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Fires dynamics in the Pantanal: Impacts of anthropogenic activities and climate change

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ABSTRACT

Anthropogenic activities responsible for modifying climatic regimes and land use and land cover (LULC) have been altering fire behavior even in regions with natural occurrences, such as the Pantanal. This biome was highlighted in 2020 due to the record number of fire foci and burned areas registered. Thus, this study aimed to understand how changes in LULC and climate affect the spatial, temporal and magnitude dynamics of fire foci. The Earth Trends Modeler (ETM) was used to identify trends in spatiotemporal bases of environmental and climatic variables. No trend was identified in the historical series of precipitation data. However, an increasing trend was observed for evapotranspiration, normalized difference vegetation index (NDVI) and temperature. For soil moisture, a decreasing trend was observed. The comparison between the mean of the historical series and the year 2020 showed that the variables precipitation, temperature, soil moisture and evapotranspiration had atypical behavior. Such behavior may have contributed to creating a drier environment with available combustible material, leading to a record number of burned areas, about three million hectares (248%) higher than the historical average. The 2020 fire foci data were used in two types of spatial statistical analyses: Grouping, showing that 76% of the registered fire foci were at high risk of fire and; Hot and Cold Spots, indicating high concentrations of Hot Spots in the northern region of the Pantanal, close to Cerrado and Amazon biomes agricultural frontier. The results of the Land Change Modeler (LCM) tool evidenced a strong transition potential from the natural vegetation to agriculture and pasture in the eastern region of the Pantanal, indicating that this could be, in the future, a region of high concentration of fire foci and possibly high risk of fire. This tool also allowed the prediction of a scenario for 2030 that showed that if measures for environmental protection and combating fires are not adopted, in this year, 20% of the Pantanal areas will be for agricultural and pasture use. Finally, the results suggest that the advance of agriculture in the Pantanal and changes in climatic and environmental variables boosted the increase in fire foci and burned areas in the year 2020.

1. Introduction

Fires can be of natural, accidental, or criminal origin (Clemente et al., 2017; Caúla et al., 2015; Van Der Werf et al., 2008). These events usually start due to unfavorable weather conditions, such as long periods of drought, high temperature and low air humidity (Viganó et al., 2018). However, these episodes are aggravated and intensified by climatic changes and human activity (Boer and Dios, 2020; Brando et al., 2019; Thielen et al., 2020; Úbeda and Sarricolea, 2016). The accumulation of dry biomass in the soil, resulting from periods of low soil moisture or deforestation, contributes to the accumulation of fuel loads, providing ideal conditions for fire propagation (Brando et al., 2019).

The use of fire is a traditional management tool in agriculture to eliminate residues and promote the renewal of pasture and agricultural cultivation areas (Bayne et al., 2019; Garcia et al., 2021). In addition, prescribed burning in savanna ecosystems should be highlighted due to

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the regulatory importance of fire. (Costa and Thomaz, 2021; Durigan, 2020; Morgan et al., 2020). However, despite being a useful and inexpensive tool, its uncontrolled use has favored the increase in the number of fire foci. Fire foci are powerful signs of burning, contributing to the megafires registered in recent years, as reported in Australia, Chile and Brazil (Boer and Dios, 2020; Garcia et al., 2021; Úbeda and Sarricolea, 2016).

It is important to highlight that prescribed burning, which uses fire in a controlled manner, is beneficial to ecosystems and aims to consume combustible material from the surface and avoid megafires (Shrestha et al., 2021; Valkó and Deák, 2021). On the other hand, the agricultural use of fire, generally used at the beginning of the dry season, contributes to the uncontrolled spread of fire (Costa and Thomaz, 2021). Furthermore, it is noteworthy that, despite the type of fire use, the particulate material resulting from the burning process is capable of causing damage to air quality and public health (Oliveira-Júnior et al., 2020).

In this context, the Pantanal biome, which covers Brazil, Bolivia and Paraguay, was highlighted in the international media in 2020 for presenting the highest number of fires ever observed in the biome. Although a part of this biome, as in the Brazilian Cerrado, has phytophysiognomies prone to fire, changes in the local microclimate have altered the fire dynamics (Filho et al., 2021; Schulz et al., 2019; Soriano et al., 2015). The study by Oliveira-Júnior et al. (2020) revealed that the Pantanal is the biome with the highest occurrence of fires compared to the Brazilian Cerrado and the Atlantic Forest biomes. However, few published studies approached the causes and consequences of fires in the biome.

The combination of the strong drought and high temperatures of 2020, with the intensification of anthropogenic activity and the negligence of the Brazilian Federal Government, opened space for the biggest fire recorded in the Brazilian Pantanal since the beginning of its monitoring (Libonati et al., 2020). According to the Brazilian National Institute for Space Research (INPE) (https://queimadas.dgi.inpe.br/queimadas/bdqueimadas) and the ALARMES alert system (https://lasa.ufrj.br/news/burned-area-pantanal-2020/), in 2020, about 3.9 million hectares of the biome were affected by fire, and more than 15,000 fire foci were registered, about three times more than the previous year.

A major impasse for the Pantanal is the lack of consolidated legislation that aims to protect the biome. An important example is the new Forest Code of Brazil (Law nº 12.651/2012), which represents a milestone in Brazilian environmental legislation, but does not address Legal Reserves in wetlands, such as the Pantanal. The first legislation to deal specifically with the Pantanal was instituted in 2008 with the approval of the law that provides for the state policy for management and protection of the Upper Paraguay River basin in the state of Mato Grosso (Law no. 8830). However, it is a state law that does not cover the entire extent of the biome.

Agribusiness is the main cause of the expansion of deforestation in the Pantanal, with cattle raising being the main economic activity in the region (Bergier et al., 2019). Furthermore, the intensification of extensive pastures, which have more than 3.8 million heads of cattle, and the planting of grains threaten the native vegetation and biodiversity of the biome (Oliveira et al., 2016). Another important point was recently reported by Marengo et al. (2021), which drew attention to the prolonged drought that has hit the Pantanal since 2019, which has had serious hydrological consequences on the Paraguay River. Thus, it is essential to investigate the correlation between changes in land use and land cover (LULC), interannual climate variability and current fires in the region.

The analysis of forest fires is multivariate. Beyond that, the peculiar characteristics of the Pantanal associated with the difficulties in accessing the interior of its floodplains make it difficult to monitor the vegetation dynamics in this biome (Bui et al., 2018). In this scenario, geographic information systems (GIS) emerge as an indispensable tool for this study (Leite et al., 2018). GIS, including open-source applications, are ideal tools to manage and incorporate the spatial information of various factors that influence forest fires and, in addition, contribute to the visualization of results (Bui et al., 2018; Teodoro and Duarte, 2013; Chuvieco et al., 2010).

The burnings that occurred in 2020 were unprecedented. Beyond that, according to the Brazilian National Center for Monitoring and Alerts on Natural Disasters, the year 2021 may be worse than the previous one. Consequently, if these events are not re-evaluated, associated with the comprehension of their causes, fires in the biome will increase incessantly. Thus, this study aimed to investigate and relate the climatic conditions and LULC with the burnings that occurred in 2020 in the biome Pantanal using satellite images and GIS tools. Furthermore, future conditions were analyzed within the context of environmental preservation and fire control in the region. This work is structured in (i) introduction, (ii) material and methods, with a brief explanation of the study area, database and GIS tools used, (iii) results found, (iv) discussion, and finally, (v) conclusion.

2. Materials and methods

To analyze the influence of LULC dynamics and climate change on the increase in fires in the Pantanal over a historical series, the following steps were carried out: (i) survey of the geographic database; (ii) standardization of data; (iii) data processing; and (iv) analysis of results (Fig. 1).

2.1. Study area definition

The Pantanal is one of the most biodiverse seasonal flood savannas in the world and extends to the countries Brazil (80%), Bolivia (19%) and Paraguay (1%) (Manrique-Pineda et al., 2021). This biome is located in the Upper Paraguay River Basin, which belongs to the River Plate Basin, the second largest in South America. According to Marinho et al. (2021), this biome is considered the largest remaining wetland area of natural vegetation in the world.

This study focused on the Brazilian Pantanal, which covers the states of Mato Grosso (65%) and Mato Grosso do Sul (35%), located in the central-west region of Brazil and was divided into 11 sub-regions by Silva et al. (1998) (Fig. 2). The biome occupies about 2% of the Brazilian territory, with approximately 151,000 km^2 (Soriano et al., 2020). Its geographic location is of particular relevance, as it represents the link between the Cerrado, located in central Brazil, the Chaco, in Bolivia and the Amazon region, to the north, receiving direct influence from these biomes on their climate dynamics and the physiognomy of its vegetation

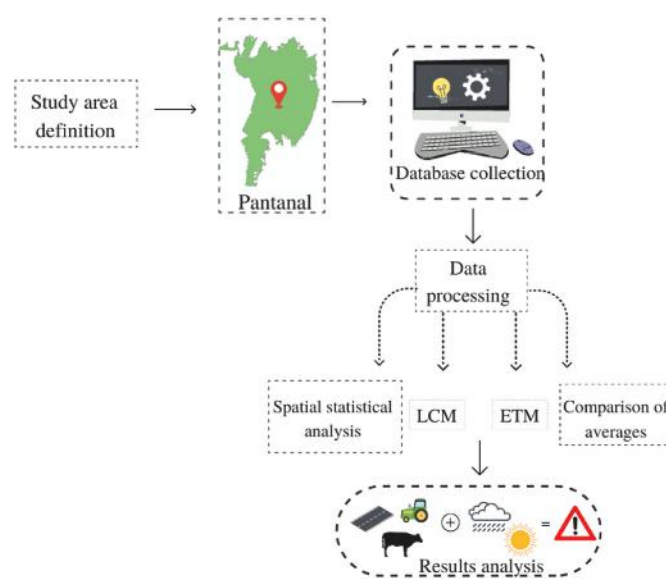

Fig. 1. Workflow chart.

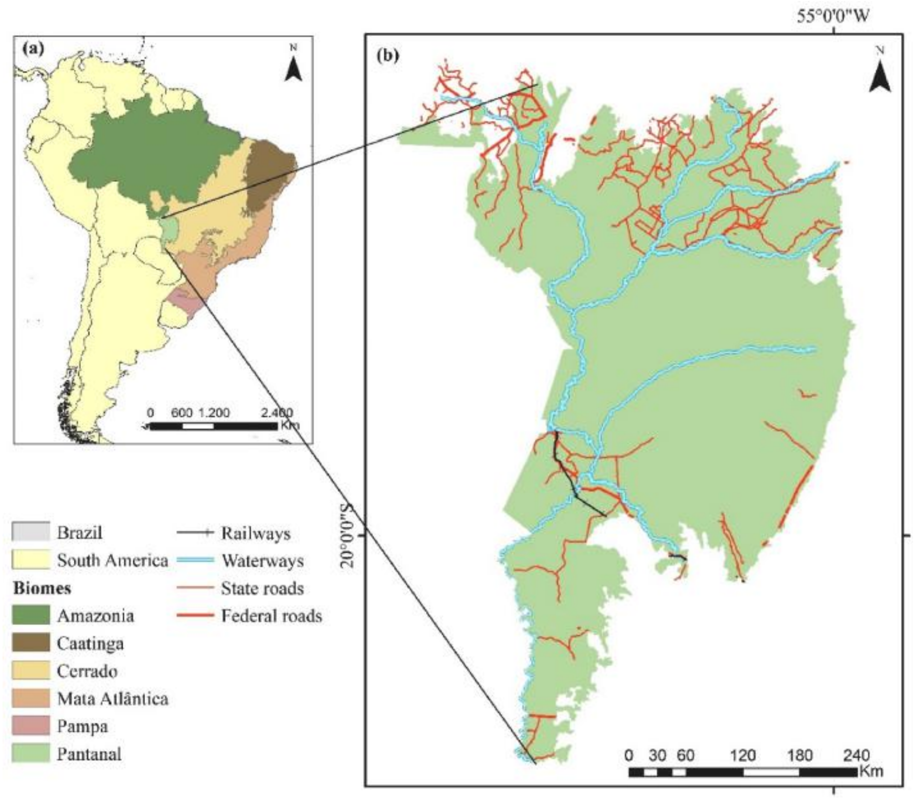

Fig. 2. Study area location: a) Brazilian biomes and b) Brazilian Pantanal.

(Marengo et al., 2021; Oliveira-Júnior et al., 2020).

The flood is the main driver of the Pantanal's biodiversity patterns, and the alternation between dry and wet seasons has made the biota adapted to survive these adverse conditions (Wantzen et al., 2008). Beyond that, the region is famous for its abundant and diverse fauna and flora. As a result, it is considered a biodiversity hotspot, playing an important role in the stability of microclimates, water security and numerous habitats (Thielen et al., 2020; Tomas et al., 2019). According to Schulz et al. (2019), this biome is a complex mosaic of many different ecosystems that climatic, ecological and anthropogenic factors have shaped.

The Pantanal climate is influenced by tropical and extratropical systems, being influenced by phenomena that occur mainly in the Amazon region. According to Köppen's classification, this region falls under the Aw type, characterized by a tropical savanna climate, marked by dry winters and hot, humid summers (Köppen and Geiger, 1928).

The biome has an average annual temperature of 25 °C, ranging from 20 °C (July) to 28 °C (January and December). The annual average relative humidity is 80%, ranging between 72% (September) and 85% (March). The lowest averages are recorded between July and November, the period with the highest records of fire foci in the Pantanal (http://www.inpe.br/queimadas/bdqueimadas/). Both temperature and air humidity are strongly associated with burning in the region, as they directly interfere with the moisture of the combustible material present in the soil (Rodrigues et al., 2002). During the dry season, a greater accumulation of dry material on the soil surface is common, which tends to behave as fuel, favoring the spread of large fires in the region (Soares et al., 2007).

The average total annual precipitation is approximately 1,184 mm. The spatial distribution of precipitation is variable within the biome, with annual averages 959 mm in the west direction and about 1,500 mm in the northeast (Zuffo, 2019). Rainfall distribution is marked by two well-defined periods: rainy (October to March), which accounts for more than 80% of the total annual rainfall and dry (April to September) (Oliveira-Júnior et al., 2020). This distribution controls the flooding cycles of the Pantanal, which, according to Schulz et al. (2019), are being changed. According to the authors, the main reasons for these changes are deforestation for agriculture, construction of waterways and construction of hydroelectric plants on the Paraguay River and its tributaries. The activities presented contribute to the formation of drier environments favorable to fire spread.

2.2. Database collection

The study used a large database, all obtained from free and validated sources. The fire foci data for 2020 were obtained from the BDQueimadas platform (https://queimadas.dgi.inpe.br/queimadas/bdqueimadas) and are available for download in a monthly database. According to INPE (2020), fire spots are represented by pixels when high temperatures occur in an area with more than 30 m in length and 1 m in width. Fire foci data is detected by polar and geostationary satellites with optical sensors operating in the thermal-medium range of 4 μm. The product of fire foci also adds the risk of vegetation burning. According to Setzer et al. (2019), this risk has the principle of meteorological estimation. In this context, the most significant risk of burning is due to the greater number of consecutive days without rain in one location.

Data from MCD64A1-Version 6 (2000–2020) were used to determine the burned areas. The MCD64A1 is a National Aeronautics and Space Administration (NASA) Terra and Aqua satellites product. It is a monthly product, and its burned area mapping approach is made with surface reflectance images from the MODIS sensor. The sensor has a resolution of 500 m and active fire images, with a resolution of 1 km. For the analysis applied here, the monthly burned area data were grouped on an annual basis, with the help of the ArcGis™ software version 10.5 from ESRI®.

Monthly data (1981–2019) of evapotranspiration, precipitation, temperature and soil moisture were extracted from the Global Land Data Assimilation (GLDAS) with a spatial resolution of 50 km. GLDAS was developed by NASA and National Oceanic and Atmospheric Administration (NOAA). The normalized difference vegetation index (NDVI) (1981–2019) was obtained from the MOD13C2-Version 6 product, derived from the NOAA - Advanced Very High-Resolution Radiometer (NOAA-AVHRR). The MOD13C2 global data is cloud-free spatial composites and is provided as a tier 3 product designed on a 5 km Geographical Climate Modeling Grid (NASA, 2021).

The Pantanal LULC map (2000, 2008 and 2019) were obtained from the Annual Land Cover and Land Use Mapping Project of Brazil (MapBiomas), collection 5. In addition, it is from the pixel-by-pixel classification of satellite images Landsat (https://mapbiomas.org/). The remaining data used in the analyses of this work are described inTable S1.

2.3. Data processing

Data processing was carried out through the analysis of LULC with the help of the Land Change Modeler (LCM) tool. Historical series analysis of climatic and environmental variables and evaluation of burned areas were carried out with the help of the Earth Trends Modeler (ETM) tool. Both interfaces are coupled to Clark Labs Idrisi Selva® software, version 17.02. Spatial statistical analyses were performed using the tools “Hot and Cold Spots” and “Grouping analysis” from the ArcGis™ software version 10.5 from ESRI®.

2.3.1. Land Change Modeler (LCM)

Several studies have used remote sensing associated with GIS tools to predict LULC in highly critical regions (Mohajane et al., 2018; Wang et al., 2021). Eastman (2016) states that LCM can predict LULC under different scenarios. This prediction through LCM provides a better comprehension of the analyzed systems and supports planning, policy formulation and decision-making. Fig. 3 shows the methodology used in the LCM interface.

In this work, the LCM was used to analyze the Pantanal LULC from 2000 to 2008, from the Markov Chain analysis, as performed by Magalhães et al. (2020) for the Brazilian Cerrado and Wang et al. (2021) for Thimphu, the capital of Bhutan. Furthermore, the LCM tool “Planning” was applied to evaluate the agriculture and pasture class in 2030. This tool allows the addition of incentives or disincentives, characterized by variables that favor or not, respectively, the loss in any specific LULC class, for the evaluated transition.

The preprocessing of the input data in LCM was performed using the ArcGis™ software version 10.5 from ESRI®. During this step, the standardization of lines, columns and cell size was carried out based on the map of burned areas since this has the lowest resolution. This step was carried out to place the database within a processing standard, as proposed by Amaral e Silva et al. (2020). Thus, higher resolution files, which present a more significant amount of information, are resized to the lowest resolution. This resizing is consistent with the burned areas file, in which there is a generalization of information without compromising the processing quality. Then, the data was transferred to IDRISI software to perform the LCM configuration.

Land use maps from 2000 to 2008 were used to calibrate the potential transition model from natural vegetation to agriculture and pasture classes. The year 2000 was used as the initial year for the modeling because land use monitoring was initiated this year in the Pantanal. The 2000–2008 period is satisfactory for calibrating the prediction model. It comprises a series of critical events: low rainfall (2002), large records of fire foci (2002, 2005 and 2008) and significant deforestation (Ferreira et al., 2018; Oliveira-Júnior et al., 2020). The spatial change trend between these land use classes was fitted to a third-degree equation.

According to Magalhães et al. (2020), LCM considers the explanatory power of “Driver Variables” to model the most significant transition potential areas. To this end, federal and state highways, railways and waterways were used, which induce and drive patterns of change over the years (Reydon et al., 2019). The areas that burned more frequently in the period 2000 to 2008, the deforested areas and those referring to the agriculture and pasture class were also used as variable drivers. The “Image Calculator” tool was used to obtain the most frequent burned areas. First, all the burned area maps were added for the period, and then the resulting map was divided by the number of months in the period (96 months).

Thus, the potential transition model was created from the Multilayer Perceptron (MLP) algorithm. The algorithm can extract samples from the evaluated areas that have or have not changed from the LULC maps provided initially (Magalhães et al., 2020). The MLP was configured from the tool's original (default) settings. As a result, a potential transition map from the natural vegetation class to the agriculture and pasture class was obtained. Consecutively, the validation of the model was established from the 2019 LULC map. First, the Crosstab algorithm was used, followed by evaluating the Kappa index, which assesses the degree of agreement between two data sets (Cohen, 1960).

The Pantanal LULC prediction was performed for a ten-year scale (2030). The period coincided with the target year for the United Nations (UN). The UN considered 2030 as the year to achieve goals for plans and promotions of sustainable actions globally. The prediction for 2030 used the burned areas that occurred in 2020 as incentives for the transition from the “natural vegetation” class to the “agriculture and pasture” class. 2020 was used to show the consequences if the burned areas observed in this year continued to spread. These results were compared with the 2019 LULC map.

2.3.2. Earth Trends Modeler (ETM)

Interannual change trends in the historical series of burned areas were analyzed using the Mann-Kendall Monotonic trend (MKMT) using the ETM tool. In addition, the same analysis was carried out for climatic and environmental variables. The ETM is a tool from the Idrisi software capable of analyzing trends and dynamic characteristics of environmental phenomena (Lamchin et al., 2019; Silva et al., 2021).

The MKMT test is used to determine the existence or not of a statistically significant temporal trend for a given series of data. As it is a non-parametric test, the MKMT test does not vary with the magnitude, failures, or periodicity in the database, nor does it assume any

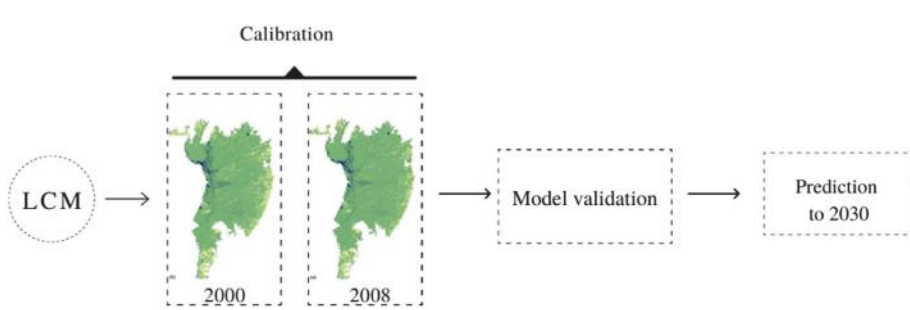

Fig. 3. Methodological flowchart of the LCM tool.

assumptions about how these are distributed (Mann, 1945).

The Z value statistic evaluates the presence of a statistically significant trend. This statistic is used to test the null hypothesis, that is, the absence of a trend. The MKMT results, as a function of the Z statistic, vary between −1 and +1. The +1 value represents the continuously increasing trend and shows a trend that never decreases. Values −1 and 0 show a downward trend of the data and no consistent trend, respectively (Gilbert, 1987). Fig. 4 shows the methodology used in the ETM interface.

In this study, trend analyses were applied to monthly data for the period between 1981 and 2019. The variables analyzed were precipitation, evapotranspiration, temperature, soil moisture and NDVI. NDVI is based on the red and near-infrared bands and performs measuring the amount of chlorophyll and energy absorption (Reed et al., 1994). Furthermore, these variables' historical series were divided into two periods: beginning (1981–2000) and end (2001–2019) of the historical series. The monthly modeled trend curves were obtained to analyze and compare their seasonal variations. Finally, the burned areas variable was added to the model, in which trend analyses were applied to the annual data for the period 2001 to 2020. From this analysis, it was possible to observe the existence of change trends, on an annual basis, related to climate and environmental changes.

2.3.3. Hot Spots spatial statistics

In this study, Hot Spots spatial analyses were performed to identify and describe possible clustering patterns. That is, whether regions with increased fire foci are associated with LULC and climate change in 2020. To proceed with the statistical spatial analyses, cells without values (no data) were removed from the fire foci database as they refer to water bodies and urban areas (INPE - Instituto Nacional de Pesquisas Espaciais, 2020).

The local autocorrelation statistic of the Optimized Hot Spot Analysis index was used to identify Hot Spots (regions with high concentrations of fire foci) and Cold Spots (regions with low concentrations of fire foci) at different confidence levels (90%, 95% and 99%). The mean, standard deviation and minimum and maximum values for fire foci were calculated by Grouping Analysis, which mainly consists of creating distinct groups of values through similarity. Fire foci data were grouped into three categories associated with degrees of fire risk, as follows: (i) high risk, ranging from 0.8 to 1.0; (ii) medium risk, ranging from 0.4 to 0.7 and (iii) low risk, ranging from 0.0 to 0.3.

Spatial statistics represent the dynamics of fire foci in the Pantanal and help to interpret the results obtained in the trend analysis generated by LCM and ETM.

2.3.4. Climatic, environmental and burned areas variables average comparative analysis

This step aimed to verify the behavior of the historical series of the burned areas and the climatic and environmental variables. The historical series were compared with the years 2002, 2019 and 2020, as they are, respectively, the second-largest year in the quantity of burned areas, the last year of the historical series and the year with the more significant number of burned areas.

To calculate the averages of the climatic and environmental variables, pixel by pixel, of the historical series (1981–2019), comparing them with the years 2002, 2019 and 2020, the TSTATS command coupled with the Idrisi Selva® software was used, version 17.02 from Clark Labs. To calculate the average burned area of the Pantanal historical series, the "area" tool was used in the same software.

3. Results

3.1. LULC analysis and prediction for 2030

Fig. 5 shows the Pantanal LULC maps for 2000 and 2008. It is possible to observe the growth of areas related to agriculture and pasture, which increased about 28% from 2000 to 2008 and expanded mainly over natural vegetation, as shown in Fig. 6c.

It is still possible to verify a less pronounced change in the other land use classes (2%), confirming that the change was focused between the natural vegetation and agriculture and pasture (98%) (Fig. 6a). Based on this result, the focus of the analysis on the transition between these two classes is justified. The overall change trend is shown in Fig. 7b, where the warmer colors represent the areas where change has been focused.

The model developed had a Kappa index of 91.82%, indicating a good relationship between the LULC classes of the real and predicted

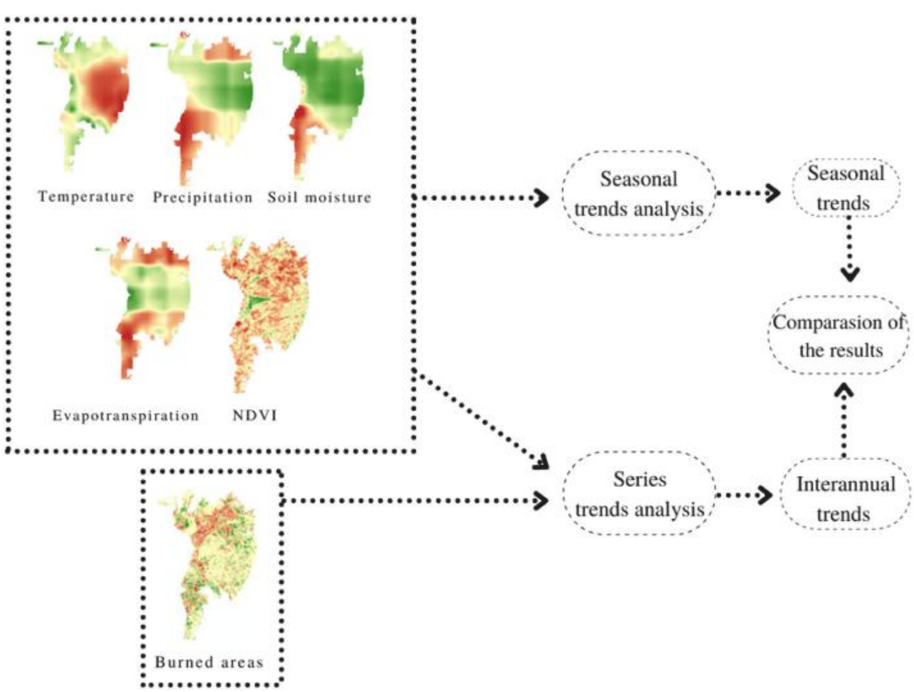

Fig. 4. Methodological flowchart of the ETM tool.

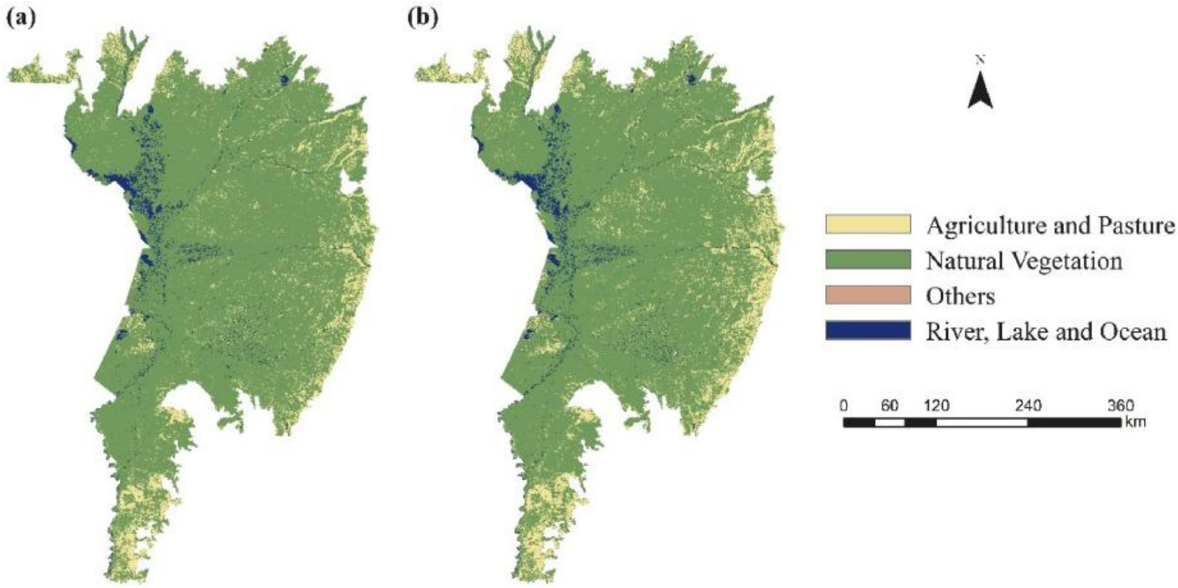

Fig. 5. Maps containing observed data of the Pantanal LULC for (a) 2000 and (b) 2008.

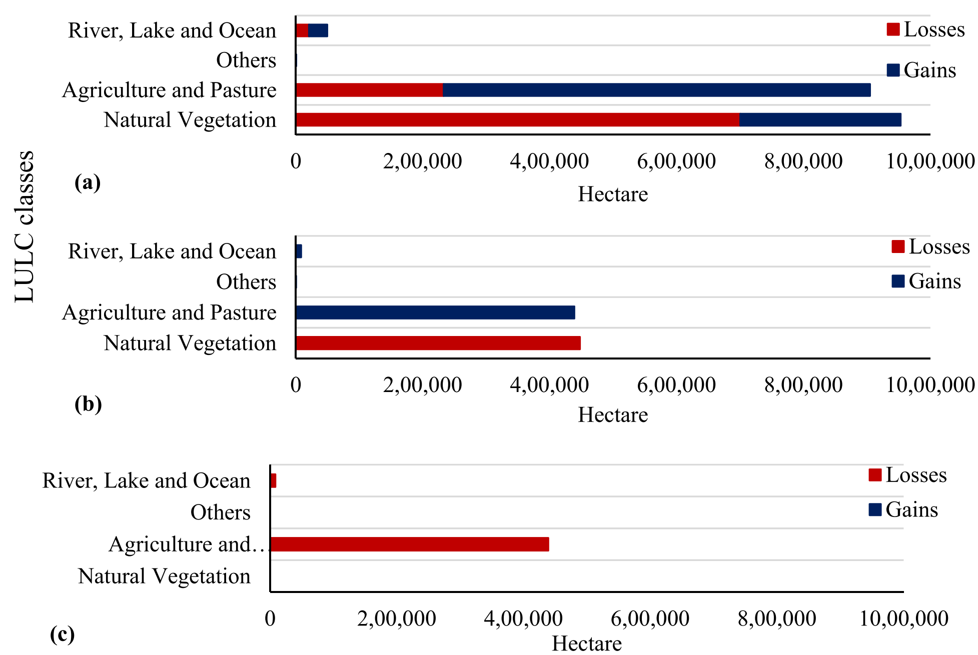

Fig. 6. Changes in LULC for the period of 2000–2008 based on LCM interface: (a) Gains and losses; (b) Net change and (c) contribution for change on natural vegetation class.

2019 maps (Fig. S1). The model was then validated and used to predict the Pantanal LULC for 2030. Fig. 8 shows the Pantanal LULC maps for 2019 and the predicted for 2030. It is understood that the burned natural vegetation has the potential to become agricultural areas in the future. The results indicate that in 2030, if the burning areas observed in 2020 are recurrent, about 20% of the Pantanal will be for agricultural and pasture use, showing an increase of 50% compared to 2019. Beyond that, in 2030, only about 62% will correspond to native vegetation, against 68% in 2019 e 73% in 2000.

3.1.1. *Climatic and environmental variables trend in the pantanal*

Fig. 9 presents the first (1981–2000) and the second (2001–2019) half of the historical series monthly average variations. It is possible to observe significant increases in temperature values between June and December in the second half of the historical series compared to the first half (Fig. 9a). Precipitation did not present significant changes between the two periods analyzed. However, it is possible to observe the concentration of this phenomenon occurring in the summer (Fig. 9b).

From the intra-annual analysis, evapotranspiration presented an increase in the average values between January and June in the second half of the historical series. On the other hand, it showed a decrease in the period between July and December, compared to records up to the year 2000 (Fig. 9c). Furthermore, in a seasonal view, this variable showed an increasing behavior between November and January, then decreasing until July. Although soil moisture maintains its behavior, there was a decrease in its values throughout all the months of the

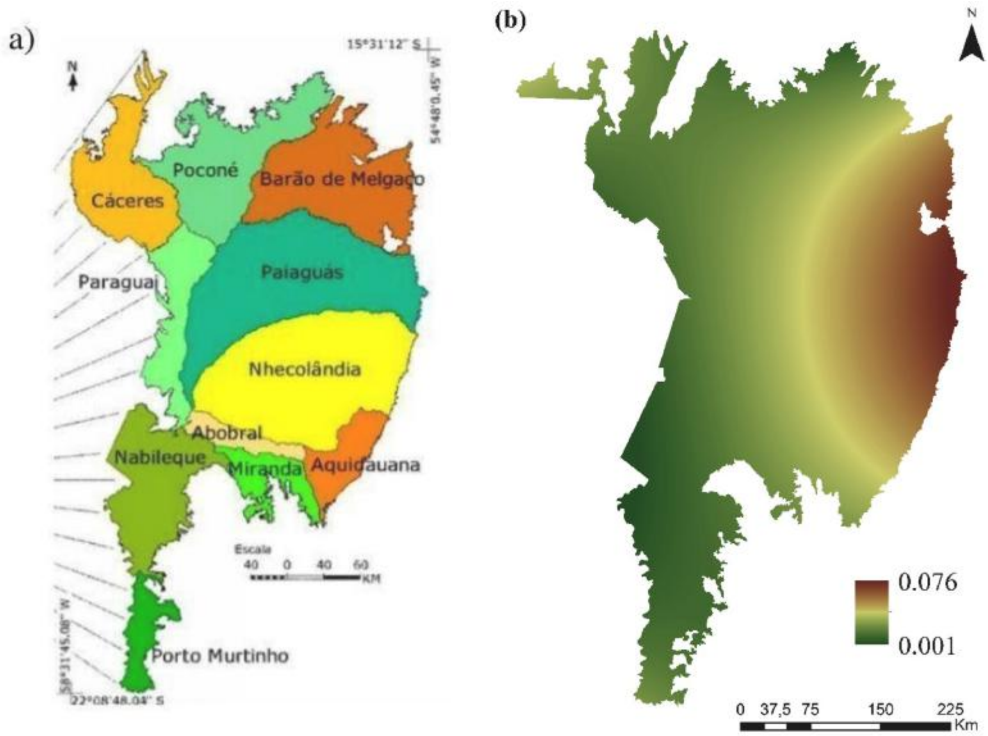

Fig. 7. (a) Pantanal sub-regions (Source: Carvalho et al., 2018); (b) Spatial change trend.

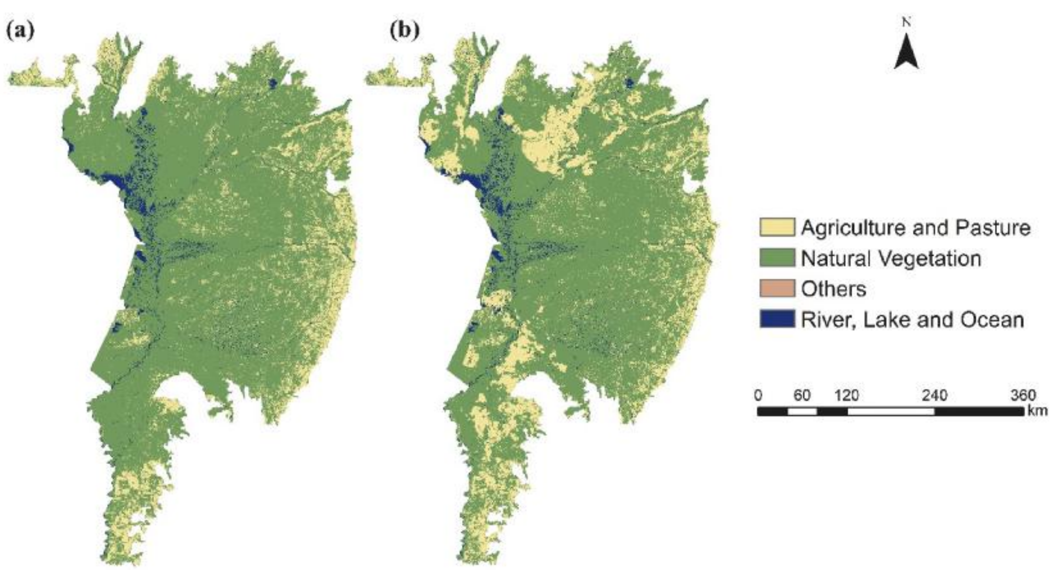

Fig. 8. LULC maps: (a) 2019; (b) prediction for 2030.

second half of the historical series (Fig. 9d). Finally, the NDVI showed a notable increase in January, indicating impacts of seasonality and changes in vegetation types during the rainy season (summer) (Fig. 9e).

Fig. 10 shows the trend graphs of the variables obtained by the MKMT analysis. It was possible to observe that during the analyzed period, soil moisture tended to decrease (Fig. 10d), while evapotranspiration (Fig. 10c), NDVI (Fig. 10e) and temperature (Fig. 10a) showed a tendency to increase. Precipitation (Fig. 10b) revealed an almost constant behavior over the recorded years.

From the interannual analysis, it can be seen that the extreme north and west edge of the Pantanal showed a tendency to decrease in temperature throughout the analyzed historical series. In contrast, the east edge showed a tendency to increase for this variable (Fig. 11a). On the other hand, precipitation (Fig. 11b) and evapotranspiration (Fig. 11c) tend to increase in a portion of the north and south regions. Also, precipitation showed a tendency to decrease in the eastern edge. Soil moisture (Fig. 11d) showed a tendency to decrease in the central region and the extreme northwest and increase in the southern region. NDVI (Fig. 11e) showed an increasing trend in most of the study area, except for some eastern and western edge regions, which exhibited a decreasing trend. Finally, Fig. 11f shows an increasing trend in burned areas in the northwestern region and on the western edge of the Pantanal.

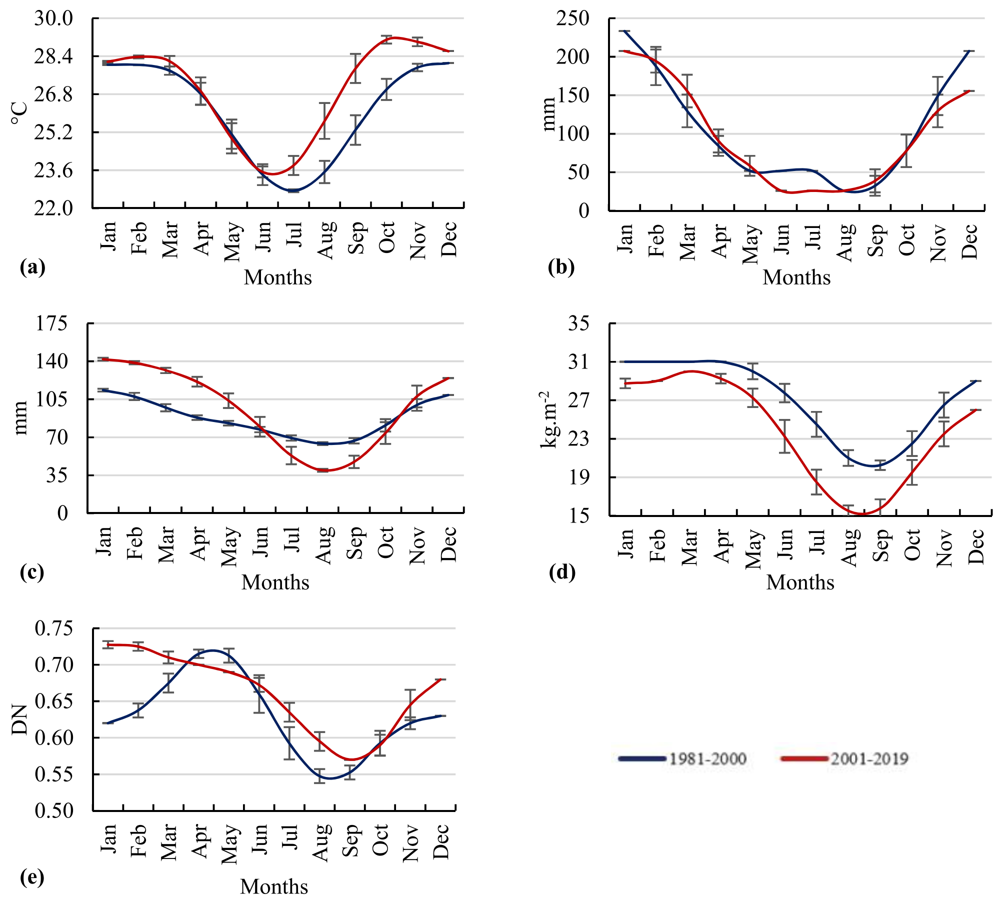

Fig. 9. Monthly average of the first (1981–2000) and second (2001–2019) half of the historical series of the variables: (a) temperature (°C), (b) precipitation (mm), (c) evapotranspiration (mm), (d) soil moisture (kg.m^{-2}) and (e) NDVI (ND).

3.2. Hot Spots spatial statistics

The result of Hot Spot statistical analysis (Fig. 12) shows the concentration of Hot Spots (places with high concentrations of fire foci) with 99% confidence in the northern region and the distribution of Cold Spots (locations with low concentrations of fire foci) along the western edge and the south of the Pantanal.

The result of the grouping analysis showed that of the 21,706 fire foci registered, 16,380 (76%) had a high risk of fire, with an average of 0.98; 3,134 (14%) presented a medium risk, with an average of 0.56 and; 2,192 (10%) showed low risk, with an average of 0.15.

3.3. Climatic, environmental and burned areas variables average comparative analysis

The quantification of burned areas in the Pantanal (Fig. 13) throughout the historical series (2001–2020) showed the severity of fires in the region in 2020. Therefore, 2020 was the most critical year since the beginning of monitoring (2000). This year presented approximately 3 thousand ha of burned area, 29% more than the second year with the largest burned area (2002) and 50% more than the previous year (2019).

When comparing the average behavior of the historical series with 2020, an atypical behavior is observed in the latter. It can be observed a substantial increase in the average burned areas and temperature in 2020. Nevertheless, on the other hand, it is seen a decrease in the average precipitation, evapotranspiration, soil moisture and NDVI in that year. It is noteworthy that the quantity of burned areas in 2020 was the highest since the beginning of monitoring (2000). That year occurred an increase of almost 3 million hectares (248%) compared to the average of its historical series. Table 1 presents the average climatic and environmental variables and burned areas in the Pantanal for the historical series and the years with the largest burned areas in ascending order, 2019, 2002 and 2020.

4. Discussion

The number of fire foci in 2020 was the highest since the beginning of the monitoring, being almost three times higher than the average recorded between 2000 and 2015 (INPE - Instituto Nacional de Pesquisas Espaciais, 2020). In addition, in 2020, the largest quantity of burned areas in the Pantanal (Fig. 13) occurred. It was about 50% higher than in 2019. The grouping analysis provided another indication of the atypical behavior in 2020, showing that 76% of the fire foci recorded in this period presented a high fire risk. It is in agreement with the results of Marengo et al. (2021), who confirmed that the fires in the Pantanal in 2020 are truly unprecedented.

Results in Fig. 12 show that the fire foci that occurred in 2020 were concentrated in the Pantanal northern region. The result in Fig. 11f corroborates this information, which indicates an increasing trend along with the historical series of burned areas in the region. In addition, there is a tendency to decrease soil moisture (Fig. 11d), which can be influenced by the decrease in precipitation. This combination affects vegetation moisture, favoring conditions that encourage fires (Viganó et al., 2018).

During the dry period, various weather conditions enhance fire spread, as rainfall tends to decrease, temperature increases and the air becomes drier. Although this region shows a trend towards increasing

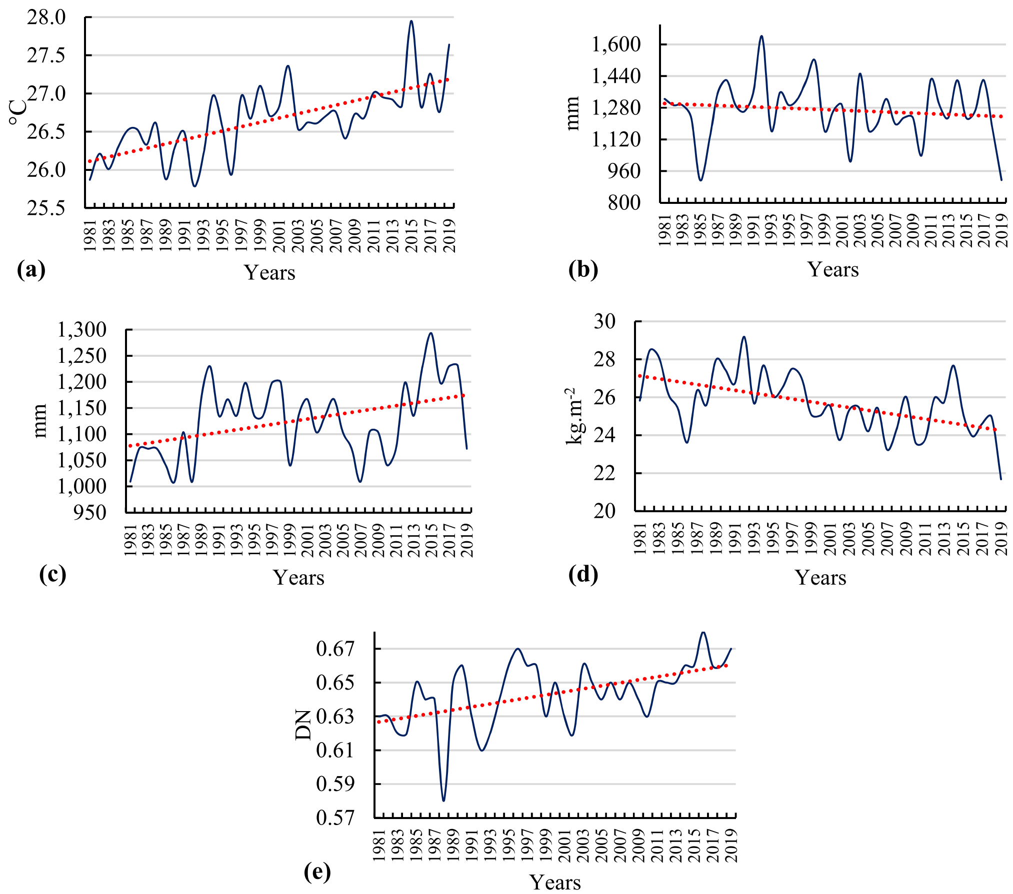

Fig. 10. Interannual variations trends of: (a) temperature (°C), (b) precipitation (mm), (c) evapotranspiration (mm), (d) soil moisture (kg.m^{-2}) and (e) NDVI (ND).

rainfall (Fig. 11b) and decreasing temperature (Fig. 11a), when the behavior of these variables in the historical series is compared with 2020, an atypical behavior is observed in the latter (Table 1).

The year 2019 was already establishing preconditions for the megafires of 2020. From the results shown in Table 1, it is possible to identify the reduction in evapotranspiration, soil moisture, precipitation and the increase in temperature and burned areas in 2019 compared to the historical series. When analyzing the historical series, it can be seen that, despite 2002 being the second in the ranking of burned areas in the Pantanal (Fig. 13), the climatic and environmental conditions in 2019 were even worse (Table 1).

Compared to the historical series, the reduction of soil moisture and precipitation in the Pantanal in 2020 and 2019 may indicate a decrease in water in the environment. Although no increase in actual evapotranspiration was observed in 2020, potential evapotranspiration has likely increased. It stimulated the creation of an environment conducive to the occurrence of fires in the Pantanal. Furthermore, according to Marengo et al. (2021), in 2020, the emergence of an area of high atmospheric pressure prevented the formation of rain in the entire Midwest region of South America. This phenomenon contributed to the increased risk of fire in the Pantanal associated with increased temperature and low relative humidity.

Several studies indicate that the average number of rainy days in the Pantanal is significantly decreasing. That is, the annual total precipitation has been concentrated in the wettest months, making the droughts more prolonged and severer (Bergier et al., 2018; Lázaro et al., 2020; Marengo et al., 2015; Oliveira-Júnior et al., 2020), which can also be seen in Fig. 9b. Thus, drought intensification during the dry season may be contributing to the increase in the number of fires recorded during this period. In addition, 2020 showed a reduction of about 465 mm compared to the historical series (Table 1). It has been decreasing since 2019, showing the creation of preconditions for the occurrence of fires.

To fully understand the dynamics of fire in the Pantanal territory, it is also necessary to approach the influence of other biomes, such as the Amazon. The Amazon Forest plays a significant role in controlling humidity and rainfall in South America through its high transpiration and water vapor transport from the Atlantic Ocean. This phenomenon is known as "flying rivers" (Diele-Viegas et al., 2020; Marengo, 2006). Marengo et al. (2021) stated that the lack of summer rainfall in 2020 is related to reducing hot and humid air transport from the Amazon to the Pantanal region.

Amaral e Silva et al. (2020) reported that deforestation in the Legal Amazon generates changes in rainfall and temperature regimes in the region. This deforestation is also capable of influencing the climate dynamics of the Pantanal. Consequently, when there is a drier season in the Amazon or an increase in deforestation, there is an imbalance of these flying rivers and the entire hydrological system involved. It is a possible reason for reduced rainfall and humidity in the Pantanal, which favors fires (Bergier et al., 2018).

The importance of joint analysis of climatic variables with LULC is also highlighted. The advance of agriculture and pasture areas in the Pantanal is frequently reported in several studies (Alho et al., 2019; Guerra et al., 2020; Leite et al., 2018; Silva et al., 2018). According to Guerreiro et al. (2019), LULC is a challenge to protect this biome. Comparing the results in Fig. 7b with the map of the Pantanal sub-regions (Fig. 7a), the Nhecolândia, Paiaguás and Barão de Melgaço sub-regions, located on the eastern edge and northeastern part of the Pantanal, respectively, stand out.

Cáceres, Poconé and Barão de Melgaço sub-regions, in the northeast region of the Pantanal, border the Cerrado biome. Beyond that, it is in

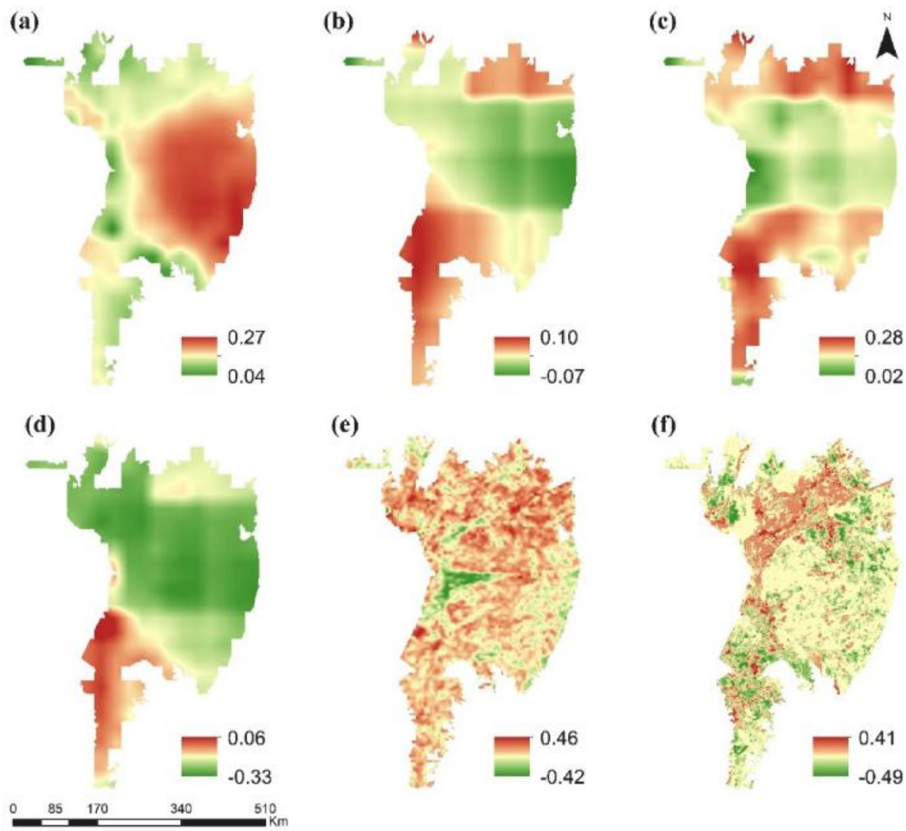

Fig. 11. Spatial trend of the variables (a) temperature (°C), (b) precipitation (mm), (c) evapotranspiration (mm), (d) soil moisture (kg.m^{-2}), (e) NDVI (ND) and (f) burned areas (ha).

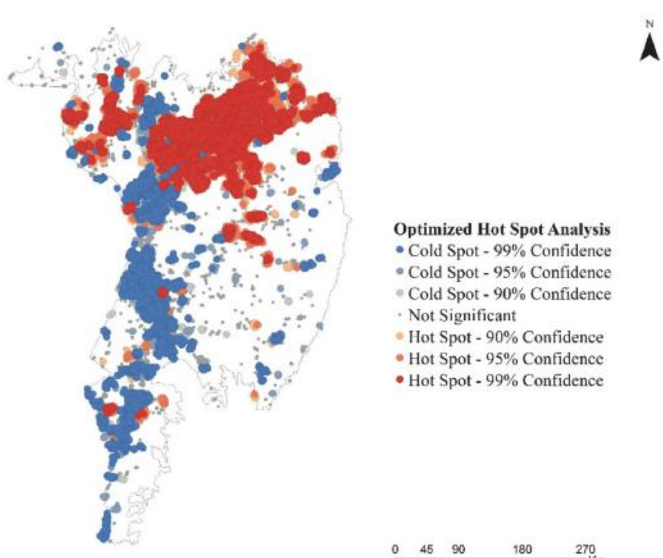

Fig. 12. Fire foci spatial distribution in 2020 in the Pantanal.

the vicinity of the area called the "agricultural frontier". Historically, this area stands out for converting natural vegetation areas into new agricultural production zones, mainly through illegal deforestation and the misuse and management of fire (Mota et al., 2019). In addition, there is a concentration of state and federal waterways in the northern region of the Pantanal (Fig. 2). According to Ribeiro et al. (2012), these waterways boost pasture opening and increase fire risk. Therefore, these results suggest that the concentration of fire foci in this region was driven by the union of anthropogenic causes and climate change. Furthermore, this region is considered the arc of springs of the Pantanal. Hence, the reduction of precipitation in these areas directly influences the flooding regime in the lower regions of the studied area (Observatório Pantanal, 2021).

The southern region of the Pantanal does not show signs of burning in 2020 and has a lower density of transport networks. On the other hand, compared to the northern region (Fig. 2), between 2000 and 2015, it was the one with the highest number of fire foci in the biome (Lázaro et al., 2020). Fig. 13 shows that 2002 was the second year with the highest quantity of burned area in the Pantanal, showing atypical behavior of climatic variables compared to the historical series (Table 1). However, the severity of the burnings in 2020 stands out, which were about 30% greater than those in 2002.

The eastern region (Paiaguás and Nhecolândia sub-regions) and northeast region of the Pantanal (Barão de Melgaço sub-regions) were those with the greatest potential for transitioning from the natural vegetation to agriculture and pasture (Fig. 7b). The Nhecolândia sub-region stands out historically for its large extensive cattle ranches (Silva et al., 2018). It is supported by the decreasing trend of the NDVI in this region (Fig. 11e). Guerra et al. (2020) also noted intense changes in this region and delimited an area called the "Arc of Pantanal Vegetation Loss", similar to that observed for the Amazon biome.

The western edge of the study area also requires attention to avoid future megafires. Despite not showing potential for a transition from natural vegetation class to agriculture and pasture (Fig. 7b), the municipality of Corumbá, located in this region, stands out for its extensive cattle raising. In 2015, the region had about 0.8% of the country's cattle population (IBGE – Instituto Brasileiro de Geografia e Estatística, 2017; Galvanin et al., 2019). Furthermore, this region showed a tendency to decrease in NDVI (Fig. 11e) and soil moisture (Fig. 11d) and a tendency to increase in burned areas (Fig. 11f). The decreasing trend in the NDVI

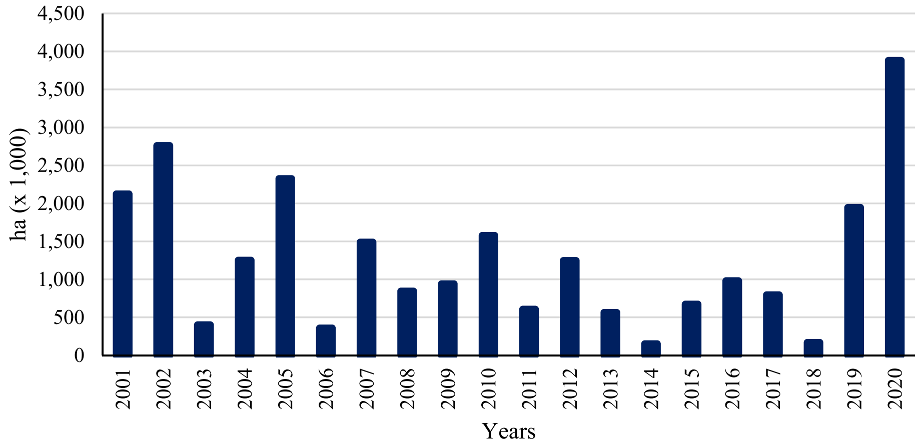

Fig. 13. Quantity of burned areas per year in the Pantanal.

Table 1
Average climatic and environmental variables and burned areas in the Pantanal for the historical series and 2002, 2019 and 2020.

Variables	Historical series (HS)	Average HS values	2002	2019	2020
Temperature (°C)	1981–2019	26.53	27.29	27.49	27.28
Precipitation (mm)		1,353.12	1,110.95	1,079.10	888.62
Evapotranspiration (mm)		1,125.93	1,108.49	1,061.69	938.32
Soil Moisture (kg.m^{-2})		25.81	23.73	21.58	19.65
NDVI (ND)		0.65	0.63	0.66	0.62
Burned areas (ha)	2001–2020	1,116,926	2,760,968	1,946,007	3,881,917

indicates the potential for drier areas and, consequently, prone to future fires.

The great potential for converting natural vegetation into land for agricultural use in the eastern region indicates that this may be, in the future, an area of high concentration of fire foci. It is inferred considering the events reported for the southern and northern regions of the Pantanal. The interannual trend analysis demonstrates this hypothesis. Such analysis shows an increase in temperature (Fig. 11a) and a decrease in precipitation in this region over the years (Fig. 11b).

In this sense, the absence of fast and efficient firefighting policies may have aggravated this scenario even further. According to official data from the Brazilian Transparency Portal and the Brazilian Integrated Planning and Budgeting System, the total budget for fire prevention and control decreased by 15% from 2019 to 2020. Beyond that, from R $173.8 million released in 2020 for the firefighting, only a third of that quantity was used.

The biome's resilience will only be improved by reducing the risk of fire and overexploitation of its natural resources (Marengo et al., 2021). Given this scenario, the prediction of LULC for the year 2030 shows a challenging panorama compared to the projections and targets stipulated by the United Nations. The advance of burned areas in almost the entire extension of the biome was noted when its 2020 map was used as an incentive factor for the transition from native vegetation to agricultural and pasture areas (Fig. 8b). This result is similar to that of Miranda et al. (2018). They analyzed the vegetation cover of the Pantanal from 2000 to 2015 and projected a scenario for 2030. The projected scenario indicated the undergrowth as predominant.

Illegal deforestation combined with outdated land management practices has increased fire foci in the Pantanal. Furthermore, uncontrolled anthropogenic advances result in landscape simplifications and severe negative impacts on biodiversity, as evidenced by Manrique-Pineda et al. (2021). If the current management trend in the Pantanal persists and the scenario in Fig. 8b is reached, the consequences will be numerous, as discussed by Mota et al. (2019). The authors associate forest fires with disturbances to fauna and flora, damage to water infiltration into the soil, increased surface runoff, and, consequently, the loss of nutrients and organic matter in the soil.

5. Conclusion

This study showed that the concentration of fire foci in 2020 in the northern region of the Pantanal was influenced by anthropogenic activities, resulting mainly from the opening of pastures and agricultural areas. This relationship becomes even more evident when considering the advance and influence of the agricultural frontier region in the Cerrado and the Amazon biomes. This advance and influence have the potential to change LULC and the climate dynamics of the Pantanal. Furthermore, climatic and environmental trend analysis variables showed severe drought periods in the most recent years of the historical series. This situation, combined with anthropogenic activities, contributed to the intensification of fire foci in 2020.

There is great replacement potential of native vegetation by agricultural and pasture areas in the eastern region of the Pantanal. When burned areas were used as an incentive factor for this transition, the prediction for 2030 showed that approximately 20% of the Pantanal territory would be used for agriculture and pasture. These results present the importance of predicting future scenarios to support decision-making and public policies. Controlling illegal deforestation and the misuse of fire will only be possible if the government, society and the agricultural sector join forces.

Credit author statement

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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

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