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Increased burned area in the Pantanal over the past two decades

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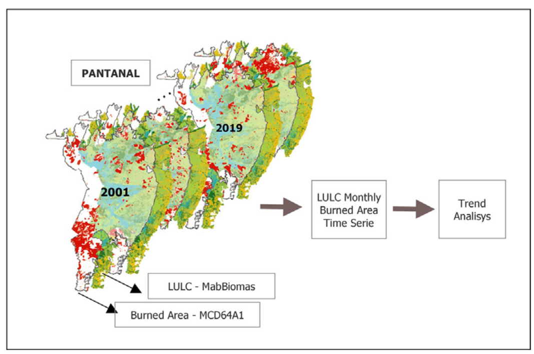
HIGHLIGHTS

- Fire patterns in the Pantanal wetland in the last two decades were analyzed by mapping burned area.
- Among land covers, grassland was the most vulnerable to fire.
- Mega-fires in 2020 have occurred exceptionally within forest.
- Large scale synoptic view is necessary for better management of fires in Pantanal.

GRAPHICAL ABSTRACT



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ABSTRACT

Wildfires are behaving differently now compared to other time in history in relation to frequency, intensity and affected ecosystems. In Brazil, unprecedented fires are being experienced in the last decade. Thus, to prevent and minimize similar disasters, we must better understand the natural and human drivers of such extreme events. The Brazilian Pantanal is the largest contiguous wetland in the world and a complex environmental system. In 2020, Pantanal experienced catastrophic wildfires due to the synergy between climate, inadequate fire management strategies and weak environmental regulations. In this study, we analyzed recent patterns and changes in fire behavior across the Pantanal based on land use and cover (LULC) classes. The inter-annual variability of the fire and land cover changes between 2000 and 2021 was assessed using BA from MCD64A1 V.6 product and LULC data from Landsat satellite. Our work reveals that fires in the Pantanal over the last two decades tended to occur more frequently in grassland than in others land cover types, but the 2020 fires have preferentially burned forest regions. Large fire patches are more frequent in forest and grasslands; in contrast, croplands exhibit small patches. The results highlight that a broad scale analysis does not reflect distinct localized patterns, thus stratified and refined studies are required. Our work contributes as a first step to disentangling the role of anthropogenic-related drivers, namely LULC changes, in shaping the fire regime in the Pantanal biome. This is crucial not only to predict future fire activity but also to guide appropriated fire management in the region.

1. Introduction

Over the past few decades, human activities and climate change have been contributing to more frequent and intense spikes in forest fire activity around the world, leading to harmful impacts on the environment, wildlife, human health, economy, and infrastructure (Bowman et al., 2020). More recently, not only are fire-prone ecosystems experiencing more intense wildfires, but areas that typically burn less are also facing large-scale burning events (UNEP, 2022). The 2019 and 2020 fire seasons are being considered the worst in recent decades in many parts of the world – for instance, in Australia (Boer et al., 2020), California (Li and Banerjee, 2021), the Arctic

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(Witze, 2020) and the Pantanal (Libonati et al., 2020). In 2020, the Brazilian Pantanal, the largest contiguous wetland in the world had one third of its area affected by fires (Libonati et al., 2020). It was considered the largest fire event in history, with a 376% increase in the extent of fires, compared to the annual average from the last two decades (Damasceno-Junior et al., 2021; Garcia et al., 2021).

Fire shapes biological and physical dimensions of ecosystems (Bowman et al., 2020), as well as socioeconomic frameworks (Pausas and Parr, 2018; Steenvoorden et al., 2019). Fire effects can be beneficial or harmful to biodiversity conservation and human lives depending on where, when, and how frequent ecosystems burn: if fires reinforce natural regimes, whether naturally or human ignited, they are recognized as good and life-sustaining in environments that have evolved with them (Hardesty et al., 2005). For instance, fires have been found to be important in maintaining vegetation diversity, structure, and functions in fire prone ecosystems such as savannas (Fidelis et al., 2007; Durigan et al., 2020).

Conversely, fires can be detrimental in fire sensitive formations (rainforests) (Prestes et al., 2020; Sansevero et al., 2020). Although the Brazilian Pantanal formations are classified as savannas, they are directly influenced by other biomes (IBGE, 2012), i.e., savannas of Cerrado and Atlantic and Amazon rainforests. For this reason, this biome is a mix between fire prone and fire sensitive ecosystems. Fire-sensitive sites in the Pantanal are therefore negatively affected by burnings through biodiversity loss (Miranda, 2010; Martins et al., 2022). As such, the future of Pantanal depends largely on proper fire management practices (Berlinck et al., 2022).

Fire occurrences can be attributed to both natural and anthropogenic causes with land use change being recently identified as a major driver in Brazil (Pivello et al., 2021). Native grasslands of Pantanal have been historically used for low intensity cattle ranching (embrapa.br/pantanal); since the 2000s, native grasses are being substituted by exotic grasses in pastures or being converted into croplands (mainly soybean) (Pott and Pott, 2004). The transition from natural vegetation to agriculture and pasture has led to high concentration of fire foci and increased risk of fire (Marques et al., 2021). However, fire studies focusing on the influence of land cover change remains scarce in this region, except for the recent work of Kumar et al. (2022) who used coarse land cover and burned area data to understand the main causes of the 2020 Pantanal fires.

A deeper understanding about past and current fire variability in the Pantanal considering different land covers is central to predicting future fire behavior and anticipating new trends and disasters (Pivello et al., 2021). Considering multiple land covers and land use changes over Pantanal, together with other important drive factors such as drought-heat waves episodes (Thielen et al., 2020; Thielen et al., 2021; Libonati et al., 2022) and regional fire management and regulations, is therefore crucial to developing an integrated understanding about current and future fire regime in the region (Libonati et al., 2020). However, such a comprehensive and long-term representation of fire occurrence per land use and land cover type (LULC) in the Pantanal is still not available.

The goal of this study is to analyze the recent observed patterns and changes in fire behavior over the Pantanal according to land use and land cover classes. Here, we analyzed long-term and annual variability of fire and land cover changes from the end of 2000 to the beginning of 2021 using burned area (BA) from MCD64A1 V.6 product and LULC classes from 2000 until 2019. First, we assessed fire frequency over the region by considering inter and intra-annual variability per LULC classes. Then, we examined trends to infer the role of LULC on Pantanal fire dynamics, paying particular attention to the year 2020 due the catastrophic fire events registered that year (Libonati et al., 2020; Damasceno-Junior et al., 2021; Garcia et al., 2021).

2. Materials and methods

2.1. Study site

Pantanal is the world's largest contiguous wetland at approximately 150,000 km^2 and is located in the interior of the South America continent, covering part of Mato Grosso (35%) and Mato Grosso do Sul (65%) states in Brazil (Fig. 1 a. and b.). Known as "Pantanal complex", this biome is influenced by the Amazon, Cerrado (Brazilian Savanna) and Atlantic Forest biomes in its north, east and south, respectively (Fig. 1 b., Marengo et al., 2021). On the west, the Brazilian Pantanal borders Bolivia and Paraguay in a region known as Chaco. The current LULC distribution (Fig. 1c.) shows pasture class advancing from east to west with small portions of cropland and other non-vegetated areas. The main continuous forestland and savanna classes are found in central to north portions while wetland class is concentrated in the west.

According to the Köppen's climate Classification (Koppen, 1948, Peel et al., 2007, Embrapa, 2020), the Tropical Wet-Dry or Tropical Savanna climate is predominant in the Pantanal, with cold and dry months varying between May to October, and hot and wet months varying between November and April. Different regions typically experience a flooding peak which lags the precipitation peak (Fig. 1 e.), and this timing can be as much as three months. As for rivers such as Miranda and Cuiabá, their flooding peaks occur soon after the peak of rain. Considering large-scale climate phenomena, Thielen et al. (2020) found oscillations in sea surface temperature (SST) of the Pacific and Atlantic Oceans as the main drivers for rainfall variability in these basins.

While the hydrology of the Pantanal landscape is driven by multiple factors, flood pulse is considered the main driver (Ivory et al., 2019). The Pantanal acts as a large reservoir in Paraguay River basin, where its flat terrain (Fig. 1 d.), varying soil classes (mainly Gleyic Podzols in the center, Luvic Planossols in the south and close to main rivers and Dystric Plintosols in the north (Embrapa Solos, 2017) and regional hydroclimate conditions influence floods in the area (Fernandes et al., 2007; Assine et al., 2015; Marengo et al., 2021). Pluriannual humidity and rainfall cycles can also result in severe floods or pronounced dry seasons that then influence flooding patterns (Damasceno-Junior et al., 2021; Garcia et al., 2021; Marengo et al., 2021). Processes that maintain Pantanal's landscape and wetland functioning is also likely to be disrupted by changes in rainfall regime and the flood pulse (Ivory et al., 2019). Increased sedimentation over a large area in the last 30 years that drastically modified the Taquari megafan, the largest alluvial fan comprised on Paraguay trunk river located in the central portion of the Pantanal and representing almost one third of the biome (Assine, 2005), is probably also associated with increased vulnerability to deforestation and fire.

The geographical location, difficult access, low soil nutrients availability, periodic floods, fires and traditional low-intensity cattle ranching in the natural plane grasslands since the 17th century (the current main economic activity) contributed to keeping the Pantanal's population density low, making it worthy of preservation (Junk and Cunha, 2005; Junk et al., 2006; Machado and da Costa, 2018). The implementation of development programs, crossroads, small hydroelectric reservoirs, and mining since the mid of 1970 and 1980, in addition to intensive farming in the Upper Paraguay Basin plateau, contributed to the degradation of natural vegetation and biophysical stability (Junk and Cunha, 2005; Alho and Sabino, 2011). It comprises almost 2000 km^2 of protected areas considered as UNESCO Natural World Heritage Site, and encompasses three Ramsar Sites, due to its ecological significance and high biodiversity. However, the expansion of agriculture frontiers in the Cerrado and Amazon biomes, exert a strong influence on natural resources on its surroundings (Nobre, 2010; Guerra et al., 2020) and the Pantanal biome susceptibility to changes appears again in this regional context (Hamilton, 2010).

2.2. Land use and land cover (LULC) data

The time series of LULC class data is an annual 30 m product from MapBiomas Project (Souza et al., 2020). The LULC maps from Collection 5 were made from Landsat imagery using the Random Forest machine learning classification process on Google Earth Engine cloud processing (see more at https://mapbiomas.org/en/methodology-overview). For Pantanal biome, the making of LULC mosaics prioritized Landsat scenes of dry period (May to August) by MapBiomas and the reported overall accuracy of Brazil classification is 89% (Souza et al., 2020).

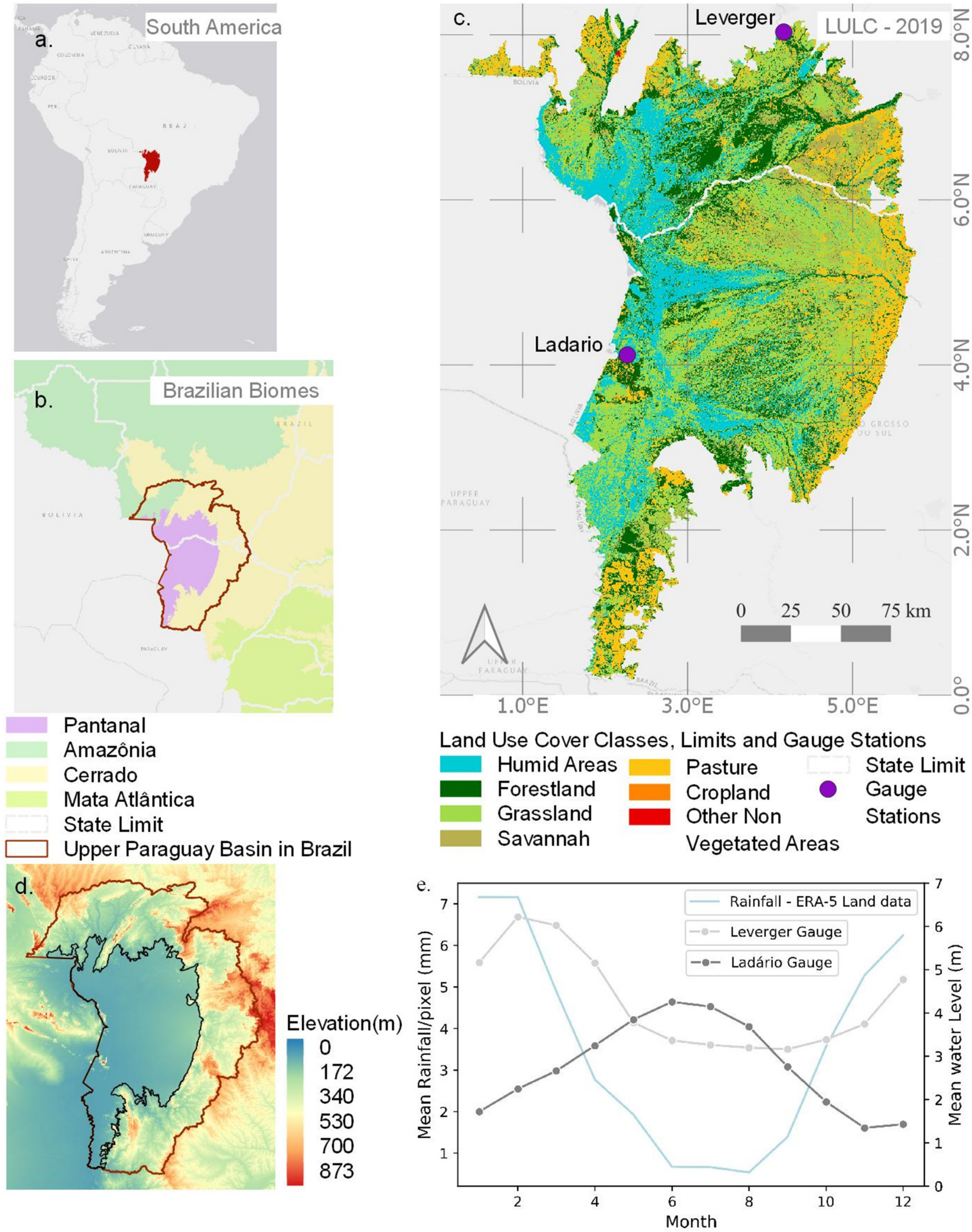


Fig. 1. Overview of the Pantanal biome. (a) Location of the Pantanal in South America (b) Delimitation of the Upper Paraguay Basin, highlighting the Brazilian biomes. (c) Land use and land cover (LULC) studied classes in 2019 and gauge stations locations. (d) Elevation from ASTER-GDEM of the Pantanal and its surroundings. (e) Historical Monthly averages of Rainfall/pixel and water level at Leverger (light gray: 15°52′12.0″S; 56°04′37.2″W) and Ladario Gauge Stations (dark gray:19° 0′ 7.2″S; 57° 35″42.0 W), from November 2000 to January 2021.

The time range selected from MapBiomas was from 2000 to 2019, where 2000 was the earliest year available in the dataset. For the purpose of this research, the original LULC data was reclassified from 14 to 7 classes for each year, according to the amount of biomass availability or fire load material classification proposed by Shimabukuro et al., 2020. The converted classes with its original attributes' values are as follow: Forest (3 and 9), Humid Areas (11 and 33), Savanna-Shrubland (4), Grassland (12), Pasture (15) and Cropland (20, 39 and 41). Other non-vegetated areas (attributes 0, 24, 25 and 30) were not considered in this analysis. The meaning of the Attributes values can be found on https://mapbiomas.org/en/codigos-de-legenda?cama_set_language=en. Fig. 1 c. is an example of the final reclassified 2019 map.

2.3. Burned area (BA) data

Time series of BA data was acquired from MCD64A1 Version 6, a monthly global gridded 500 m product (Giglio et al., 2015), derived from a composition between processed MODIS Surface Reflectance imagery coupled with MODIS active fire observations. “BurnDate” band was used, and the original values assigned for each pixel are the Julian days of the year on which the burn emerged. The date range went from November 2000 to January 2021 (Fig. 2a).

Precipitation (PREC) data was obtained as a supporting variable as is considered an important parameter to infer drought magnitude and fuel load availability assessment (Gomes et al., 2017; Franke et al., 2018).

Precipitation data was retrieved from ERA5-Land monthly average, a re-analysis dataset with 0.1 arc degrees resolution (approximately 11.1 km at equator) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Sabater, 2019). The selected date range for PREC is equal to MODIS BA and is also originally a global gridded product.

2.4. Remote sensing data processing

The Google Earth Engine (GEE) environment was used to obtain, prepare, and process the data in the Pantanal perimeter (IBGE, 2019). The global products were available as collections while National Mapbiomas dataset, as assets. Monthly variables (BA, PREC) were extracted for each LULC class by an iterative process. These monthly variables were subsequently filtered by and indexed with the LULC class and its area from November of a year to October of the following year (due to the methodology applied by MapBiomas on LULC classification). Beyond 2019, LULC map from year 2019 was used as data was unavailable. The PREC grid spatial layers were monthly reduced by each LULC using averages. The detailed authorial code for BA accountability by LULC over the months can be accessed through the following link: https://code.earthengine.google.com/a0ab1632e4ae6cf36cc72d415a78be69. A similar code was employed to PREC variable (https://code.earthengine.google.com/521cfe6c3a9d9953bff2c52b86b8596c).

For the fire recurrence maps, the monthly BA data layers were stacked, and the pixel overlap was spatially accounted for. A reduced map covering the 243 burned months was divided by seasons (Koppen, 1948; Peel et al., 2007) late wet (LW), early dry (ED), late dry (LD) and early wet (EW) which correspond to the union of February to April, May to July, August to October and November to January, respectively. Seasons were defined based on total burning area in biome and Aw (or namely, Tropical Savanna/Wet-dry climate) Koppen's classification. Trimestral burn frequency maps are bivariate, including the year of last burn spatialized information in its viewing.

2.5. Statistical and spatial analysis

Monthly Absolute BA (ABA, km^2) by LULC, as well as Relative BA (RBA, %) by the respective yearly LULC area class were represented by time series graphics (zero values were masked). The ABA data corresponds to the monthly burned area by each LULC in each year of analysis and the RBA data is the ABA data divided by each LULC and then multiplied by 100.

Monthly BA time series (absolute and relative) by LULC were tested to identify for autocorrelation as well as seasonality characteristics. For these, Durbin Watson (D) and Augmented Dickey-Fuller (ADF) tests were used, respectively, considering *p*-value <0.05. D test is widely used to test autocorrelation in non-lagged dependent variables and when size sample is reduced. It ranges from 0 to 4, and when values are close to 2, there is no autocorrelation; when close to 0, there is a positive autocorrelation; when close to 4, there is a negative autocorrelation (Durbin and Watson, 1950, 1951, Uyanto, 2020). The null hypothesis is that there is no autocorrelation. ADF stationarity test is used to check for stability of mean, standard deviation, and presence of seasonality over BA timeseries (Fuller, 1996). In this case, the null hypothesis is that the time series possesses a unit root and is non-stationary. When seasonality is presented, the series is not stationary.

ADF test was applied on time series ranging from November 2000 until January 2020 and also from November 2000 until January 2021. Since the year 2020 was a clear outlier (Garcia et al., 2021), we opted to exclude this year in the ADF tests in the Mann Kendall tests (more details of the last below). Hence, considering the three elements that defines a timeseries as stationary, if the shorter time series (until January 2020) was confirmed as stationary (*p-value* < 0.05), then it would be inferred that the non-stationarity in the longer time series (until January 2021) would be a result of the instability due to the influence of the mean and/or standard deviation - and not due to seasonality. Both tests, D and ADF, were supported by the Statsmodel library on Python (Fig. 2 b.).

Due to the series characteristics obtained from the aforementioned tests, BA (absolute and relative) trend analysis tests were performed using Yue and Wang Modified Mann Kendall test, appropriated for serial autocorrelation (Yue and Wang, 2004). The null hypothesis to be tested is that there are no trends, with *p-value* < 0.05. Lastly, series trends for the variables by LULC were confirmed by Theil-Sen Robust Linear Regression (TS) (Sen, 1968; Theil, 1992, Helsel and Hirsch, 2002).

Theil-Sen, also known as Kendall-Theil robust line, is a median-based and non-parametric estimator that does not make assumptions about the dataset distribution and is insensitive to outliers. It has been applied in

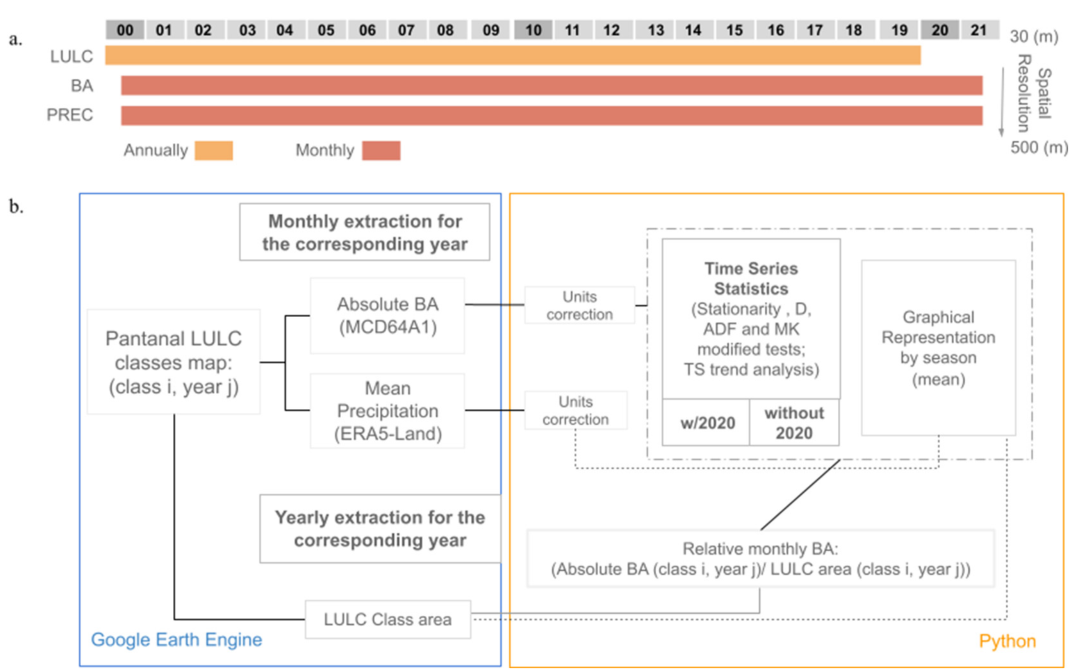


Fig. 2. Methodology flowchart. a. Temporal coverage of each used dataset: Land use and cover (LULC), burned area (BA) and Precipitation (PREC). b. Workflow on the used processing environments.

many hydrological and environmental studies (Somorowska, 2016; Alves et al., 2021). As a linear fit estimator, it returns the slope (the degree of line decline of units/time, in this case) and y intercept values (studied monthly variables values in time zero), compounding the classical regression line equation (y = αx + b). Both statistical analyses were performed with pyMannKendall Python package (Hussain and Mahmud, 2019). LULC classes' monthly variables were aggregated by trimester as averages for graphical representation.

3. Results

3.1. LULC changes

LULC in Pantanal composed mostly of forestland, humid areas, shrubland-savanna, grassland, pasture, and cropland (Fig. 1 c.); the LULC data from 2000 to 2019 showed a consistent increase (51%) in pasture area from 15,497.60 km^2 to 23,384.30 km^2 (Fig. 3) while croplands exhibited a small increase and savannah areas decreased. Other landcover types showed high variability between years. Forestland for instance, showed the lowest area variability.

Burned area time series by LULC.

The burned areas were not uniformly distributed across LULC classes, time, and seasons, across the past 20 years in Pantanal (Fig. 4). Major monthly ABA were observed in September of 2020, August of 2005, August of 2020, August of 2001 and September of 2007 in different areas of the biome, respectively ranging from 9.43% to 5.6% of the total area of the biome.

Grasslands had the largest ABA among land use classes for 2005 and 2001 (August) and in 2020 (September) with 6903, 5305 and 5887 km^2 respectively (Fig. 4 a. and b.). This represented 53.3, 54.9 and 39.9% of total burnings respectively, and made up between 3.7 and 4.6% of the biome area. Temporally, 2020 (August) and 2007 (September) were years with higher ABAs (especially forest and grasslands). In addition, 2002 and 2019 had longer burning seasons: from August to November, totaling to 26,767 and 19,600 km^2 respectively. Although September and October saw the highest ABA, fire was observed during the whole year in the Pantanal.

BA patterns look different when using a relative scale to assess BA patterns for each land use and land cover class. In 2020, forest, humid areas, and pasture responded with a higher proportion of burned areas (Fig. 4 b). In 2005, grassland, pasture, and savanna had a higher proportion of burned areas instead. Forest presented larger monthly burned area values in 2020 (August and September) and 2005 (August), humid areas in 2020 (from July to October), 2019 (August to October), 2012 (August to September) and 2002 (November), savanna in 2004 (September) and 2005 (August), grasslands in 2005, 2001 and 2020 (August for the first two and September for the last), pasture in 2020, followed by 2005 and

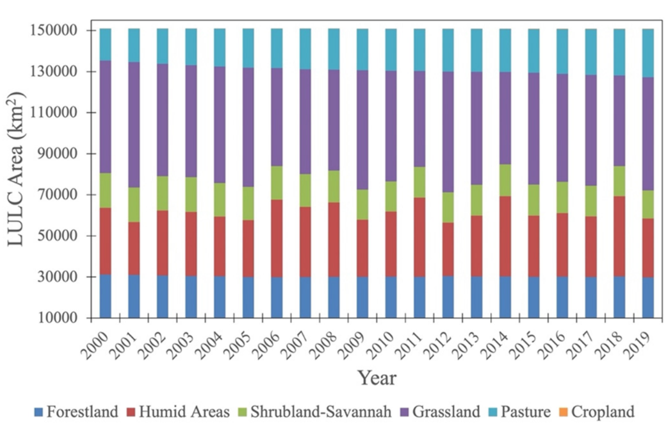


Fig. 3. LULC changes in Pantanal from 2000 to 2019. Source: MapBiomas Collection 5 (Souza et al., 2020).

2002 (September for the first, August for the last two) and cropland in 2015 (November) and other months in the LW season in 2016, 2018 and 2019. Relatively, forests, grasslands and croplands were classes with higher burned areas (Fig. 4 c), especially during dry season months (August and September) and pastures, with lower relative burned area than the others LULC.

The average yearly variation of absolute burned area, relative burned area, and monthly average precipitation during the ED season is shown in Fig. 5. In all LULC classes, burned areas from 2014 to 2016 were lower compared to other years. In the same years, the highest precipitation in the time series was observed. Shrubland-savanna, grassland and pasture showed larger burned area in 2002, 2005 and 2020. Forest showed low values of burned area (<75 km^2) for most of the entire time series, except in 2020. Cropland on the other hand, did not show increased burned area in 2020.

During the LD season (Fig. 6) the burned areas increased, compared to the ED season (Fig. 5). For instance, in 2002, forest showed an increase from approximately 75 km^2 (ED season) of burned area to 900 km^2 (LD season). During the LD season, precipitation variability was also larger compared to the ED season, i.e., from 2014 to 2016, precipitation in the LD season was lower than in the same period of ED season.

The mega fire of 2020 was pronounced for almost every LULC, except for shrubland-savanna, because the burned area in 2002 was higher than 2020. The same analysis for LW season and EW can be found in the S1 and S2.

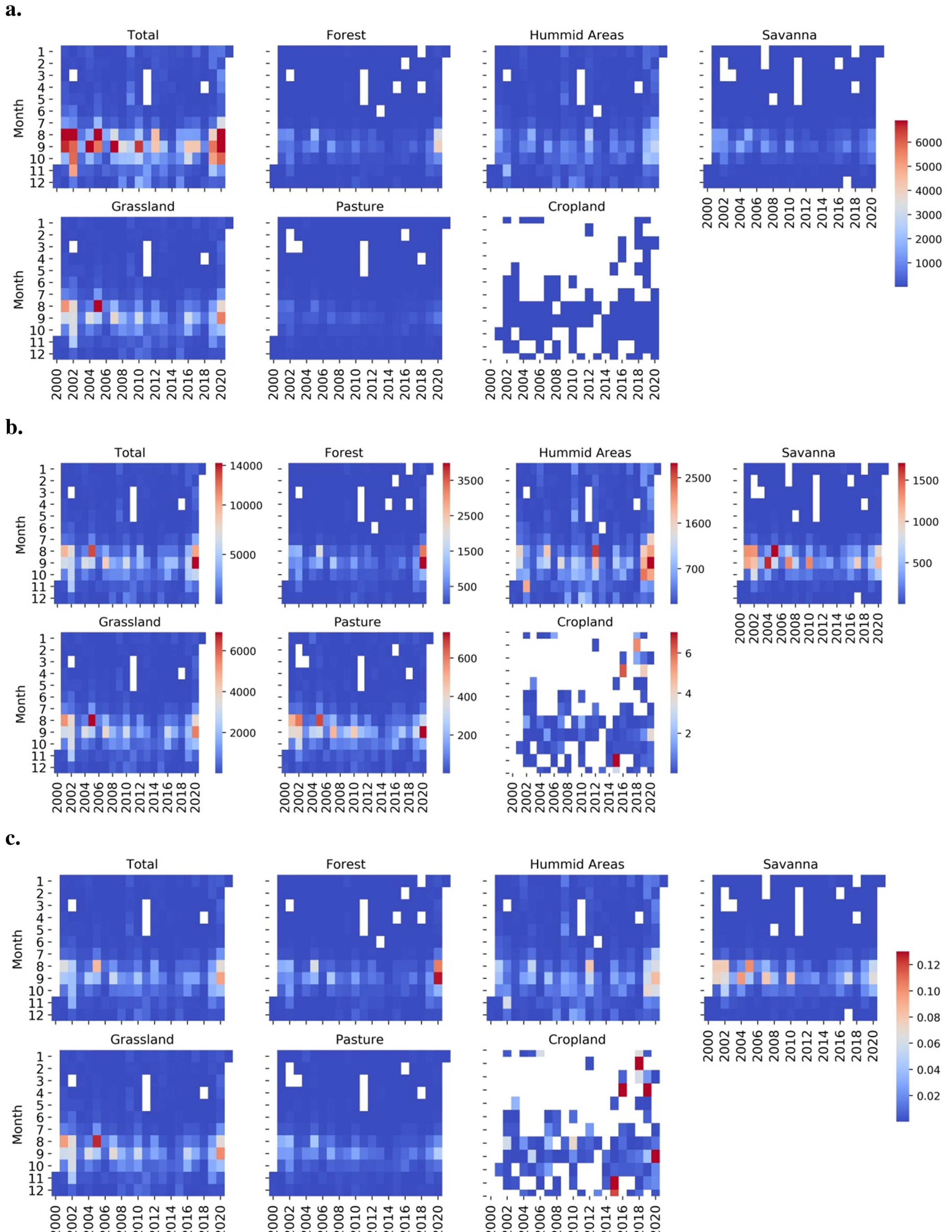
For both shorter (Nov/2000 until Jan/2020) and longer time series (Nov/2000 until Jan/2021), only cropland presented a significant increase in absolute and relative burned areas (Table 1). The results in Table 1 shows that, only cropland indicated signs of increased burned area during the past twenty years.

Over the last years, fire occurrences in forest, savanna, grassland and pasture classes have been decreasing, while the fire occurrences for the cropland have been increasing. However, in 2020, a different trend signal was observed for the forest class and as well as for the entire biome; the other classes (savanna, grassland and pasture) appeared less negative than the results excluding this year.

Most of Pantanal was burnt at least once in the last twenty years (Fig. 7). The map showed that across the 243 analyzed months, the maximum burn frequency reached 19 times that of fire recurrence in the same area. It can be also understood as a mean of almost one burn per year in most of the regions. Larger values were seen mainly at southwest Pantanal. The higher values were also mostly found over the current grassland. Conversely, smaller and low frequent burnt patches were seen in central and southeast portion of Pantanal. Some portions of Pantanal remain fire-free.

S3 illustrates the fire frequency per burned area (km^2) per LULC. It revealed that smaller burned areas were frequent for all LULC classes. Large burned areas were observed in forest and grassland at a lower frequency. Cropland showed the smallest burned area among all LULC classes. For grassland, an area of 11,457.10 km^2, representing 20.8% of the entire Pantanal, burned once during the past twenty years while an area of 0.32 km^2 (0.001% of the grassland area) burned at least one time in each year. For cropland, an area of 40.11 km^2 (18.9% of the cropland area) burned only once during the entire time series and 0.02 km^2 (0.01% of the cropland area) burned 8 times during the past two decades. For humid class, the biggest area burned amounted to 5360.94 km^2 (18.7% of the cover class), which burned once in the entire study period; on the other hand, small burned areas of 0.09 km^2(representing 0.0003%) in this class, burned 19 times.

Fires were concentrated on western side during the LW season and was observed to spread towards the east in the following seasons, reaching its peak in the LD season (Fig. 8). During LW season, recent burns appeared more extensive than other seasons, where older burned areas are greater. In LD season, higher values of burn frequency were present, especially in the southern and northeast portions of the biome. In this season, recent low frequency burns were seen in the north portion. In addition, old fires (from 2000) generally covered a smaller area than recent fires (2021), especially during the LD season. Overall, small burned areas were more frequent than large burned areas for all land use across all seasons. Forest and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Forest
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1500
500
Hummid Areas
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1600
700
Savanna
1500
1000
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Grassland
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Cropland
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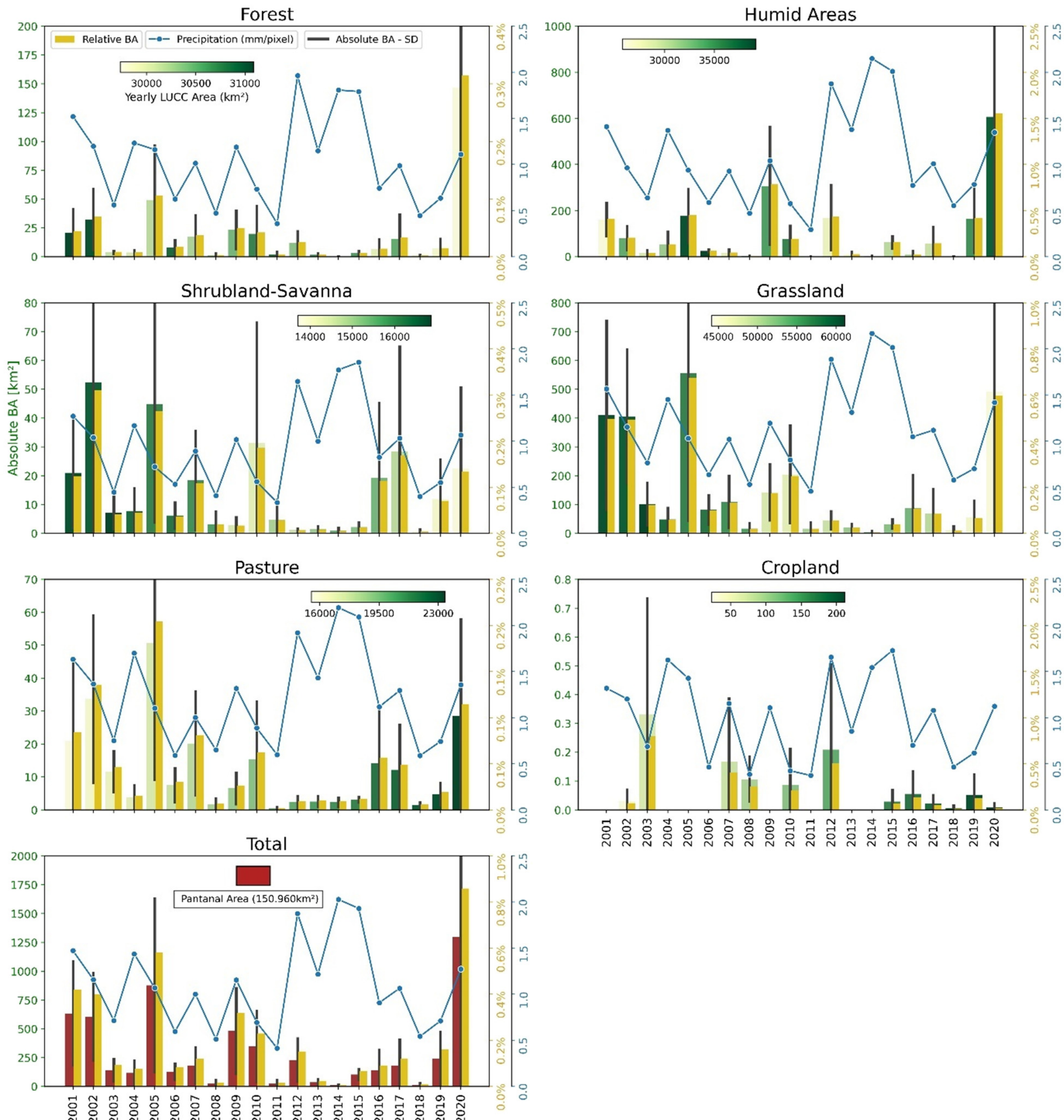

Fig. 5. Yearly distribution of absolute BA average (left axis - green), relative BA average (right axis - yellow) and monthly precipitation average (right axis - blue) in ED season (from May to July) by LULC. Green hue of colour bars indicates the total area accounted yearly by LULC. Red bars are the constant Pantanal biome total area according to IBGE, 2019 dataset. Thin gray bars correspond to standard deviation (SD) of absolute BA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

grassland represented larger burned areas, while cropland represented the smaller ones (S3).

4. Discussion

Pantanal is a complex ecosystem composed by grasslands, savannas, forests and humid areas. Fire has played an important role in sustaining many of these ecosystems. For grasslands and savannas, burning is an important ecological factor (Hardesty et al., 2005), and appropriate fire management protocol which needs to be undertaken (Pivello, 2011; Pivello et al., 2021). Grasslands usually accumulate an excess of dry grass and when an ignition occurs, naturally or by humans, fire easily spread around the LD season (Soriano et al., 2020).

As highlighted by Souza et al. (2020), cattle ranching and sugarcane expansion are driving the suppression of Pantanal natural vegetation grassland and extensive wetlands. The expansion of cattle ranches was favored

Fig. 4. Time series graphics with Monthly BA by LULC Class from November/2000 to January/2021 (zero values were masked). (a) Absolute values in km^2, legends scale common between classes. (b) Absolute values in km^2, maximum and minimum legends in relative scale for each class. (c) Relative values: relative to the respective LULC class area.

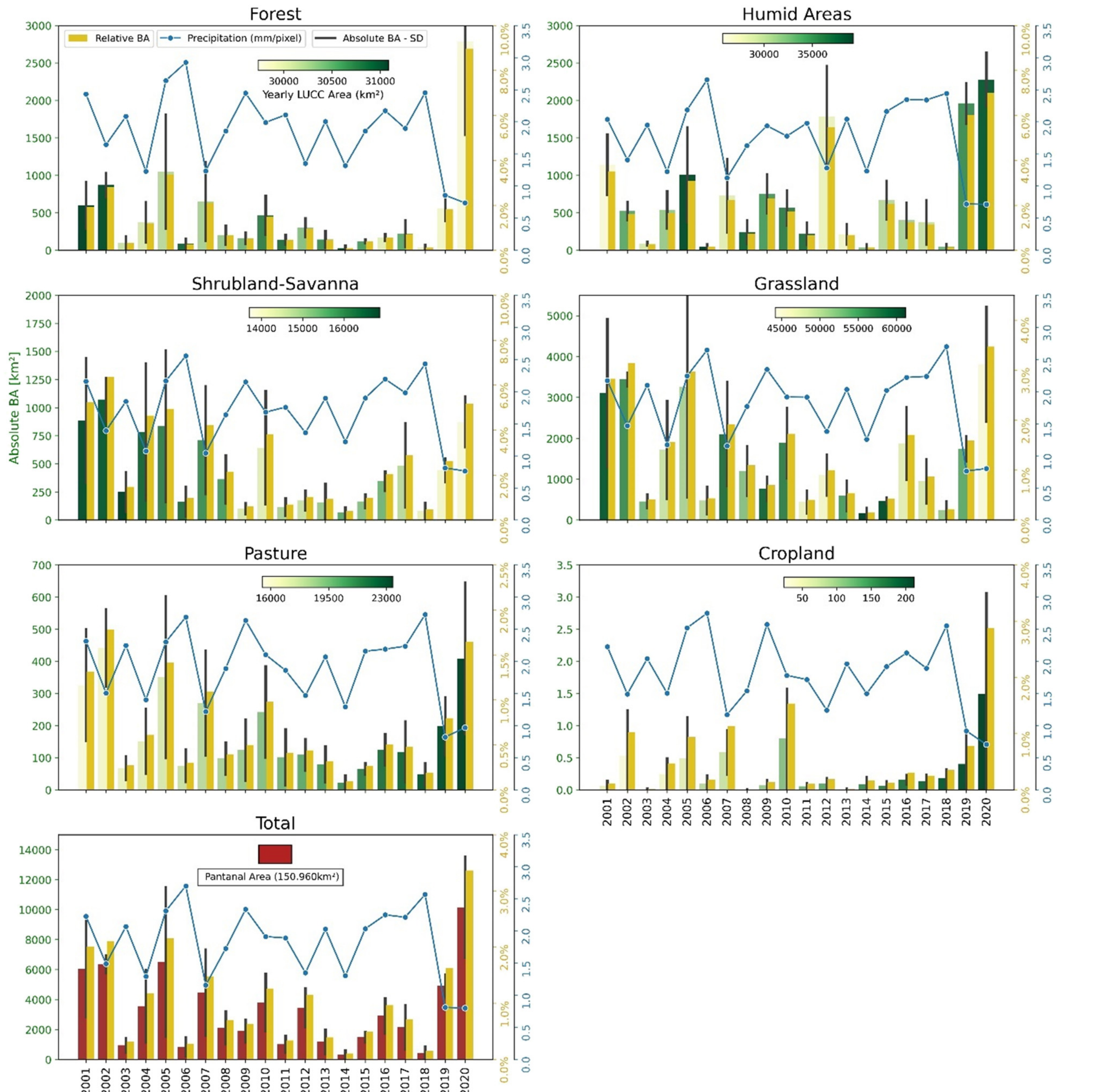

Fig. 6. As in Fig. 5 but for LD season (from August to October). Red bars are the constant Pantanal biome total area according to IBGE, 2019 dataset. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by a sequence of dry years from 1991 to 2004 (Mourão et al., 2010) and this pattern of pressure that resulted in LULC conversion is similar to the anthropic activities practiced on elevated basin portions (Guerra et al., 2020). Coutinho et al. (2016) showed that sugar cane production in the Pantanal expanded by 48% and agriculture by 39% from 2001 to 2013.

Fires can be detrimental for other parts of Pantanal, such as the tropical forest. Surface fires in tropical forests usually burn litter, duff and the understory grasses and herbs. They may cause extensive top-kill in small trees (Hoffmann et al., 2009) and change the composition, structure and function of forest ecosystems (Prestes et al., 2020; Sansevero et al., 2020). Undoubtedly, fires in the Pantanal forests peaked in 2020, and is mainly responsible for the increased burned area values showed in Table 1 (in the "total" column).

Our results of burned areas for the last 20 years across different LULC classes in the Pantanal showed that the fires of 2020 was a significant event even though the biome has been continually burning for the past two decades. Most of the Pantanal has burnt at least once during the study period, especially during the dry season. In addition, the results suggest that small patches of burning were frequent in the last 20 years.

The year of 2020 was noted as one of the years in this study period that had a comparatively large burned area, which corroborates with previous studies (Garcia et al., 2021; Kumar et al., 2022). This is likely due to severe droughts in the region caused by a decrease in precipitation (Fig. 6; S1 and S2). This finding was supported by Marengo et al. (2021), Lázaro et al. (2020) and Thielen et al. (2021) which reported that precipitation and river levels have been decreasing in 2020 and its preceding years (2018 and 2019). Lower precipitation values after 2015 are also shown on our studies for ED season (Fig. 5) and after 2018 for LD season (Fig. 6).

Marengo et al. (2021) showed that in 2020, Pantanal experienced a persistent extreme drought with 60% less rain than a normal year, due to an

Table 1
Results of linear regression params BAs time series by LULC applied with SciPy library (95% confidence intervals considered). Slope red values indicates a positive slope (BA increasing). *p-value* < 0.05 are highlighted in bold. (a) time series ranging from Nov/2000 until Jan/2021. (b) time series ranging from Nov/2000 until Jan/2020.

(a)	Nov/2000-Jan/2021 Original Theil Sen trend | Modified Mann Kendall Test Yue Wang (p-value < 0.05)							
		Forest	Savanna	Humid	Grassland	Pasture	Cropland	Total
Slope (α)	ABA (km^2/yr)	0.004	−0.018	0.700	−0.460	−0.069	0.000	0.157
	RBA (%/yr)	0.00001	−0.00011	0.00215	−0.00077	−0.00047	0.00000	0.00018
Intercept (b)	ABA (km^2)	7.49	3.76	44.10	84.65	7.18	0.00	170.64
	RBA (%)	0.024	0.022	0.135	0.154	0.047	0.000	0.112
p-Value	ABA	0.921	0.390	0.212	0.395	0.264	**0.031**	0.867
	RBA	0.921	0.381	0.211	0.424	0.238	**0.034**	0.779
(b)	Nov/2000-Jan/2020 Original Theil Sen trend | Modified Mann Kendall Test Yue Wang (p-value < 0.05)							
		Forest	Savanna	Humid	Grassland	Pasture	Cropland	Total
Slope (α)	ABA (km^2/yr)	−0.069	−0.040	0.019	−1.312	−0.125	0.000	−1.473
	RBA (%/yr)	−0.0002	−0.0002	0.0001	−0.0024	−0.0008	0.0000	−0.0010
Intercept (b)	ABA (km^2)	6.83	3.53	46.91	83.51	7.50	0.00	165.22
	RBA (%)	0.022	0.021	0.144	0.152	0.048	0.000	0.109
p-Value	ABA	0.217	0.234	0.838	0.108	0.164	**0.048**	0.268
	RBA	0.217	0.234	0.838	0.108	0.164	**0.048**	0.268

anomalous warming of the tropical north Atlantic. As a result, unprecedented wildfires ripped through the region even in January and February, despite it being the wet season (Marengo et al., 2021). Garcia et al. (2021) also noted a reduced moisture inflow coming from the Amazon region in 2020 which could have exacerbated the drought. Our results showed that extreme droughts in 2020 and 2005 (Figs. 5 and 6) affecting all LULC classes coincided with great fire events reported in other studies (Kumar et al., 2022; Garcia et al., 2021). Coupled with 2020's climate and biomass conditions, wildfires in Pantanal reached huge proportions.

2020's fire season was exceptional, but conditions that led to this extreme event, such as increase of ignition sources, biomass availability, drier and warmer climate, are becoming increasingly common in the Pantanal (Libonati et al., 2020). For instance, Libonati et al. (2022) showed that the recent warming over this region since 1980 is around four times greater than the average global temperature increase. Decreasing trends in air humidity and in precipitation, together with higher temperatures, are increasing fire danger over the last 40 years. Recently, Kumar et al. (2022) showed that anthropogenic-caused fires are exacerbating climate effects on natural ecosystem within the Pantanal. On the Pantanal portion of Mato Grosso do Sul State, Oliveira-Júnior et al. (2020) had already identified a positive trend of fire foci from 2000 to 2015.

The Brazilian Pantanal mainly composes savannas (IBGE, 2012) and it is also closely situated to the other biomes, i.e., savannas of Cerrado and the Atlantic and the Amazon rainforests. Deforestation in the Amazon forests have affected rainfall and temperature regimes in the Pantanal region (Amaral e Silva et al., 2020), increasing the Pantanal's vulnerability to fire (Bergier et al., 2018).

However, long-term consequences of these fire occurrences on biodiversity and ecological services remain largely unknown (Libonati et al., 2020; Garcia et al., 2021; Damasceno-Junior et al., 2021). The implication of fires on the distribution of flora and fauna across Pantanal is yet not fully understood (Junk and Cunha, 2005). A recent effort revealed that around 17,000 million vertebrates were directly killed by the fires in the Pantanal during 2020 (Tomas et al., 2022). However, the authors point out that this value may be underestimated. For some areas affected by the fires during 2020 in the Pantanal, Martins et al. (2022) estimated the cost of post-fire restoration to be around 123 million USD.

Between other global and long coverage BA datasets available online, MCD64A1 shows important gains even with its gross spatial resolution of 500 m. Its inputs operate on short-wave infrared (SWIR) electromagnetic spectrum region and with a daily revisit. These qualities makes it a good data source, especially under tropical conditions where post-fire signals are swiftly lost by sensors, and cloud persistence limits imagery quality (Chuvieco et al., 2019). Further, MCD64 collections were robustly validated for Brazil under varying spatial and climate conditions (Rodrigues et al., 2019). Chuvieco et al. (2018) consider that these main different global BA products complement each other as also highlighted by Long et al. (2019). Depending on the size of studied region, very high spatial resolution demands more computer capacity processing ant it can result also in impractical processing time (Long et al., 2019). MCD64A1 is broadly used over the globe, and it favors comparisons between regions around the world. Its cloud processing due the dataset availability on GEE platform also, makes convenient processing for our regional scale study.

According to Damasceno-Junior et al. (2021), fire regime in Pantanal is closely linked to the annual and pluriannual flood pulse and from August to October, the biomass produced during the flooding period becomes available as fuel for burning during the next dry season. As shown during the 2020 burns, Paraguay River, the main river of Pantanal (Fig. 1 b.), recorded the lowest water level during flooding periods in the last 47 years (Marengo et al., 2021). Consequently, most of the 2020 wildfires occurred in this flood zone (Damasceno-Junior et al., 2021; Garcia et al., 2021; Kumar et al., 2022). Nevertheless, an interannual to biannual/triannual scale burning cycles was also observed between grassland and humid areas formations. It coincides with respective LULC change due boundaries reshaping in transition zones and flooding dynamic alterations in drier-wetter years seen in works of Damasceno-Junior et al. (2021) and Thielen et al. (2020).

The results observed in Fig. 8 highlights the combined influence of the flood pulse and rainfall regime in modulating the fire regime. During the LD season (Fig. 8c), for instance, it is highlighted that the occurrence of fire is increasingly frequent and consistent with the increase of more frequent extreme drought events. Based on our results, we hypothesized a growing trend in burned areas in all LULC in Pantanal, especially in grasslands, savannas and pastures. We have found an increase in burned areas, but in cropland land use class. In general, cropland expansion does not imply an increase in burnings since it takes place in older pasture areas, already converted from natural to anthropic stage (Chuvieco et al., 2019). The land use changes linked to deforestation of native vegetation traditionally involve fire for opening new pasture areas (Archibald et al., 2013). As such, deforestation and the increase in large agribusiness properties in Pantanal could be linked to these recent fire events (Mota et al., 2019; Marques et al., 2021). The higher BAs proportions found on native vegetation compared to managed areas also highlight the lack of adequate fire management.

Taking into consideration the Pantanal's flooding cycle along Paraguay River, where flooding reaches peak from May to July, near the months with lowest rainfall values (from June to August), the floodplain cannot catch fire during dry season except in dry years. In the case of dryness asynchrony, a larger amount of accumulated biomass produced during the last flooding will remain available and exposed as fuel – mainly the histosols (organic soils), that are wet and not available to fire in “normal” years (, Holden et al., 2018; Garcia et al., 2021).

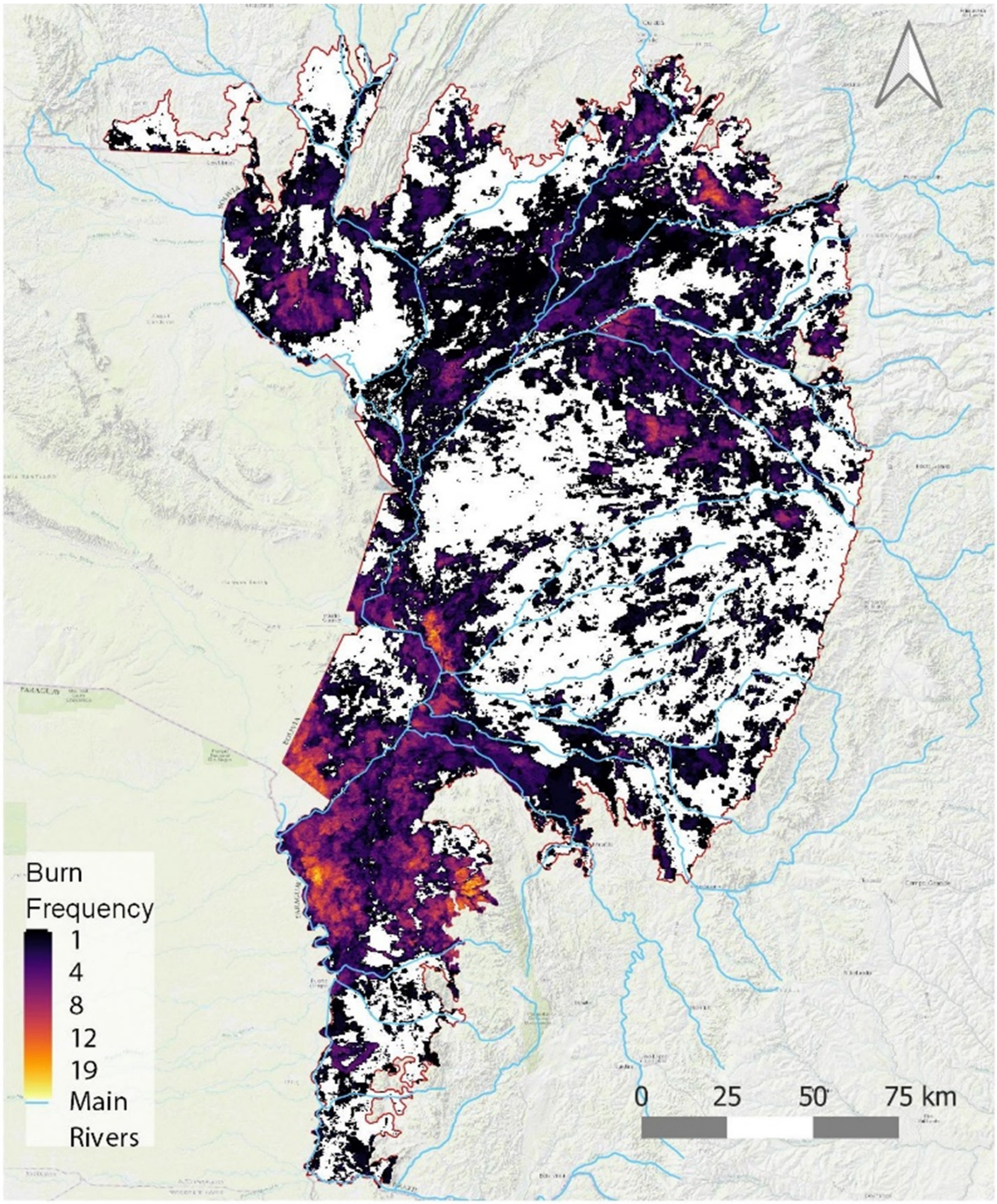

Fig. 7. 20 years of burn frequency map from monthly MCD64A1 dataset, 500 m resolution.

Some works also detected that the drought patterns in Pantanal trended towards becoming more frequent (Thielen et al., 2020; Cardoso and Marcuzzo, 2010), amplifying the susceptibility of the biome to fires (Libonati et al., 2020). Relying directly on fire data, most studies in the Pantanal have focused on a single discipline, for example, plant ecology (Libonati et al., 2020). Integrated knowledge about how fire distribution occurs over Pantanal different phytophysiognomies and historical comparisons between land use and land cover were scarce until this present study.

Fire ignition by natural causes (lightning strikes) typically occurs during the summer (from December to February) and reaches small extents. As such, fires occurring during the dry season are mainly human related and accounts for the major amount of burned area (Menezes et al., 2022). According to Damasceno-Junior et al. (2021), integrated fire management during ED season helps to reduce biomass in grasslands, which reduces large, high-intensity fires during the LD season (Eloy et al., 2018).

4.1. Limitations and uncertainties

Greater spatial resolution than 500 m, for example, will be fundamental for more localized, small-scale studies (Chuvieco et al., 2018; Rodrigues et al., 2019). Omission of small fires are, as well, a limitation of daily burned area products, as MCD64A (Campagnolo et al., 2021) and filtering spatial data with such a different spatial resolution as used here can also reduce accuracy in edge areas and small patches, typical for cropland class in Pantanal, for example. On the other hand, with the use of higher resolution imageries, such and Landsat and Sentinel, it may improve burned areas detection. In LULC classes formed by small patches this higher resolution mapping can indicate burned areas that are not considered in gross LULC and BA classifications, particularly when more than a decade of burns time series is being analyzed.

LULC maps were only available until 2019, therefore we were not able to analyze changes in land cover in more recent history. LULC maps in 2019

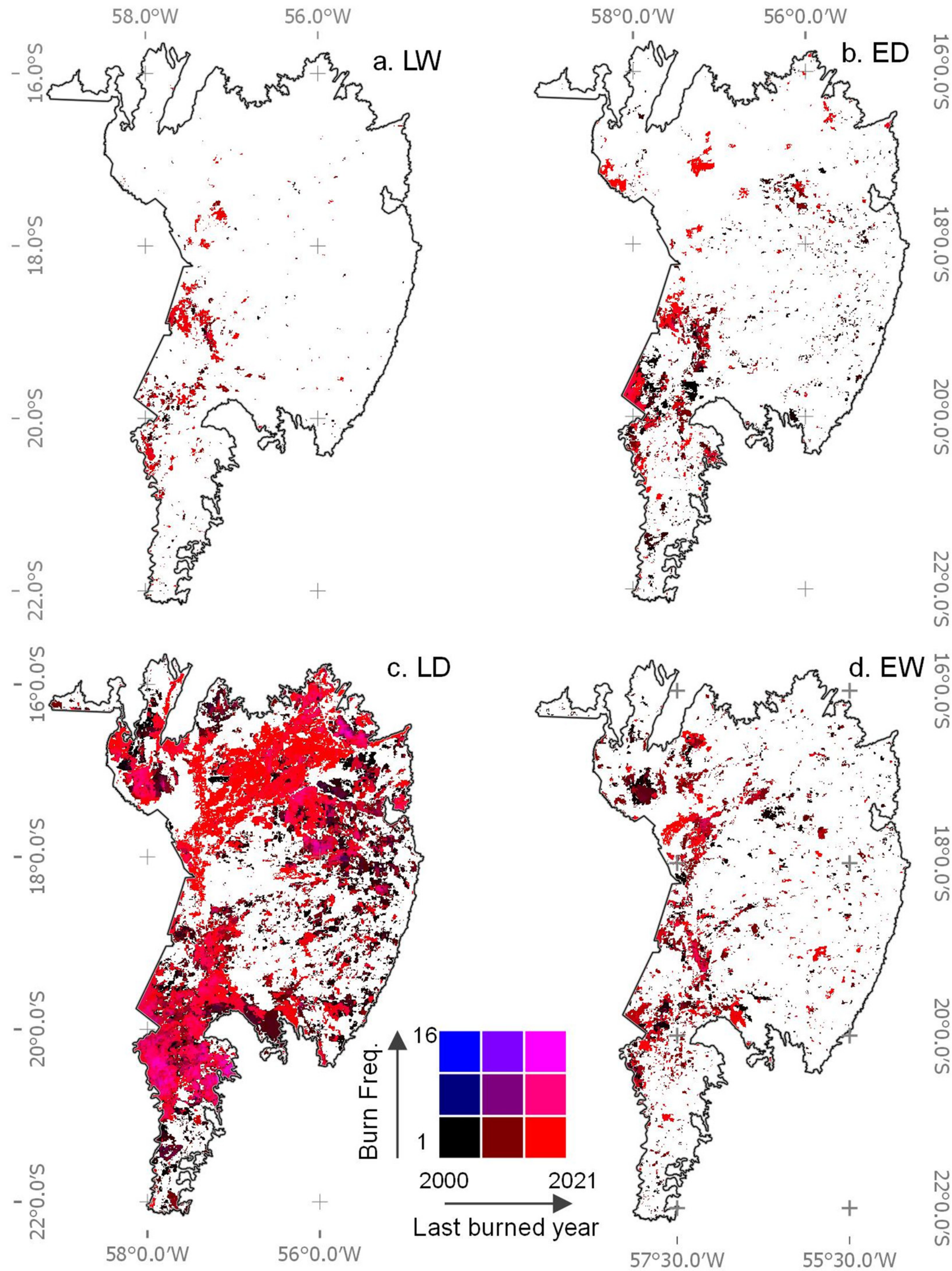

Fig. 8. Bivariate map (burn frequency versus last burned year) by season. (a) LW are the BA detections by MCD64A1 during Late Wet season months (February, March, April), summing 60 months of 20 years. (b) ED are the detections during Early Dry season months (May, June, and July), summing 60 months of 20 years. (c) LD are the detections during Late Dry season months (August, September, October), summing 60 months of 20 years. (d) EW shows detections over Early Wet Season months (November, December and January), summing 63 months of 21 years.

was used as a surrogate for 2020 and 2021 in the analysis here performed, which may lead to some overestimation (or underestimation) of burned areas in land cover that have changed in the last two years.

4.2. Implications for management and future perspectives

Despite the severity of 2020 fires in Pantanal, it has led to a better understanding of fire dynamics in the biome and allowed the identification of crucial structural gaps in local fire knowledge (Libonati et al., 2020). As adopted in this study, comparisons of fire occurrences across different LULC, the availability of fuel loads, and across different fire seasons have revealed interannual trends of fire in Pantanal. This is crucial to predicting future fire frequencies, extensions, intensity, seasonality, and severity. It also aids fire managers in anticipating new trends and disasters.

More detailed research is needed on the weather conditions that fan fires, as well as the influences of ecology and management (Libonati et al., 2020). Information concerning fire in tropical wetlands are scant and the major fire studies are based on savannas and forests (Damasceno-Junior et al., 2021). In Brazil, most fire research has been developed in the Cerrado and Amazonia biomes (Pivello et al., 2021). Long and consistent datasets available for analysis are also crucial for environmental studies in general, including for the understanding of drivers of fire activity and its consequences (Chuvieco et al., 2019).

While Pantanal has been historically subjected to much environmental stress with its recurrent dry-wet episodes, fires are likely to worsen in the future. Given our future climate change scenarios, the environmental conditions (low precipitation, soil moisture, high air temperature) optimal for fire occurrences is likely to persist (Thielen et al. (2020), Marques et al., 2021). Thus, knowing the vulnerability of each LULC class in this sensitive biome will help local policymakers to plan and manage Pantanal to improve resilience.

5. Conclusion

Despite the significant remaining natural vegetation in Pantanal, we should not negate the pressures brought about by land conversion and degradation and the Pantanal's susceptibility to major disasters. Growth of pasture areas in lower land reflects intensive anthropogenic activity on the basin's higher catchment areas. Burnings in croplands have also been on the rise, particularly during the LD season, despite still constituting a relatively small area. On the other hand, humid areas and grassland areas are more susceptible to burnings during extreme dry weather conditions. For instance, grassland has been the main area burned in the Pantanal over the past twenty years. But in 2020 fire season, when comparing by proportion to the respective class area (RBA), forest, humid areas, and pasture became greatly affected by fires. Still, our study showed that the fires of 2020 was the most important event even though the biome has been continually burning in the past two decades. We conclude that when accounting BAs at regional level, we must understand and compare values from a stratified approach since burns can have different drivers and implications to fauna, flora and climate depending on LULC and periods of the year. Also, different rates of recovery and regeneration of the multiple land covers in Pantanal post-fire must be closely monitored, to better fire management strategies for long-term mitigation of the negative consequences on the conservation of the world's largest wetland.

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.scitotenv.2022.155386.

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