Paulo.
- Oliveira, M.T. de, Damasceno-Junior, G.A., Pott, A., Paranhos Filho, A.C., Suarez, Y.R., Parolin, P., 2014. Regeneration of riparian forests of the Brazilian Pantanal under flood and fire influence. *Ecol. Manag.* 331, 256–263. <https://doi.org/10.1016/j.foreco.2014.08.011>.
- Pereira, J.M.C., 2003. Remote sensing of burned areas in tropical savannas. *Int. J. Wildl. Fire* 12, 259–270. <https://doi.org/10.1071/WF03028>.
- Pereira, A.A., Libonati, R., Rodrigues, J.A., Nogueira, J., Santos, F.L.M., Oom, D., Sanches, W., Alvarado, S.T., Pereira, J.M.C., 2021. Multi-sensor, active fire-supervised, one-class burned area mapping in the Brazilian Savanna. *Remote Sens.* Vol. 13, 4005. <https://doi.org/10.3390/RS13194005>.
- Pereira, J.M.C., Sá, A.C.L., Sousa, A.M.O., Silva, J.M.N., Santos, T.N., Carreiras, J.M.B., 1999. Spectral characterisation and discrimination of burnt areas. *Remote Sensing of Large Wildfires*. Springer Berlin Heidelberg, pp. 123–138. [https://doi.org/10.1007/978-3-642-60164-4\\_7](https://doi.org/10.1007/978-3-642-60164-4_7).
- Pinto, M.M., Trigo, R.M., Trigo, I.F., DaCamara, C.C., 2021. A practical method for high-resolution burned area monitoring using sentinel-2 and VIIRS. *Remote Sens.* 13, 1608. <https://doi.org/10.3390/rs13091608>.
- Pivello, V.R., 2011. The use of fire in the cerrado and amazonian rainforests of Brazil: past and present. *Fire Ecol.* 7, 24–39. <https://doi.org/10.4996/fireecology.0701024>.
- Pivello, V.R., Vieira, I., Christianini, A.V., Ribeiro, D.B., da Silva Menezes, L., Berlink, C. N., Melo, F.P.L., Marengo, J.A., Tornquist, C.G., Tomas, W.M., Overbeck, G.E., 2021. Understanding Brazil's catastrophic fires: causes, consequences and policy needed to prevent future tragedies. *Perspect. Ecol. Conserv.* 19, 233–255. <https://doi.org/10.1016/j.pcon.2021.06.005>.
- Pott, A., Oliveira, A.K.M., Damasceno-Junior, G.A., Silva, J.S.V., 2011. Plant diversity of the Pantanal wetland. *Braz. J. Biol.* 71, 265–273. <https://doi.org/10.1590/S1519-69842011000200005>.
- Pott, A., Pott, V.J., 2004. Features and conservation of the Brazilian Pantanal wetland. *Wetl. Ecol. Manag.* 12, 547–552. <https://doi.org/10.1007/S11273-005-1754-1/METRICS>.
- Quilcaille, Y., Batibeniz, F., Ribeiro, A.F.S., Padrón, R.S., Seneviratne, S.I., 2023. Fire weather index data under historical and shared socioeconomic pathway projections in the 6th phase of the Coupled Model Intercomparison Project from 1850 to 2100. *Earth Syst. Sci. Data* 15, 2153–2177. <https://doi.org/10.5194/ESSD-15-2153-2023>.
- Ramsar, 2023. About the Convention on Wetlands [WWW Document]. URL (<https://www.ramsar.org/about-convention-wetlands>) (accessed 11.2.23).
- Reboita, M.S., Ambrizzi, T., Crespo, N.M., Dutra, L.M.M., Ferreira, G.W. de S., Rehbein, A., Drumond, A., da Rocha, R.P., Souza, C.A. de, 2021. Impacts of teleconnection patterns on South America climate. *Ann. N. Y. Acad. Sci.* 1504, 116–153. <https://doi.org/10.1111/NYAS.14592>.
- Rego, F.C., Morgan, P., Fernandes, P., Hoffman, C., 2021. Integrated Fire Management. *Springer, Cham*, pp. 509–597. [https://doi.org/10.1007/978-3-030-69815-7\\_13](https://doi.org/10.1007/978-3-030-69815-7_13).
- Ribeiro, A.F.S., Brando, P.M., Santos, L., Rattis, L., Hirschi, M., Hauser, M., Seneviratne, S.I., Zscheischler, J., 2022. A compound event-oriented framework to tropical fire risk assessment in a changing climate. *Environ. Res. Lett.* 17, 065015 <https://doi.org/10.1088/1748-9326/AC7342>.
- Ribeiro, D.B., Pereira, A.M.M., 2023. Solving the problem of wildfires in the Pantanal Wetlands. *Perspect. Ecol. Conserv.* 21, 271–273. <https://doi.org/10.1016/j.pcon.2023.10.004>.
- Rodrigues, J.A., Libonati, R., Pereira, A.A., Nogueira, J.M.P., Santos, F.L.M., Peres, L.F., Santa Rosa, A., Schroeder, W., Pereira, J.M.C., Giglio, L., Trigo, I.F., Setzer, A.W., 2019. How well do global burned area products represent fire patterns in the Brazilian Savannas biome? An accuracy assessment of the MCD64 collections. *Int. J. Appl. Earth Obs. Geoinf.* 78, 318–331. <https://doi.org/10.1016/j.jag.2019.02.010>.
- Santos, F.L.M., Nogueira, J., Souza, R.A.F. de, Falleiro, R.M., Schmidt, I.B., Libonati, R., 2021. Prescribed burning reduces large, high-intensity wildfires and emissions in the Brazilian Savanna. *Fire* 4, 56. <https://doi.org/10.3390/fire4030056>.
- Schmidt, I.B., Fonseca, C.B., Ferreira, M.C., Sato, M.N., 2016. Implementação do programa piloto de manejo integrado do fogo em três unidades de conservação do Cerrado. *Biodiversidade Brasileira - BioBrasil*. <https://doi.org/10.37002/biodiversidadebrasileira.v6i2.656>.
- Schmidt, I.B., Moura, L.C., Ferreira, M.C., Eloy, L., Sampaio, A.B., Dias, P.A., Berlink, C. N., 2018. Fire management in the Brazilian savanna: first steps and the way forward. *J. Appl. Ecol.* 55, 2094–2101. <https://doi.org/10.1111/1365-2664.13118>.
- Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's Tau. *J. Am. Stat. Assoc.* 63, 1379–1389. <https://doi.org/10.1080/01621459.1968.10480934>.
- Sesc, 2023. Plano de Manejo Integrado do Fogo da RPPN Sesc Pantanal.
- Siefert, C.A.C., Netto, N.D., Marangon, F.H.S., Schultz, G.B., Dos Reis Silva, L.M., Fontenelle, T.H., Dos Santos, I., 2022. Avaliação de Séries de Velocidade do Vento de Produtos de Reanálises Climáticas para o Brasil. *Rev. Bras. Meteor.* 36, 689–701. <https://doi.org/10.1590/0102-7786360026>.
- Silva, P.S., Bastos, A., Libonati, R., Rodrigues, J.A., DaCamara, C.C., 2019. Impacts of the 1.5 °C global warming target on future burned area in the Brazilian Cerrado. *Ecol. Manag.* 446, 193–203. <https://doi.org/10.1016/j.foreco.2019.05.047>.
- Silva, P.S., Geirinhas, J.L., Lapere, R., Laura, W., Cassain, D., Alegria, A., Campbell, J., 2022. Heatwaves and fire in Pantanal: Historical and future perspectives from CORDEX-CORE. *J. Environ. Manag.* 323, 116193 <https://doi.org/10.1016/j.jenvman.2022.116193>.
- Souza, C.M., Shimbo, J.Z., Rosa, M.R., Parente, L.L., Alencar, A.A., Rudorff, B.F.T., Hasenack, H., Matsumoto, M., Ferreira, L.G., Souza-Filho, P.W.M., Oliveira, S.W., de, Rocha, W.F., Fonseca, A.V., Marques, C.B., Diniz, C.G., Costa, D., Monteiro, D., Rosa, E.R., Vêlez-Martin, E., Weber, E.J., Lenti, F.E.B., Paternost, F.F., Pareyn, F.G. C., Siqueira, J.V., Viera, J.L., Neto, L.C.F., Saraiva, M.M., Sales, M.H., Salgado, M.P. G., Vasconcelos, R., Galano, S., Mesquita, V.V., Azevedo, T., 2020. Reconstructing three decades of land use and land cover changes in Brazilian biomes with landsat



- archive and earth engine. *Remote Sens* Vol. 12, 2735. <https://doi.org/10.3390/RS12172735>.
- Stoof, C.R., Kettridge, N., 2022. Living with fire and the need for diversity. *Earth's Futur* 10, e2021EF002528. <https://doi.org/10.1029/2021EF002528>.
- Theil, H., 1950. A rank-invariant method of linear and polynomial regression analysis, 3; confidence regions for the parameters of polynomial regression equations. *Indag. Math.* 1, 467–482.
- Thielen, D., Schuchmann, K.-L., Ramoni-Perazzi, P., Marquez, M., Rojas, W., Quintero, J. I., Marques, M.I., 2020. Quo vadis Pantanal? Expected precipitation extremes and drought dynamics from changing sea surface temperature. *PLoS One* 15, e0227437. <https://doi.org/10.1371/JOURNAL.PONE.0227437>.
- Tomas, W.M., Berlinck, C.N., Chiaravalloti, R.M., Faggioni, G.P., Strüssmann, C., Libonati, R., Abrahão, C.R., do Valle Alvarenga, G., de Faria Bacellar, A.E., de Queiroz Batista, F.R., Bornato, T.S., Camilo, A.R., Castedo, J., Fernando, A.M.E., de Freitas, G.O., Garcia, C.M., Gonçalves, H.S., de Freitas Guilherme, M.B., Layme, V.M. G., Lustosa, A.P.G., De Oliveira, A.C., da Rosa Oliveira, M., de Matos Martins Pereira, A., Rodrigues, J.A., Semedo, T.B.F., de Souza, R.A.D., Tortato, F.R., Viana, D.F.P., Vicente-Silva, L., Morato, R., 2021. Distance sampling surveys reveal 17 million vertebrates directly killed by the 2020's wildfires in the Pantanal, Brazil. *Sci. Rep.* 2021 111 (11), 1–8. <https://doi.org/10.1038/s41598-021-02844-5>.
- Tomas, W.M., Roque, F., de, O., Morato, R.G., Medici, P.E., Chiaravalloti, R.M., Tortato, F.R., Penha, J.M.F., Izzo, T.J., Garcia, L.C., Lourival, R.F.F., Girard, P., Albuquerque, N.R., Almeida-Gomes, M., Andrade, M.H., da, S., Araujo, F.A.S., Araujo, A.C., Arruda, E.C., de, Assunção, V.A., Battirola, L.D., Benites, M., Bolzan, F. P., Boock, J.C., Bortolotto, I.M., Brasil, M., da, S., Camilo, A.R., Campos, Z., Carniello, M.A., Catella, A.C., Cheida, C.C., Crawshaw Jr., P.G., Crispim, S.M.A., Junior, G.A.D., Desbiez, A.L.J., Dias, F.A., Eaton, D.P., Faggioni, G.P., Farinaccio, M. A., Fernandes, J.F.A., Ferreira, V.L., Fischer, E.A., Fragoso, C.E., Freitas, G.O., Galvani, F., Garcia, A.S., Garcia, C.M., Graciolli, G., Guariento, R.D., Guedes, N.M.R., Guerra, A., Herrera, H.M., Hoogesteijn, R., Ikeda, S.C., Juliano, R.S., Kantek, D.L.Z. K., Keuroghlian, A., Lacerda, A.C.R., Lacerda, A.L.R., Landeiro, V.L., Laps, R.R., Layme, V., Leimgruber, P., Rocha, F.L., Mamede, S., Marques, D.K.S., Marques, M.I., Mateus, L.A.F., Moraes, R.N., Moreira, T.A., Mourão, G.M., Nicola, R.D., Nogueira, D.G., Nunes, A.P., Cunha, C. da N. da, Oliveira, M.D., Oliveira, M.R., Paggi, G.M., Pellegrin, A.O., Pereira, G.M.F., Peres, I.A.H.F.S., Pinho, J.B., Pinto, J.O. P., Pott, A., Provete, D.B., Reis, V.D.A. dos, Reis, L.K. dos, Renaud, P.-C., Ribeiro, D. B., Rossetto, O.C., Sabino, J., Rumiz, D., Salis, S.M., Santana, D.J., Santos, S.A., Sartori, A.L., Sato, M., Schuchmann, K.-L., Scremin-Dias, E., Seixas, G.H.F., Severo-Neto, F., Sigrist, M.R., Silva, A., Silva, C.J., Siqueira, A.L., Soriano, B.M.A., Sousa, L. M., Souza, F.L., Strussmann, C., Sugai, L.S.M., Tocantins, N., Urbanetz, C., Valente-Neto, F., Viana, D.P., Yanosky, A., Junk, W.J., 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>.
- UNEP, 2022. Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires, A UNEP Rapid Response Assessment. Nairobi.
- UNESCO, 2023. Fires in the Pantanal ecoregion [WWW Document]. URL (<https://www.unesco.org/en/articles/fires-pantanal-ecoregion>) (accessed 4.15.24).
- UNESCO, 2024. Pantanal Conservation Area [WWW Document]. World Herit. Cent. URL (<https://whc.unesco.org/en/list/999/>) (accessed 4.15.24).
- UNESCO, n.d. Pantanal [WWW Document]. Man Biosph. Program. URL (<https://www.unesco.org/en/mab/pantanal>) (accessed 4.15.24).
- USGS, n.d. Landsat 7 [WWW Document]. URL (<https://www.usgs.gov/landsat-mission/s/landsat-7>) (accessed 4.15.24).
- Van Wagner, C.E., 1987. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service.
- Vitolo, C., Di Giuseppe, F., Barnard, C., Coughlan, R., San-Miguel-Ayanz, J., Libertá, G., Krzeminski, B., 2020. ERA5-based global meteorological wildfire danger maps. *Sci. Data* 2020 71 (7), 1–11. <https://doi.org/10.1038/s41597-020-0554-z>.