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FABRÍCIA CRISTINA SANTOS

DESMATAMENTO NO CERRADO E QUEIMADAS NO PANTANAL: análise de correlação pautada no processamento de dados de Sensoriamento Remoto

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Dissertação apresentada ao Instituto de Ciência e Tecnologia, Universidade Estadual Paulista (Unesp), Campus de São José dos Campos; Centro Nacional de Monitoramento e Alertas de Desastres Naturais (Cemaden), como parte dos requisitos para obtenção do título de MESTRE pelo Programa de Pós-Graduação em DESASTRES NATURAIS.
Área: Desastres naturais. Linha de pesquisa: Desastres associados a eventos extremos, secas, estiagens, incêndios florestais e escassez de água.

Orientador: Prof. Dr. Rogério Galante Negri
Coorientadora: Profa. Dra. Klécia Gili Massi

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IMPACTO POTENCIAL DESTA PESQUISA

Do ponto de vista científico e ambiental, esta pesquisa buscou responder a uma questão ainda pouco explorada, que aponta a influência do Cerrado no Pantanal.
Do ponto de vista técnico e inovador, apresenta uma aplicação metodológica diferenciada para encontrar as relações entre as variáveis ambientais e áreas queimadas.
Do ponto de vista social, a nível internacional e nacional, mostrar a relação das variáveis poderá sensibilizar a comunidade e aumentar o combate ao desmatamento e as queimadas.

POTENTIAL IMPACT OF THIS RESEARCH

From a scientific and environmental point of view, this research aims to answer a question still little explored, which points to the influence of the Cerrado in the Pantanal.
From a technical and innovative point of view, it presents a differentiated methodological application to find the relationships between environmental variables and burned areas.
From a social point of view, at an international and national level, showing the relationship between the variables could sensitize the community and increase the combat against deforestation and burns.

BANCA EXAMINADORA

Dr. Rogério Galante Negri (Orientador)
Universidade: Universidade Estadual Paulista
Instituição: ICT- Unesp
Campus: São José dos Campos

Dra. Tatiana Sussel Gonçalves Mendes
Universidade: Universidade Estadual Paulista
Instituição: ICT- Unesp
Campus: São José dos Campos

Dra. Rita de Cássia Von Randow
Universidade: Faculdade de Tecnologia do Estado de São Paulo
Instituição: Faculdade de Tecnologia do Estado de São Paulo - FATEC - Jacareí
Campus: Jacareí

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RESUMO

SANTOS, Fabrícia Cristina. **Desmatamento no Cerrado e queimadas no Pantanal:** análise de correlação pautada no processamento de dados de Sensoriamento Remoto. 2023. Dissertação Mestrado em Desastres Naturais - Universidade Estadual Paulista (Unesp), Instituto de Ciência e Tecnologia; Centro Nacional de Monitoramento e Alertas de Desastres Naturais (Cemaden), São José dos Campos, 2023.

Queimadas e desmatamentos inapropriados compreendem questões ambientais enfrentadas por diferentes países. Apesar da sua conservação ser de interesse mundial, os biomas brasileiros Cerrado e Pantanal têm sofrido ao longo dos anos diversas alterações devido às ações antrópicas. Especificamente, enquanto o desmatamento sobre o bioma Cerrado avança progressivamente, queimadas cada vez mais severas têm ocorrido no Pantanal. Diferentes pesquisas discutem que o comportamento das queimadas no Pantanal surgem como efeito colateral dos desmatamentos no Cerrado. No entanto, não são encontradas análises quantitativas que relacionem tais eventos. Neste contexto, fazendo uso de técnicas de aprendizado de máquina e dados temporais obtidos por sensoriamento remoto no período 2000–2020, este estudo busca identificar as interação entre os biomas Cerrado e Pantanal. Os resultados alcançados permitem verificar que a redução das áreas florestais no Pantanal e a expansão agropecuária no Cerrado estão vinculadas ao comportamento das queimadas no Pantanal.

Palavras-chave: mudança de cobertura do solo; cerrado; pantanal; queimadas; sensoriamento remoto; série temporal; aprendizado de máquina; modelos de regressão.

ABSTRACT

SANTOS, Fabrícia Cristina. ***Deforestation in the Cerrado and fires in the Pantanal:*** *correlation analysis guided by the processing of Remote Sensing data. 2023. Dissertation Master's degree in Natural Disaster - São Paulo State University (Unesp), Institute of Science and Technology, National Center for Monitoring and Early Warning of Natural Disasters (Cemaden), São José dos Campos, 2023.*

Inappropriate fires and deforestation comprise environmental issues faced by different countries. Despite its conservation being of worldwide interest, the Brazilian Cerrado and Pantanal biomes have undergone several changes over the years due to anthropic actions. Significantly, both deforestation within the Cerrado biome and the incidence of severe fires in the Pantanal have witnessed a worrisome escalation. Different studies argue that the behavior of fires in the Pantanal arises as a side effect of deforestation in the Cerrado. However, no quantitative analysis relating to such events is found. In this context, making use of machine learning techniques and temporal data obtained by Remote Sensing in the period 2000–2020, this study aims to identify the interactions between the Cerrado and Pantanal biomes. The obtained results verify that the reduction of forest areas in the Pantanal and the agricultural expansion in the Cerrado are linked to the behavior of fires in the Pantanal.

Keywords: land cover changes; cerrado; pantanal; burns; remote sensing; time series; machine learning; regression models.

SUMÁRIO

1 INTRODUÇÃO

O bioma Pantanal é a maior área úmida do mundo, ocupa cerca de 150 mil km^2, distribuídos 74% nos estados do Mato Grosso e Mato Grosso do Sul, e o restante entre a Bolívia e o Paraguai (ALHO et al., 2005; HARRIS et al., 2005; JUNK; CUNHA, 2005). As depressões do bioma retém a água, levando por sua vez a formação de lagos ou lagoas. Esta característica faz com que o bioma seja considerado uma enorme janela de evaporação, uma vez que consegue reter de 30 a 60% da água que incide sobre ele. Atualmente o bioma sofre diversas ameaças como: desmatamento, manejo inadequado para agropecuária, construção de barragens, crescimento urbano e populacional, alteração de habitat natural, efeitos do uso do fogo, alteração do regime hídrico, entre outros (ALHO et al., 2019). O bioma apresenta apenas 4,68% de sua área total protegida por Unidades de Conservação, tanto de Proteção Integral, quanto de Uso Sustentável (MMA, 2023).

Tão importante quanto, o bioma Cerrado é o segundo maior do país, ocupa mais de 2 milhões de km^2, o que equivale a aproximadamente 23% do território nacional, sendo considerada a savana mais biodiversa do mundo (KLINK; MACHADO, 2005). Algumas das maiores Bacias Hidrográficas da América do Sul, possuem nascentes no bioma Cerrado, evidenciando assim sua contribuição na manutenção dos recursos hídricos regionais (OLIVEIRA et al., 2014). Ademais, este bioma possui apenas 8,99% do seu território em áreas protegidas, sendo mais vulnerável às alterações antrópicas (MMA, 2023). De acordo com o projeto MapBiomas (Mapeamento Anual de Cobertura e Uso do Solo do Brasil), no ano de 2020, 45,6% do Cerrado encontram-se em áreas antropizadas (MAPBIOMAS, 2022).

Apesar de parte dos biomas Pantanal e Cerrado serem propensas ao fogo (HARDESTY et al., 2005), o regime errado deste fator pode levar à degradação do solo, invasões biológicas e perda da biodiversidade (PIVELLO, 2011). O fogo que atualmente ocorre no Pantanal é uma combinação de fatores climáticos e atividades antrópicas. A nível de exemplo, muitos canais de fluxo de água foram bloqueados para evitar a inundação de pastagens criadas, causando o não espalhamento da água e uma irrigação inadequada, fatores estes que, quando associados à práticas agrícolas inadequadas, influenciam no abastecimento de importantes rios locais e podem implicar em períodos de estiagem mais longos e severos (LEAL FILHO et al., 2021).

Segundo discussões presentes na literatura, a citar Schulz et al. (2019) e Guerra et al. (2020), áreas úmidas geralmente dependem de seus arredores, logo, as atividades realizadas em regiões vizinhas ao Pantanal podem gerar impactos nos sistemas socioecológicos do bioma. De acordo com Ivory et al. (2019), a relação entre as regiões é impulsionada principalmente por fluxos de água e produção de sedimentos. Os desmatamentos realizados no Cerrado, geralmente motivados pela conversão de áreas naturais em agrícolas e executados sem a devida conservação do solo, causam erosão e provocam o aumento do escoamento e transporte de nutrientes e sedimentos, que por sua vez implicam no assoreamento dos rios e impactam a vazão e os regimes hidrológicos no Pantanal (BERGIER et al., 2013; GUERRA et al., 2020).

Diante das questões apontadas, este estudo apresenta análises de tendência e de correlação entre as variáveis de uso e cobertura do solo, corpos hídricos e áreas queimadas, com o objetivo de comprovar ou refutar que o desmatamento no Cerrado influencia nas queimadas no Pantanal, para tanto foram utilizados dados obtidos por Sensoriamento Remoto no período de 2000-2020, e modelos de regressão, aplicados em uma área de estudo que compreende três Bacias Hidrográficas que ocupam simultaneamente porções dos biomas Cerrado e Pantanal.

2 ARTIGOS

2.1 Santos, F. C.; Chaves, F. M.; Negri, R. G.; Massi, K. G. Fires in Pantanal are directly linked to agriculture conversion in Cerrado and native vegetation loss and hydrological changes in Pantanal

Artigo elaborado de acordo com as diretrizes do periódico “Remote Sensing Applications: Society and Environment”, submetido em 09 de maio de 2023.

Fires in Pantanal are directly linked to agriculture conversion in Cerrado and native vegetation loss and hydrological changes in Pantanal

Fabrícia Cristina Santos[a*], Fellipe Mira Chaves[b], Rogério Galante Negri[a,b], Klécia Gili Massi[a,b]

a Graduate Program in Natural Disasters, São Paulo State University (UNESP)/National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), São José dos Campos 12245-000, Brazil;

b Science and Technology Institute (ICT), São Paulo State University (UNESP), São José dos Campos 01049-010, Brazil.

* Corresponding author. Email: fabricia.cristina@unesp.br

Abstract

Wildfires and deforestation are severe threats to global ecosystems. In Brazil, Cerrado (a tropical savanna) and Pantanal (a tropical wetland) biomes have undergone several changes over the years due to anthropic actions. Both deforestation in Cerrado biome and wildfires in Pantanal have increased lately. Some studies argue that both processes could be related, but there is a scarcity of quantitative analysis evaluating that. In this context, making use of machine learning techniques and temporal data obtained by Remote Sensing in the period 2000–2020, this study aimed to identify the interactions between Cerrado land use and land cover change in native vegetation and fire incidence in Pantanal. Our results corroborate that and showed that fires in Pantanal were directly linked to large scale and commodities agriculture conversion in Cerrado and native vegetation loss and hydrological changes in Pantanal.

Keywords: Burns – Pantanal – Cerrado – Remote Sensing – Time Series – Machine Learning.

1. Introduction

Deforestation is still a major threat for boreal, temperate, and tropical ecosystems around the world (LEBLOIS et al., 2017). In Brazil, deforestation peaked in the last few years damaging mostly Amazon and Cerrado biomes (INPE, 2023). Brazilian Cerrado (a tropical savanna) and Pantanal (a tropical wetland) are threatened by deforestation and several other anthropic uses. In Pantanal, these uses include deforestation, mismanagement for agriculture and livestock, construction of dams, urban sprawl, natural habitat degradation, fire use and floods and ebbs changes (ALHO et al., 2019), and in Cerrado, the main environmental problem is conversion of natural areas to commodities agriculture (MAPBIOMAS, 2022). In 1985, Cerrado and Pantanal had 68.4% and 95.6% of its original cover, while in 2020 they had 54.4% and 83.9% of the biome, respectively (MAPBIOMAS, 2022).

Cerrado is a biodiversity hotspot (MYERS et al., 2000; KLINK; MACHADO, 2005). Pantanal is the largest wetland in the world, in addition to being considered a complex of ecosystems, it borders other biomes such as Cerrado, Bolivian Chaco, Amazon, Atlantic Forest, and Bosque Seco Chiquitano (SOS Pantanal, 2021). Pantanal and Cerrado are Biosphere Reserves recognized by Unesco since 2000 and 2001, respectively (UNESCO, 2023). Despite the importance of these biomes, only 4.7% of the Pantanal and 9.0% of the Cerrado are within protected areas, making them more vulnerable to anthropic actions (MMA, 2023a).

Deforestation in Cerrado, generally motivated by the conversion of natural areas into commodities agricultural areas, without soil conservation measures, causes erosion and an increase in the flow and transport of nutrients and sediments through the Pantanal basin, which in turn imply silting up rivers, impact hydrological regimes and changes natural floods and ebbs in Pantanal (BERGIER et al., 2013; GUERRA et al., 2020; LEAL FILHO et al., 2021). That may alter vegetation cover, leading to drier conditions in some portions of Pantanal, and making natural and anthropogenic fires more probable. In Pantanal, prolonged droughts and higher temperatures result in low soil moisture, which affects the flammability of vegetation, thus providing ideal conditions for the widespread burning of this biomass (LIBONATI et al., 2020). In 2020, fire affected areas increased by 376% compared to the average observed between 2013 and 2019 (GARCIA et al., 2021).

Burns affect ecosystems around the world. Biomes are considered fire dependent (positively influenced by fire), sensitive (negatively influenced by fire), or independent (neutral effect) (HARDESTY et al., 2005). In Brazil, Cerrado and Pantanal are fire dependent ecosystems, but even an environmental effect (as fire in these biomes) could threaten several ecological processes, if natural regimes are altered (ROCES-DIAZ et al., 2022). Burns that currently occur in the Pantanal are a combination of climatic factors and anthropic activities. As Cerrado-Pantanal are directly linked by water flows and sediment production (IVORY et al., 2019), the fires in Pantanal related to deforestation in Cerrado urge to be investigated.

The use of data obtained by Remote Sensing emerges as a convenient, effective, and economical way to carry out environmental analysis in space and time, as the one intended in this study (SAUSEN, 2007). Such data can be used in different areas and for different purposes, as detections of environmental damage, monitoring of impacts, agriculture, geology, water resources, soil studies, among others (FIGUEIREDO, 2005; ORTIZ; FREITAS, 2005). Among several studies that used data obtained by Remote Sensing in environmental studies, Li et al. (2020) analyzed space-time changes and impacts on wetlands to measure fire severity. Garcia et al. (2021) used data for the period 2003-2020 in Pantanal to highlight causes and consequences of the 2020 megafires. Correa et al. (2022) analyzed fire behavior in the Pantanal using information about land use and land cover and burned areas between 2000 and 2021. Ivory et al. (2019) used spectral indices and climate data from the Tropical Rainfall Measuring Mission (TRMM) project to assess the link between vegetation, precipitation, and the flood pulse in a tropical wetland system. The convenience of gathering and automating images and data leads to the accumulation of vast amounts of information that can be analyzed through statistical methods, or even Machine Learning. Studies that utilize machine learning-based empirical models are able to emulate complex nonlinear problems (KENNEDY et al., 2015). Computer-assisted alternatives offer numerous advantages in research, such as minimizing errors associated with human operators and reducing response time (ZANGOOEI et al., 2016).

In this context, studying these biomes together is motivated by the existence of an indirect relationship between wetlands (as Pantanal) and the higher lands (as Cerrado) surrounding (SCHULZ et al., 2019; GUERRA et al., 2020). Thus, this study aimed to identify the interactions between land use and land cover, water bodies, and burned areas to prove or refute the existence of a correlation between deforestation in the Cerrado and burned areas in the Pantanal. Specifically, it is believed that deforestation in the Cerrado results in the soil loss over the water bodies that drain towards the Pantanal, triggering changes in the water regime, inducing changes in the dynamics of the vegetation and the likely increase in areas affected by fires. For this purpose, time series derived from data obtained by Remote Sensing in the period 2000-2020, and regression models based on Machine Learning concepts were used. The article is organized as follows: Section 2 presents the study area, data, and procedures; in Section 3 approaches the design of the experiment and the results; in Section 4 the results obtained are discussed; and in Section 5 the conclusions of this research are presented.

2. Materials and Methods

2.1. Study area

The study area (Figure 1) is located on three watersheds between Pantanal and Cerrado biomes, namely: Itiquira; Taquari; and Negro do Mato Grosso do Sul, covering an area of approximately 127,510.1 km^2 (Pantanal: 78,652.75 km^2; Cerrado: 48,857.35 km^2), being considered for the analyzes the division in portion Cerrado and portion Pantanal.

The Pantanal biome occupies about 150 thousand km^2 and is the largest tropical wetland in the world (HARRIS et al., 2005; JUNK; CUNHA, 2005), its depression retains 30 to 60% of the water (ALHO et al,, 2019). Two seasons, a dry one between May and September, and a rainy one between October and April determine the biological rhythms in the biome. Precipitation varies between about 1,100 mm and 1,250 mm and temperature, between 27.4°C and 21.4°C, with December and July as the hottest and coldest months, respectively (JUNK et al., 2006).

The Cerrado biome is the second largest in Brazil, occupies more than 2 million km^2 and is considered the most biodiverse savanna in the world (MMA, 2023b). Some of the largest watersheds in South America have springs in the Cerrado biome (OLIVEIRA et al., 2014). In addition, the Cerrado has a dry season between April and September and a rainy season between October and March, with an average annual precipitation of 1,500 mm and temperatures that vary between 27°C and 22°C (KLINK; MACHADO, 2005).

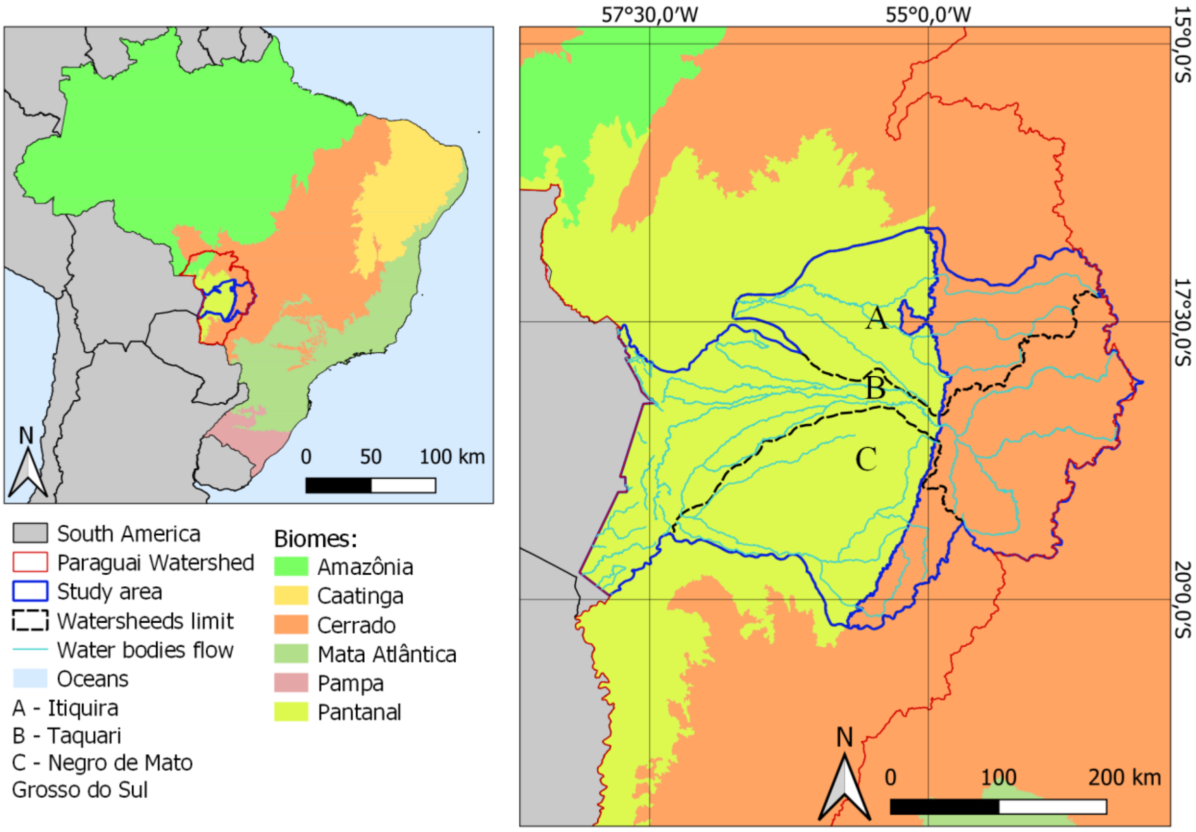


Fig. 1 Location of the study area. Representation in the WGS-84 reference system with a geographic coordinate system. The data sources are available at IBGE (2016; 2019) and ANA (2010; 2016).

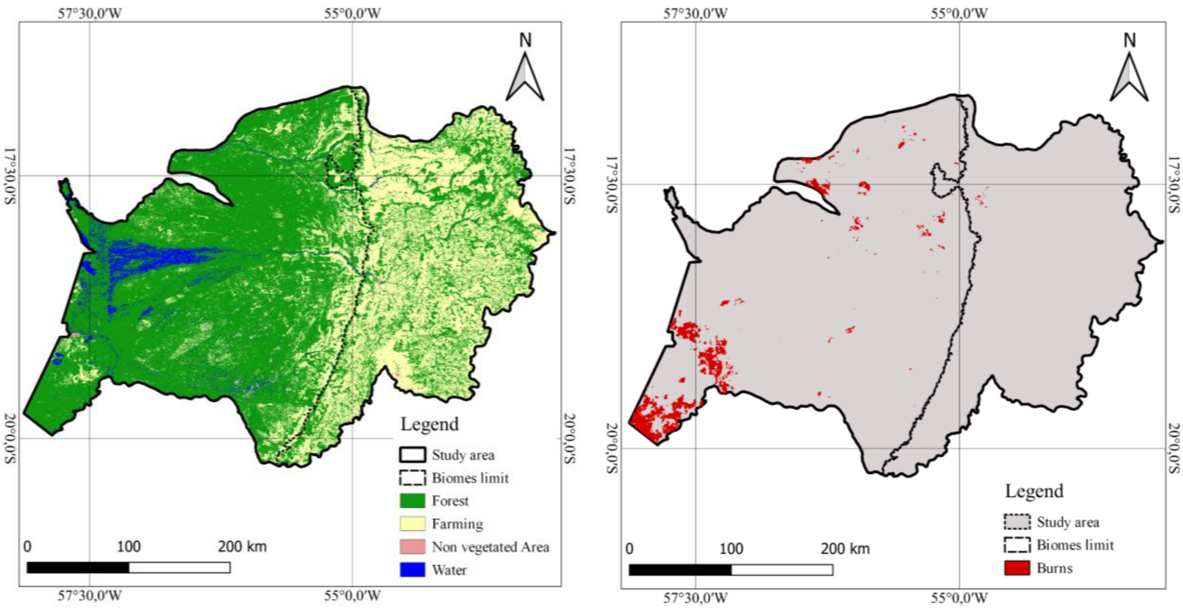
2.2. Data sources

To carry out this study, the following data sources were used: the MapBiomas project (SOUZA et al., 2020; MAPBIOMAS, 2023) and the “MODIS Burned Area Monthly” product (USGS, 2021). Because of availability of data from these two sources, the period of 2000-2020 was considered.

The MapBiomas project (SOUZA JR et al. 2020) provides yearly-updated 30-meter spatial resolution maps of land use and land cover of Brazilian territory. According to this project, in the study area (Figure 1) four land use and land cover classes were identified, namely:

Forest (FO), Farming (FA), Non-vegetated Area (NVA) and Water (W). Figure 2(a) illustrates the occurrence of the classes mentioned in relation to 2005.

Regarding the "MODIS Burned Area Monthly", it provides monthly maps with 500 m spatial resolution covering burned areas and its confidence estimations. Based on this, fire locations on dry, wet, and annual periods in the study areas with confidence superior to 90% were assumed as burned (as shown in Figure 2b).



(a) Land use/land cover classes.

(b) Burned areas.

Fig. 2 Land use and land cover (a) and burned areas (b) in 2005 of study area.

Lastly, concerning the data source and limits between biomes and time period (Section 2.1), the analysis considered the following set of variables: FOp - forest in Pantanal; FOc - forest in Cerrado; FAp - farming in Pantanal; FAc - farming in Cerrado; NVAp - non vegetated areas in Pantanal; NVAc - non vegetated areas in Cerrado; Wp - water bodies in Pantanal; Wc - water bodies in Cerrado, Bpd - burns in Pantanal dry season; Bpw - burns in Pantanal wet season; Bpa - burns in Pantanal annual; Bcd - burns in Cerrado dry season; Bcw - burns in Cerrado wet period; Bca - burns in Cerrado annual.

2.3. Experiment design

Firstly, with a variable set, we performed descriptive analysis to identify important parameters, using Mann-Kendall test (MANN, 1945) complemented by the coefficient of Theil-sen (THEIL, 1950; SEN, 1968). A significance of 5% was considered, and consequently, when the *p*-value resulting from the Mann-Kendall test does not exceed 0.5, the variable presents a non-monotonic regime and the trend behavior (i.e., increasing or decreasing) is determined by the Theil-Sen coefficient. Reversely, monotonic regimes (i.e., no significant trend) are characterized by p-values above the adopted significance.

Subsequently, to identify existing multiple relationships between variables involved in the analysis, linear and non-linear regression models were built. To this, a set of predictor variables responsible for modeling (i.e., target) was initially defined. Based on these, nonlinear regression models were built, according to the Random Forest (RF) (BREIMAN, 2001) and eXtreme Gradient Boost (XGB) (CHEN and GUESTRIN, 2016) methods, and linear via Ordinary Least Square (OLS) (MONTGOMERY et al., 2021). Then, models were evaluated according to the RMSE and R^2 measures, computed via 5-fold cross-validation. Randomized Search procedure (BERGSTRA; BENGIO, 2012) was adopted to choose the parameters associated with the RF and XGB methods.

Among different models obtained and based on aforementioned measurements, selection of the most adherent model is made. In turn, for such a model, the most influential variables were identified according to the methodology proposed by Altmann et al. (2010). Based on observed results (i.e., identification of the most influential variables in the target variable modeling), the described process is re-executed recurrently. In this case, the variable previously adopted as the target is removed from the variable set (to avoid cyclic relations) and each variable identified as influential is assumed as the target.

Given this rationale, the OLS, RF and XGB methods were used to model the information on the number of areas burned in the Pantanal in relation to the dry (Bpd) and annual (Bpa) periods, denoted respectively by scenarios I and II. Due to the low frequency of burns in the wet season (Bpw) a scenario was not defined for this case. The variables Forest (FO), Farming (FA), Non-vegetated Area (NVA) and Water (W), observed in Pantanal and Cerrado were considered predictive variables.

Lastly, a network was obtained relating, according to its importance, different variables inserted. The work flow is shown below (Figure 3).

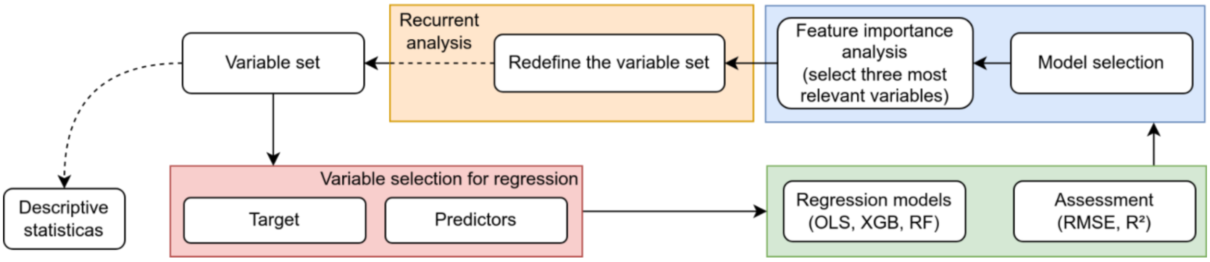


Fig. 3 The experiment design workflow.

Variables of interest were analysed using Mann-Kendall test to identify trends for each class over the time series and Theil-Sen to show the rate at which a given non-monotonic trend evolves. Subsequently, regression methods were used to identify the relationship between Pantanal burnings and the other variables. Still, based on the most adherent regression model, most influential variables were identified.

All analyses were performed using the Python 3.8 programming language (VANROSSUM; DRAKE, 2010). The computational libraries Scipy (VIRTANEN et al., 2020) and Scikit-Learn (PEDREGOSA et al., 2011) were used to obtain regression models, respectively. The QGIS software (QGIS, 2022) was employed for organizing the datasets and information extraction.

3. Results

Land use and land cover and burn data from 2000 to 2020 are provided in Supplementary Material 1.

3.1 Descriptive analysis

We found that extension of water bodies in Pantanal varied over the analyzed period, there was a decrease in 2000-2001, an increase between 2013 and 2015, followed by a decrease until the end of the analyzed period. On the other hand, water bodies in the Cerrado portion had small variability, showing a decrease in 2000-2001 and in the last years of the time series (Figure 4, blue lines).

Regarding forest, farming and non vegetated areas we verified similar patterns between Cerrado and Pantanal, i.e. forest conversion to farming (Figure 4, dark green and red lines). However, while in Pantanal forest predominated, in Cerrado farming did (Figure 4, dark green and red lines).

Burned areas showed large variations in the analyzed period. In Pantanal, especially in the years 2001, 2005, 2012, and 2020, we observed high rates of burned areas mostly in the dry seasons (Figure 4, light green and orange lines). Fires during the wet season were not noteworthy (Figure 4, light green). In Cerrado, burning variation was lower than in Pantanal over the years (Figure 4, light green and orange lines). Similarly, fires were more frequent in the dry seasons than in the wet ones (Figure 4, light green and orange lines).

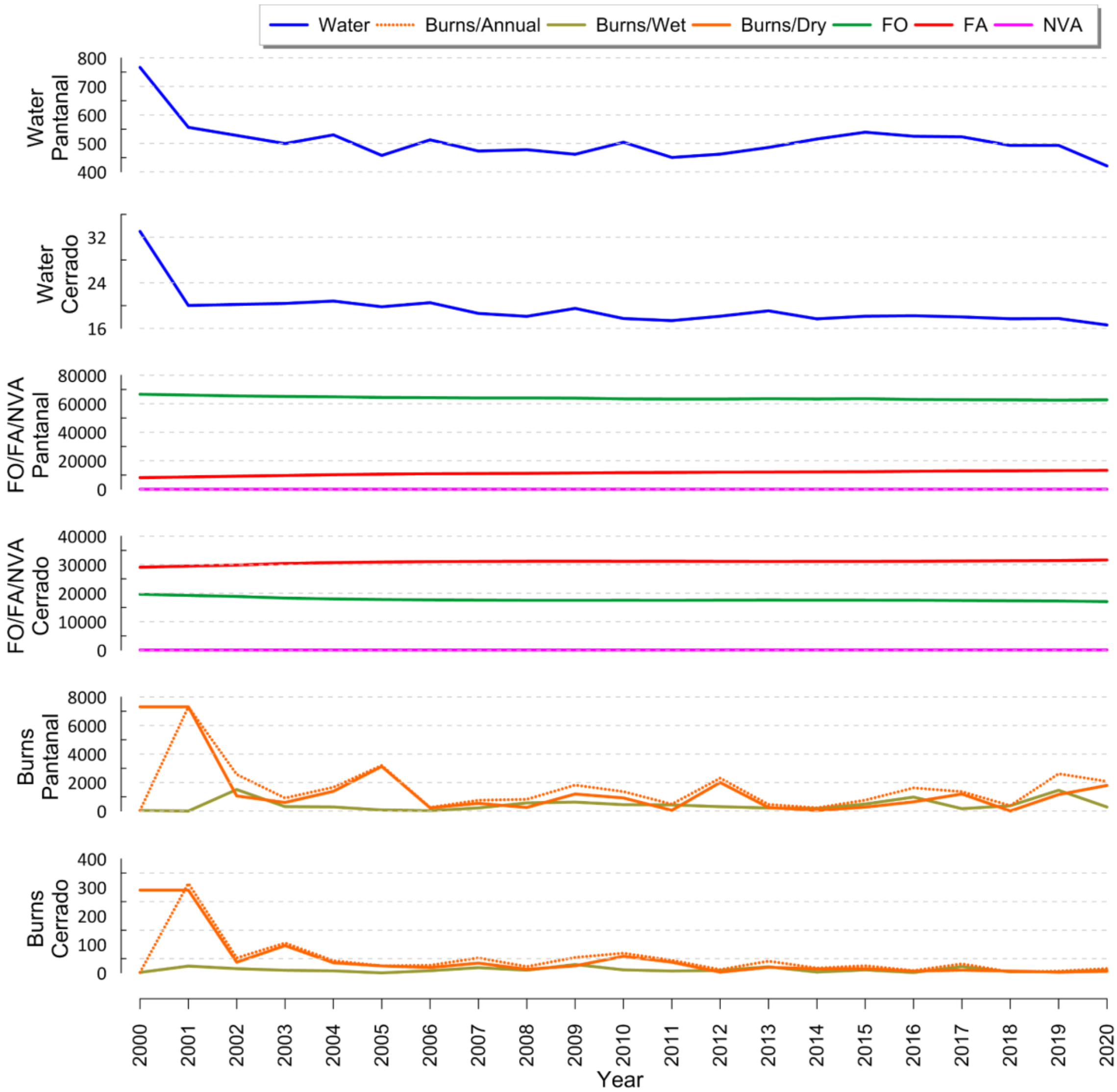


Fig. 4 Patterns of water bodies, forest (FO), farming (FA), non vegetated areas (NVA) and burnings in dry and wet seasons and annually over the time series (2000-2020).

Forest decrease and farming and non-vegetated areas increase was significant and consistent in Cerrado and Pantanal (Table 1). Regarding water bodies, while a decreasing trend was observed in Cerrado, there was no significant change in Pantanal (Table 1). Burnings in Pantanal had no trend, but in Cerrado they were decreasing in the dry season and annually (Table 1).

Tab. 1 Mann-Kendall Test results for land use and land cover changes and burnings (variables) in the study area over the 2000-2020 period.

Variables	**p-value**	**Theil-Sem**	**Trend**	**Median (km^2)**
FOc	0.000002	-58.492	decreasing	17,542.73
FAc	0.000002	57.789	increasing	31,150.52
NVAc	0.000003	0.903	increasing	78.61
FOp	0.000000	-162.710	decreasing	63,577.40
FAp	0.000000	194.732	increasing	11,683.38
NVAp	0.000000	0.086	increasing	29.35
Wc	0.000126	-0.189	decreasing	18.22
Wp	0.174190	-2.452	no trend	499.52
Bcd	0.000026	-2.635	decreasing	20.00
Bcw	0.694380	-0.125	no trend	9.25
Bca	0.014447	-2.313	decreasing	26.75
Bpd	0.147027	-48.416	no trend	920.50
Bpw	0.263872	13.971	no trend	306.00
Bpa	0.785797	-11.198	no trend	1,364.25

3.2 Regression model

Regardless of the method adopted, we observed that the adjustment measures achieved for scenario II were superior compared to scenario I. Concerning the methods, despite the equivalence shown between RF and XGB in terms of R^2, the RMSE measure highlights a better adherence to the RF method, especially scenario II. The OLS method presented the lowest adjustment levels according to the measures adopted (Table 2).

Tab. 2 Adjustment measures observed for scenarios I and II in relation to the different methods analyzed.

Model	**Scenarios**	**RMSE**	**R²**
OLS	I	1981	0.445
	II	1574	0.626
RF	I	1040	0.939
	II	**963**	**0.955**
XGB	I	1301	0.918
	II	1007	0.955

Regarding variables of the RF method in scenario II (Table 3), we verified that Forest and Water in the Pantanal (i.e., FOp and Wp), and Farming in Cerrado (i.e., FAc) were the three most relevant parameters in modeling the occurrence of fires in Pantanal (Bpa).

Tab. 3 Importance of variables in relation to the model obtained by RF method in scenario II. Normalized values for representation.

Variable	FOp	FAc	Wp	FAp	NVAp	NVAc	Bcd	Bca	Wca
Importance	1	0.859	0.784	0.766	0.708	0.568	0.151	0.150	0.069

When new regression models were processed using FOp, FAc and Wp as targets (Table 4), RF method provided more adherent models than OLS and XGB to the considered target variables. In the two tests of adjustment measures carried out, the OLS model presented a worse result than the RF and XGB models, which may have occurred because the OLS method is a linear model, while the correlation of the variables is non-linear.

Tab. 4 Adjustment measures computed on regression models using FOp, FAc and Wp as target variables.

	Target					
Methods	**FOp**		**FAc**		**Wp**	
	RMSE	**R^2**	**RMSE**	**R^2**	**RMSE**	**R^2**
OLS	1281	0.264	965	0.314	335	0.297
RF	344	**0.963**	277	**0.977**	71.8	**0.746**
XGB	363	0.954	192	0.951	70.6	0.730

In the RF method, FOp was under a strong influence of the variables FAp, NVAp and FAc; similarly, FOc, FOp and FAp were important in FAc modeling; and NVAp, FAp and FOc were relevant in Wp modeling (Table 5).

Tab. 5 Importance of variables in relation to obtained models by RF method, admitting the variables FOp, FAc, and Wp as targets.

FOp		**FAc**		**Wp**	
Variable	**Importance**	**Variable**	**Importance**	**Variable**	**Importance**
FAp	1	FOc	1	NVAp	1
NVAp	0.787	FOp	0.976	FAp	0.881
FAc	0.584	FAp	0.783	FOc	0.816
NVAc	0.527	NVAp	0.776	NVAc	0.814
Hc	0.523	NVAc	0.305	FAc	0.712
FOc	0.329	Hc	0.159	FOp	0.574
Hp	0.127	Hp	0.156	Hc	0.560

Bcd	0.099	Bca	0.111	Bca	0.328
Bca	0.084	Bcd	0.801	Bcd	0.229

Thus, in summary (Figure 5), we found that fires in Pantanal (Bp) were under greater influence of FOp, FAc and Wp, that FOp was influenced by FAp and FAc and NVAp, that FAc was influenced by FOc and FOp and FAp, and that NVAp, FAp and FOc influenced water bodies in Pantanal (Wp).

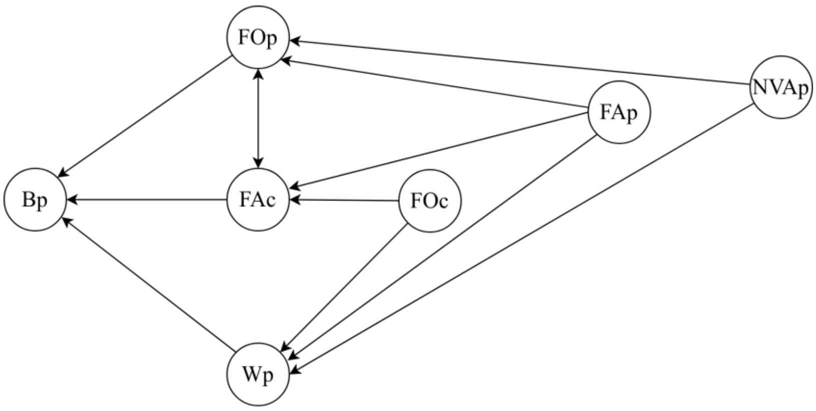


Fig. 5 Diagram of the relationship between burns in Pantanal and other variables included in the analysis.

4. Discussion

This study was motivated by the possible existence of a direct relationship between ecological processes in Brazilian wetlands (as Pantanal) and the higher lands (as Cerrado) surrounding and aimed to identify the interactions between Cerrado land use and land cover change and fire incidence in Pantanal, using a study area that occur partially in each biome. We did find that by verifying that fires in Pantanal were directly linked to large scale and commodities agriculture conversion in Cerrado and native vegetation loss and hydrological changes in Pantanal.

Pantanal biome is a complex mosaic of grasslands, savannas, tropical rainforests, seasonal forests and freshwater ecosystems (IBGE, 2012). In the study area, forest and native vegetation predominated in Pantanal. The biome is still one of the most preserved in Brazil (MAGALHÃES et al., 2016; ALHO et al., 2019), but in the last few years major threats (as native vegetation loss, commodities agriculture and degradation) are endangering the biome (CORREA et al., 2022).

On the other hand, in the study area, agriculture predominated in Cerrado, which is consistent with other mapping for the whole biome (INPE, 2023). Since the 1970s, the Cerrado region began to receive incentives to expand agricultural areas, which persisted for about 40 years (PIRES, 2000; PESSOA; INOCÊNCIO, 2014; SANTOS, 2016). Nowadays, commodities agriculture is still expanding its limits over the biome, threatening its biodiversity even more (MYERS et al., 2010). Agriculture in this region is connected to foreign ownership of land and the increased presence of transnational companies and investment funds in the acquisition of areas (PIRES, 2020). In addition, the Cerrado is the second Brazilian biome that has suffered the most from human occupation over the years (SAWYER et al., 2017).

Both native vegetation loss in Pantanal and agriculture expansion in Cerrado are making Pantanal more fire-prone. We found years with the highest rates of burning were 2001, 2005, 2012, and 2020. Correa et al. (2022) corroborated that for 2001, 2005, and 2020 identifying large fires in the dry season. Also Moraes et al. (2017), pointed out that 2005 was a year characterized by high incidences of fires in the biome. Ferreira et al. (2018) observed that burnings between 2000 and 2016 in the Pantanal occurred in all years and events were related to the water regime, more frequent in driest periods. According to Garcia et al. (2021), very dry years create ideal conditions for spread of natural and anthropogenic fires, since the water level remains very low, failing to flood all areas that normally flood, generating a large amount of biomass and favoring occurrence of major fires.

Although we did find an influence of water bodies in Pantanal on burnings, we did not find an increasing or decreasing pattern in water bodies in the Pantanal, reinforcing that other environmental and social factors may influence the water dynamic in this region. In fact, we found that, as a secondary effect, urban sprawl and agriculture expansion in Pantanal are changing hydrological cycles in this biome. And most importantly, native vegetation loss in Cerrado for commodities (cultivation of soy/corn) and beef production resulted in soil erosion and loss in Cerrado lastly altering hydrological cycles in the Pantanal in the study area region (BERGIER et al., 2013). The decrease in water bodies extension in Cerrado indicates that the eutrophication is happening in watersheds and or is linked to drier years (HOFMANN et al., 2021).

Burned areas also showed high variability over the time series, and that might be attributed to the fact that current burns in the biome are a combination of climatic factors and anthropic activities (LEAL FILHO et al., 2021). In addition, wetlands and pastures are more susceptible to burns in extreme dry weather conditions, because of the high amount of fuel load (CORREA et al., 2022). According to Libonati et al. (2020), fires in Pantanal can be summarized as a combination of inadequate fire management, climate extremes, human behavior, and weak environmental regulations. On the other hand, decreasing burnings found in Cerrado of study area are contrary to the patterns over the whole biome (HOFMANN et al., 2021).

Thus, agriculture expansion in Pantanal and Cerrado is related to the loss of natural habitats in both biomes and, lately, to burnings in Pantanal, reinforcing that events in both biomes are interconnected, since activities that take place in one biome impact activities in the other biome. As previously mentioned, wetlands tend to depend on their surroundings (GARCIA et al., 2020). Between Pantanal and Cerrado we found the same. This relationship is observed in water flows and sediment production in the Pantanal that are altered by anthropic activities in the Cerrado (IVORY et al., 2019). Also, deforestation, caused by the conversion of natural areas to large-scale and commodities agriculture without soil conservation measures in the Cerrado, ends up impacting the flow, and consequently water regimes in the Pantanal (BERGIER et al., 2013; GARCIA et al., 2020; GUERRA et al., 2020).

Finally, it should be noted that all relevant components (i.e., variables) analyzed in this study exhibited influence of other components inserted in the same or in the neighboring biome. This result again reinforces the existence of a direct interaction between Pantanal and Cerrado, and indicates that Pantanal burnings control and prevention is complex and rely on management, legislation and environmental regulations of both Pantanal and Cerrado biomes (SCHULZ et al., 2019). The conversion (legal and illegal) of forest and native vegetation areas into large-scale and commodities agriculture or to urban sprawl in Pantanal and Cerrado biomes is happening in an alarming rate (ALHO; SILVA, 2012; ARMENTERAS et al., 2017; ALENCAR et al., 2020; MAPBIOMAS, 2022) and burnings have also increased in the last few years (LIBONATI et al., 2020; GARCIA et al., 2021; CORREA et al., 2022), which makes conservation actions urgent and studies on these issues very much needed.

5. Conclusion

This study aimed to identify interactions between Cerrado land use and land cover change and fire incidence in Pantanal, using a study area located between the two biomes. We showed that fires in Pantanal were directly linked to large-scale agriculture conversion in Cerrado and native vegetation loss and hydrological changes in Pantanal.

Under these conditions, we concluded that while natural areas decreased, areas under anthropic influence increased. In addition, water bodies and fire events are dynamic in relation to the analyzed period. Also, mutual interactions between the variables of analyzed biomes were verified, thus confirming the direct relationship between changes in Pantanal and the dynamics in Cerrado.

Based on the importance of both biomes, in proving existing changes and relationships in the study area, we suggest for future work: (i) analysis of relationships between fires and climatic and environmental variables, such as precipitation, temperature, soil humidity, among others; (ii) more and larger study sites; (iii) longer analysis periods.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

Alencar, A., Shimbo, J. Z., Lenti, F., Marques, C. B., Zimbres, B., Rosa, M., Arruda, V., Castro, I., Ribeiro, J. P. F. M., Varela, V. Alencar, I., Piontekowski, V., Ribeiro, V., Bustamante, M. M. C., Sano, E. E., Barroso, M. Mapping three decades of changes in the brazilian savanna native vegetation using Landsat data processed in the google earth engine platform. **Remote Sensing**, v. 12, n. 6, p. 924, 2020.

Alho, C. J. R., Mamede, S. B., Benites, M., Andrade, B. S., Sepúlveda, J. J. O. Ameaças à biodiversidade do pantanal brasileiro pelo uso e ocupação da terra. **Ambiente & Sociedade**, v.22, n.1, p. 1-22, 2019.

Alho, C. J. R.; Silva, J. S. V. Effects of severe floods and droughts on wildlife of the pantanal wetland (Brazil) - a review. **Animals**, v.2, n. 4, p. 591-610, 2012.

Altmann, A., Tolosi, L., Sander, O., Lengauer, T., 2010. Permutation importance: a corrected feature importance measure. **Bioinformatics**, v. 26, n. 10, p. 1340-1347, 2010.

ANA. **Divisão de Bacias**, 2016. https://metadados.snirh.gov.br/geonetwork/srv/por/catalog.search#/metadata/fe192ba0-45a9-4215-90a5-3fba6abea174. Accessed in: 07 June 2021.

ANA. **Países**, 2010. https://metadados.snirh.gov.br/geonetwork/srv/por/catalog.search#/metadata/7cfd53c4-b4e1-4aba-a79b-857a19649df6. Accessed in: 07 June 2021.

Armenteras, D., Espelta, J. M., Rodríguez, N., Retana, J., 2017. Deforestation dynamics and drivers in different forest types in Latin America: three decades of studies (1980–2010). **Global Environmental Change**, v. 46, n. 1, p. 139-147, 2017.

Bergier, I.. Effects of highland land-use over lowlands of the brazilian pantanal. **Science of the Total Environment**, v. 463, n. 1, p. 1060-1066, 2013.

Bergstra, J. Bengio, Y. Random search for hyper-parameter optimization. **Journal of Machine Learning Research**, v. 13, n. 1, p. 281-305, 2012.

Breiman, L. Random Forests. **Machine Learning**, v. 45, n.1, p. 5-32, 2001.

Chen, T.; Guestrin, C. Xgboost: a scalable tree boosting system. In: Proceedings of the 22nd acm sigkdd international conference on knowledge discovery and data mining, n. 22, 2016. P. 785-794.

Correa, D. B., Alcântara, E., Libonati, R., Massi, K. G., Park, E. Increased burned area in the pantanal over the past two decades. **Science of the Total Environment**, v. 835, n. 1, p. 155386, 2022.

Ferreira, W. T. S.; Larcher, L.; Rabelo, A. P. C. Análise da distribuição espaço-temporal dos focos de incêndio no pantanal (2000-2016). In: 7º Simpósio de Geotecnologias no Pantanal, n. 7, 2018, Jardim, MS. **Anais**. p. 563-573.

Figueiredo, D. Conceitos básicos de sensoriamento remoto, **São Paulo**, 2005.

Garcia, L. C., Szabo, J. K., Roque, F. O., Pereira, A. M. M., Cunha, C. N. C., Damasceno-Júnior, G. A., Morato, R. G., Tomas, W. M., Libonati, R., Ribeiro, D. B., 2021. Record-breaking wildfires in the world's largest continuous tropical wetland: integrative fire management is urgently needed for both biodiversity and humans. **Journal of Environmental Management**, v. 293, n. 1, p. 112870, 2021.

Guerra, A., Roque, F. O., Garcia, L. C., Ochoa-Quintero, J. M., Oliveira, P. T. S., Guariento, R. D., Rosa, I. M. D. Drivers and projections of vegetation loss in the pantanal and surrounding ecosystems. **Land Use Policy**, v. 91, n. 1, p. 104388, 2020.

Hardesty, J., Myers, R., Fulks, W. Fire, ecosystems, and people: a preliminary assessment of fire as a global conservation issue. **The George Wright Forum**, v. 22, n. 4, p. 78-87, 2005.

Harris, M. B., Tomas, W., Mourão, G., Silva, C. J., Guimarães, E., Sonoda, F. Fachim, E. Safeguarding the pantanal wetlands: threats and conservation initiatives. **Conservation Biology**, v. 19, n. 3, p. 714-720, 2005.

Hofmann, G. S.; Cardoso, M. F.; Alves, R. J. V.; Weber, E. J.; Barbosa, A. A.; Toledo, P. M.; Pontual, F. B.; Salles, L. O.; Hasenack, H.; Cordeiro, J. L. P.; Aquino, F. E.; Oliveira, L. F. B. The brazilian cerrado is becoming hotter and drier. **Global Change Biology**, v. 27, n. 17, p. 4060-4073, 2021.

IBGE. **Biomas**, 2016. https://www.ibge.gov.br/geociencias/cartas-e-mapas/informacoes-ambientais/15842-biomas.html. Accessed in: 07 June 2021.

IBGE. Manual técnico da vegetação brasileira. **Manuais técnicos em geociências**, 2012.

IBGE. **Trecho da Drenagem**, 2019. https://www.ibge.gov.br/apps/basescartograficas/#/mapa/. Accessed in: 28 June 2023.

INPE. **PRODES – monitoramento do desmatamento da Floresta Amazônica brasileira por satélite**, 2023

Ivory, S. J., McGlue, M. M., Spera, S., Silva, A., Bergier. I. Vegetation, rainfall, and pulsing hydrology in the pantanal, the world's largest tropical wetland. **Environmental Research Letters**, v.14, n. 12, p. 124017, 2019.

Junk, W. J., Cunha, C. N. Pantanal: a large South American wetland at a crossroads. **Ecological Engineering**, v. 24, n. 4, p. 391-401, 2005.

Junk, W. J., Cunha, C. N., Wantzen, K. M., Petermann, P., Strussmann, C., Marques, M. I., Adis, J. Biodiversity and its conservation in the pantanal of Mato Grosso, Brazil. **Aquatic Sciences**, v. 68, n. 1, p. 278-309, 2006.

Kennedy, M. J. Gandomi, A. H., Miller, C. M.. Coagulation modeling using artificial neural networks to predict both turbidity and dom-parafac component removal. **Journal of Environmental Chemical Engineering**, v. 3, n. 4, p. 2829-2838, 2015.

Klink, C. A.; Machado, R. B. A conservação do cerrado brasileiro. **Megadiversidade**, v. 1, n. 1, p. 147-155, 2005.

Leal Filho, W., Azeiteiro, U. M., Salvia, A. L., Fritzen, B., Libonati, R. Fire in paradise: why the pantanal is burning. **Environmental Science & Policy**, v. 123, n. 1, p. 31-34, 2021.

Leblois, A., Damette, O., Wolfersberger, J. What has driven deforestation in developing countries since the 2000s? Evidence from new remote-sensing data. **World Development**, v. 92, n. 1, p. 82-102, 2017.

Libonati, R., DaCamara, C. C., Peres, L. F., Carvalho, L. A. S., Garcia, L. C. Rescue Brazil's burning pantanal wetlands. **Nature**, v. 588, n. 7837, p. 217-219, 2020.

Li, X., Song, K., Liu, G., 2020. Wetland fire scar monitoring and its response to changes of the pantanal wetland. **Remote Sensors**, v. 20, n. 15, p. 4268, 2020.

Magalhães, L. A.; Fonseca, M. F.; Castro, G. S. A.; Daltio, J.; Martinho, P. R. R.; Carvalho, C. A. Qualificação territorial da agropecuária e socioeconomia do pantanal brasileiro. In: 6° Simpósio de Geotecnologias no Pantanal, n. 6, 2016, Cuibá, MT. **Anais**. p. 642-652.

Mann, H. B. Non-parametric tests against trend. Econometria. **Math Sci Net**, v.13, n. 1, p. 245-259, 1945.

MapBiomas. **Estatísticas**. 2022. https://mapbiomas.org/estatisticas. Accessed in: 03 April 2023.

MapBiomas. **MapBiomas Brasil**. https://mapbiomas.org/. Accessed in: 06 April 2023.

MMA. **Cadastro Nacional de Unidades de Conservação**. 2023a. https://antigo.mma.gov.br/areas-protegidas/cadastro-nacional-de-ucs. Accessed in: 25 April 2023.

MMA. **Cerrado**. 2023b. https://www.gov.br/mma/pt-br/assuntos/ecossistemas-1/biomas/cerrado. Accessed in: 30 April 2023.

Montgomery, D. C., Peck, E. A., Vining, G. G. **Introduction to linear regression analysis**. New Jersey: John Wiley & Sons, 2021.

Moraes, E. C.; Mataveli, G. A.; Santos, P. R.; Oliveira, B. S. Estudo da dinâmica de queimada no bioma pantanal no período de 2002 a 2015. In: XVIII Simpósio Brasileiro de Sensoriamento Remoto–SBSR, n. 18, 2017, Santos, SP. **Anais**. p. 3424-3430.

Myers, N.; Mittermeier, R. A.; Mittermeier, C. G.; Fonseca, G. A. B.; Kent, J. . Biodiversity hotspots for conservation priorities. **Nature**, v. 403, n. 1, p. 853-858, 2000.

Oliveira, P. T. S.; Nearing, M. A.; Moran, M. S.; Goodrich, D. C.; Wendland, E.; Gupta, H. V. Trends in water balance components across the brazilian cerrado. **Water Resources Research**, v. 50, n. 9, p. 7100-7114, 2014.

Ortiz, J. L., Freitas, M. I. C.. Mapeamento do uso da terra, vegetação e impactos ambientais por meio de sensoriamento remoto e geoprocessamento. **UNESP Geociências**, v. 24, n. 1, 2005.

Pedregosa, F.; Varoquaux, G.; Gramfort, A.; Michel, V.; Thirion, B.; Grisel, O.; Blondel, M.; Prettenhofer, P.; Weiss, R.; Dubourg, V.; Vanderplas, J.; Passos, A.; Cournapeau, D. Scikit-learn: machine learning in python. **Journal of Machine Learning Research**, v. 12, n,1, p. 2825-2830, 2011.

Pessoa, V. L. S.; Inocêncio, M. E. PRODECER (re)visitado: as engrenagens da territorialização do capital no cerrado. **Revista Campo-Território**, v. 9, n. 18, 2014.

Pires, M. O. "Cerrado", old and new agricultural frontiers. **Brazilian Political Science Review**, v. 14, n. 3, p. 1-24, 2020.

Pires, M. O. Programas agrícolas na ocupação do cerrado. **Sociedade e Cultura**, v. 3, n. 1, p. 111-131, 2000.

QGIS Development Team, 2022. QGIS Geographic Information System. Open Source Geospatial Foundation. http://qgis.org.

Roces-Díaz, J. V.; Santín, C.; Martínez-Vilalta, J.; Doerr, S. H. A global synthesis of fire effects on ecosystem services of forests and woodlands. **Frontiers in Ecology and the Environment**, v. 20, n. 3, p. 170-178, 2022.

Santos, C. C. M. Programa de cooperação nipo-brasileira para o desenvolvimento dos cerrados-PRODECER: um espectro ronda os cerrados brasileiros. **Estudos Sociedade e Agricultura**, v. 24, n.1, p. 384-416, 2016.

Sausen, T. M. Sensoriamento remoto e suas aplicações para recursos naturais. **Apostila Introdução ao Sensoriamento Remoto**, v. 29. n. 5, 2007.

Sawyer, D.; Mesquita, B.; Coutinho, B.; Almeida, F. V.; Figueiredo, I.; Lamas, I.; Pereira, L. E.; Pinto, L. P.; Pires, M. O.; Kasecker, T. Ecosystem profile: cerrado biodiversity hotspot. Critical Ecosystem Partnership Fund, 2017.

Schulz, C.; Whitney, B. S.; Rossetto, O. C.; Neves, D. M.; Crabb, L.; Oliveira, E. C.; Lima, P. L. T.; Afzal, M.; Laing, A. F.; Fernandes, L. C. S.; Silva, C. A.; Steinke, V. A.; Steinke, E. T.; Saito, C. H. Physical, ecological and human dimensions of environmental change in Brazil's pantanal wetland: synthesis and research agenda. **Science of the Total Environment**, v. 687, n.1, p. 1011-1027, 2019.

Sen, P. K. Estimates of the regression coefficient based on kendall's tau. **Journal of the American Statistical Association**, v. 63, n. 324, p. 1379-1389, 1968.

SOS Pantanal. Pantanal: a maior área úmida do mundo. 2021. https://www.sospantanal.org.br/pantanal-a-maior-area-umida-do-mund. Accessed in: 28 May 2021.

Souza Jr., C. M.; Shimbo, J. Z.; Rosa, M. R.; Parente, L. L.; Alencar, A. A.; Rudorff, B. F. T.; Hasenack, H.; Matsumoto, M.; Ferreira, L. G.; Souza-Filho, P. W. M.; Oliveira, S. W.; Rocha, W. F.; Fonseca, A. V.; Marques, Cc. B.; Diniz, C. G.; Costa, D.; Monteiro, D.; Rosa, E. R.; Vélez-Martin, E.; Weber, E. J.; Lenti, F. E. B.; Paternost, F. F.; Pareyn, F. G. C.; Siqueira, J. V.; Viera, J. L.; Ferreira Neto, L. C.; Saraiva, M. M.; Sales, M. H.; Salgado, M. P. G.; Vasconcelos, R.; Galano, S.; Mesquita, V. V.; Azevedo, T. Reconstructing three decades of land use and land cover changes in brazilian biomes with landsat archive and earth engine. **Remote Sensing**, v. 12, n. 17, p. 2735, 2020.

THEIL, H. A rank-invariant method of linear and polynomial regression analysis. **Indagationes Mathematicae,** v. 12, n. 3, p. 386, 1950.

UNESCO. **Patrimônio Mundial Natural e Reservas da Biosfera no Brasil**. 2023. https://pt.unesco.org/fieldoffice/brasilia/expertise/natural-world-heritage. Accessed in: 15 April 2023.

USGS. **MODIS/Terra+Aqua burned area monthly l3 global 500 m sin grid**. 2021. https://lpdaac.usgs.gov/products/mcd64a1v006/. Accessed in: 19 May 2023.

Vanrossum, G.; Drake, F. L. **The python language reference**. Amsterdam, Netherlands: Python Software Foundation, 2010.

Virtanen, P.; Gommers, R.; Oliphant, T. E.; Haberland, M.; Reddy, T.; Cournapeau, D.; Burovski, E.; Peterson, P.; Wecksser, W.; Bright, J.; van der Walt, S. K.; Brett, M.; Wilson, J.; Millamn, K. J.; Mayorov, N.; Nelson, A. R. J.; Jones, E.; Kern, R.; Larson, E.; Carey, C.J.; Polat, I.; Feng, Y.; Moore, E. W.; VanderPlas, J.; Laxalde, D.; Perktold, J.; Cimrman, R.; Henrikesen, I.; Quintero, E. A.; Harris, C. R.; Archilbald, A. M.; Ribeiro, A. H.; Pedregosa, F.; van Mulbergt, P.; SciPy 1.0 Contributors. SciPy 1.0: fundamental algorithms for scientific computing in python. **Nature Methods**, v. 17, n. 1, p. 261-272, 2020.

Zangooei, H.; Delnavaz, M.; Asadollahfardi, G. Prediction of coagulation and flocculation processes using ann models and fuzzy regression. **Water Science and Technology**, v. 74, n. 6, p. 1296-1311, 2016

Fires in Pantanal are directly linked to agriculture conversion in Cerrado and native vegetation loss and hydrological changes in Pantanal

Fabrícia Cristina Santos[a*], Fellipe Mira Chaves[b], Rogério Galante Negri[a,b], Klécia Gili Massi[a,b]

a Graduate Program in Natural Disasters, São Paulo State University (UNESP)/National Center for Monitoring and Early Warning of Natural Disasters (CEMADEN), São José dos Campos 12245-000, Brazil;

b Science and Technology Institute (ICT), São Paulo State University (UNESP), São José dos Campos 01049-010, Brazil.

* Corresponding author. Email: fabricia.cristina@unesp.br

Postal address: São Paulo State University (UNESP) 12247-004. Rodovia Presidente Dutra, Km 137.8 – Eugênio de Melo – São José dos Campos/SP.

Supplementary Material

Fig. 1 - Land use and land cover portion Cerrado (2000-2020), MapBiomas (2021)

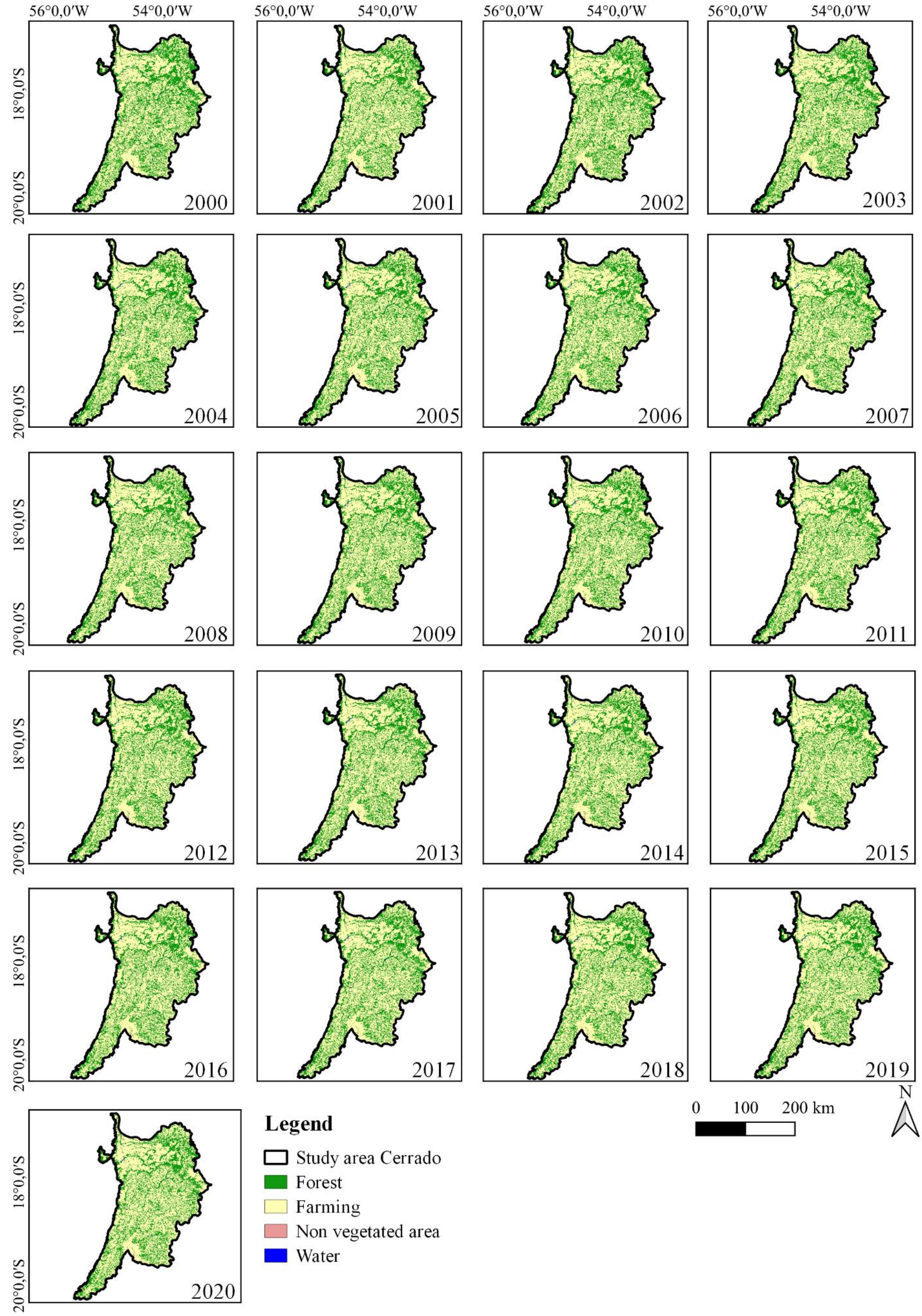


Fig. 2 - Land use and land cover portion Pantanal (2000-2020), MapBiomas (2021)

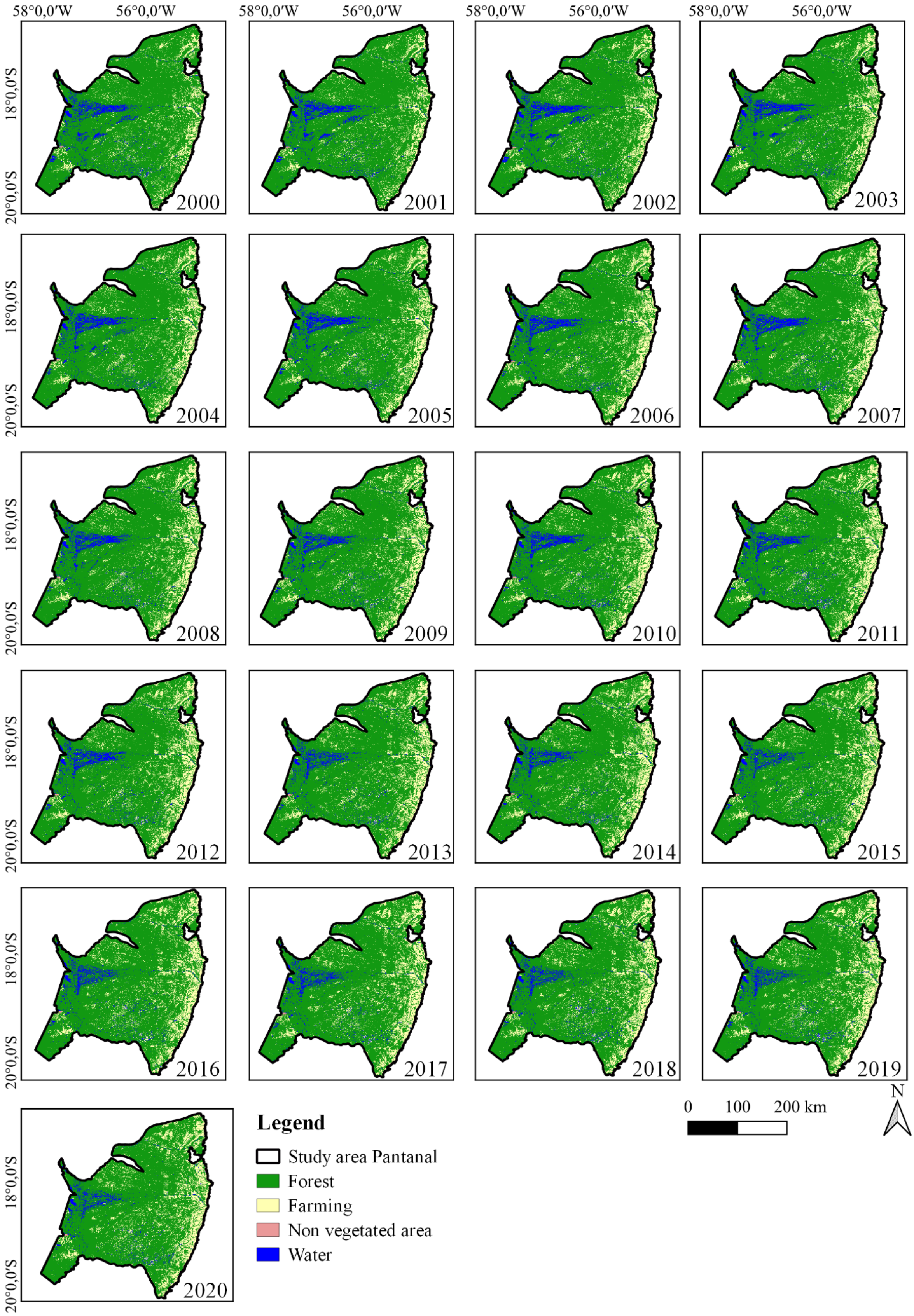


Fig. 3 - Quantified burned areas portion Cerrado dry period (2000-2020)

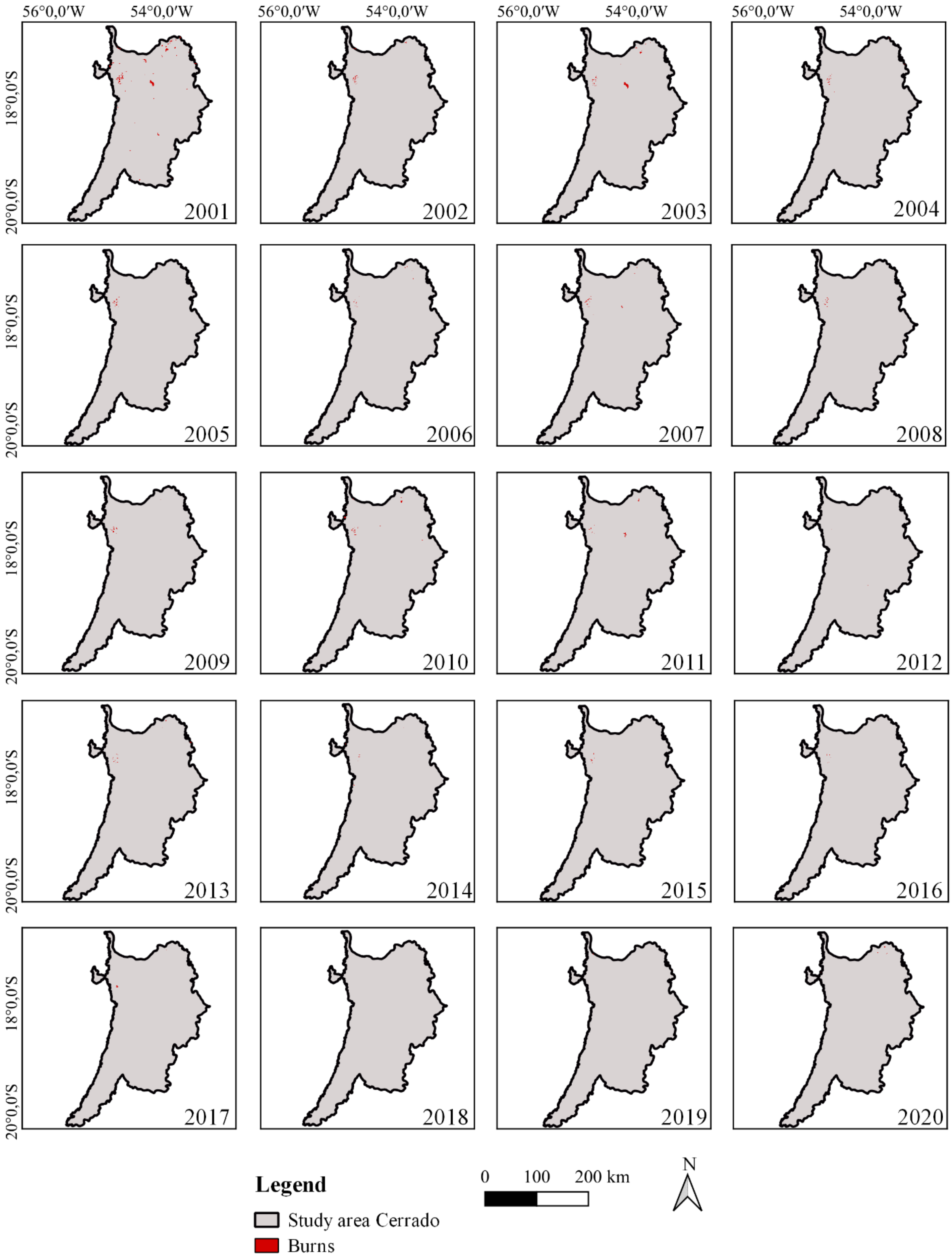


Fig. 4 - Quantified burned areas portion Cerrado wet period (2000-2020)

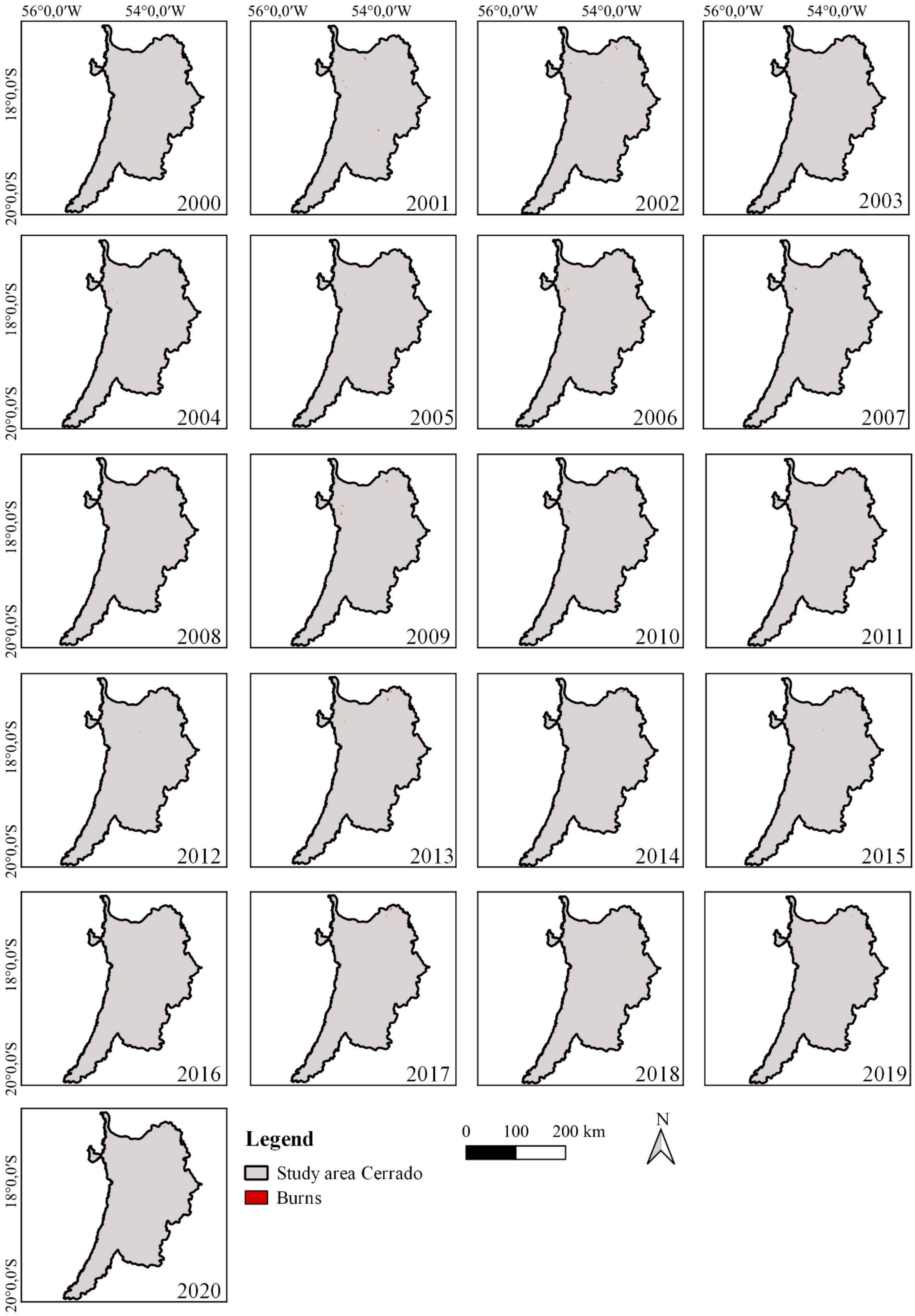


Fig. 5 - Quantified burned areas portion Pantanal dry period (2000-2020)

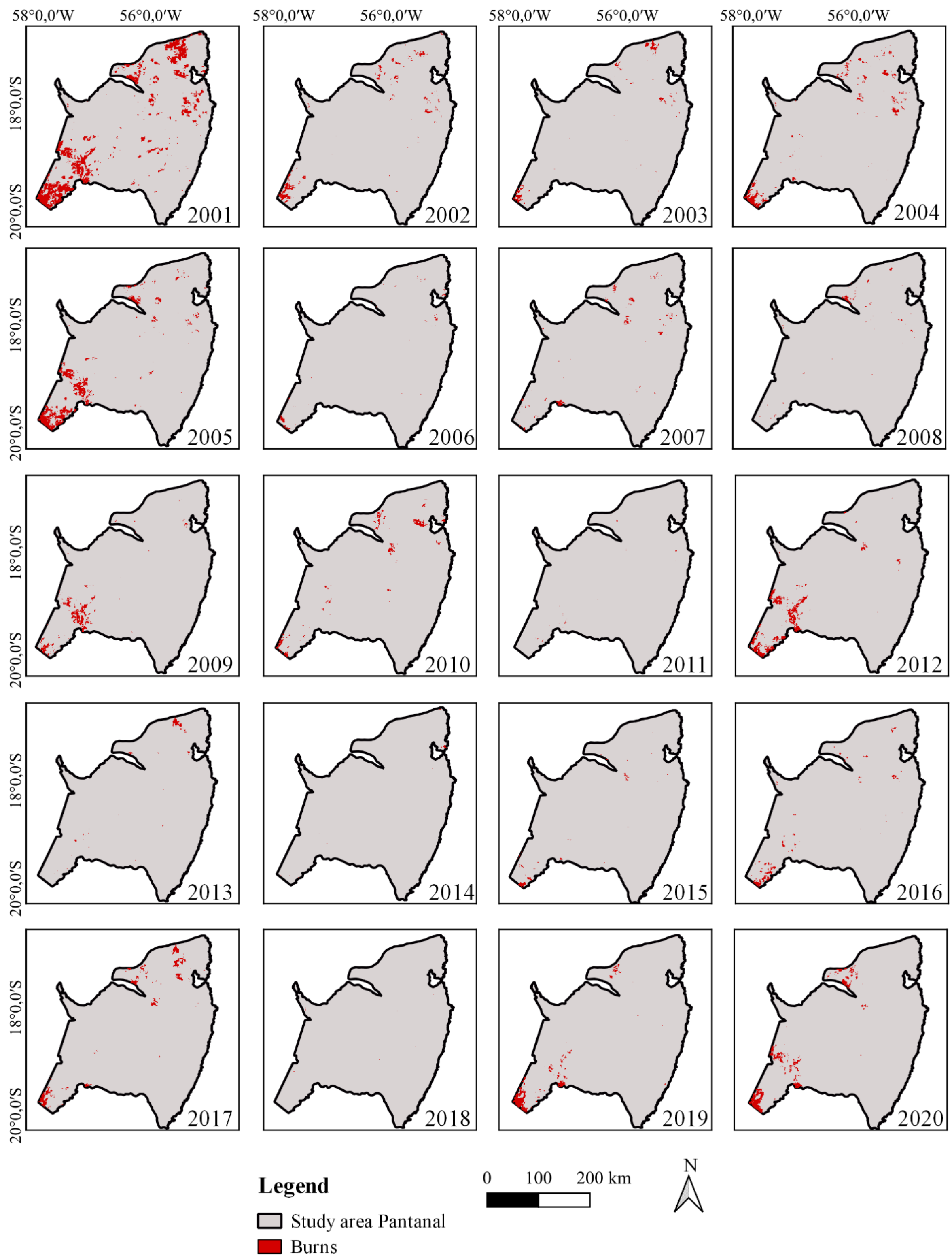
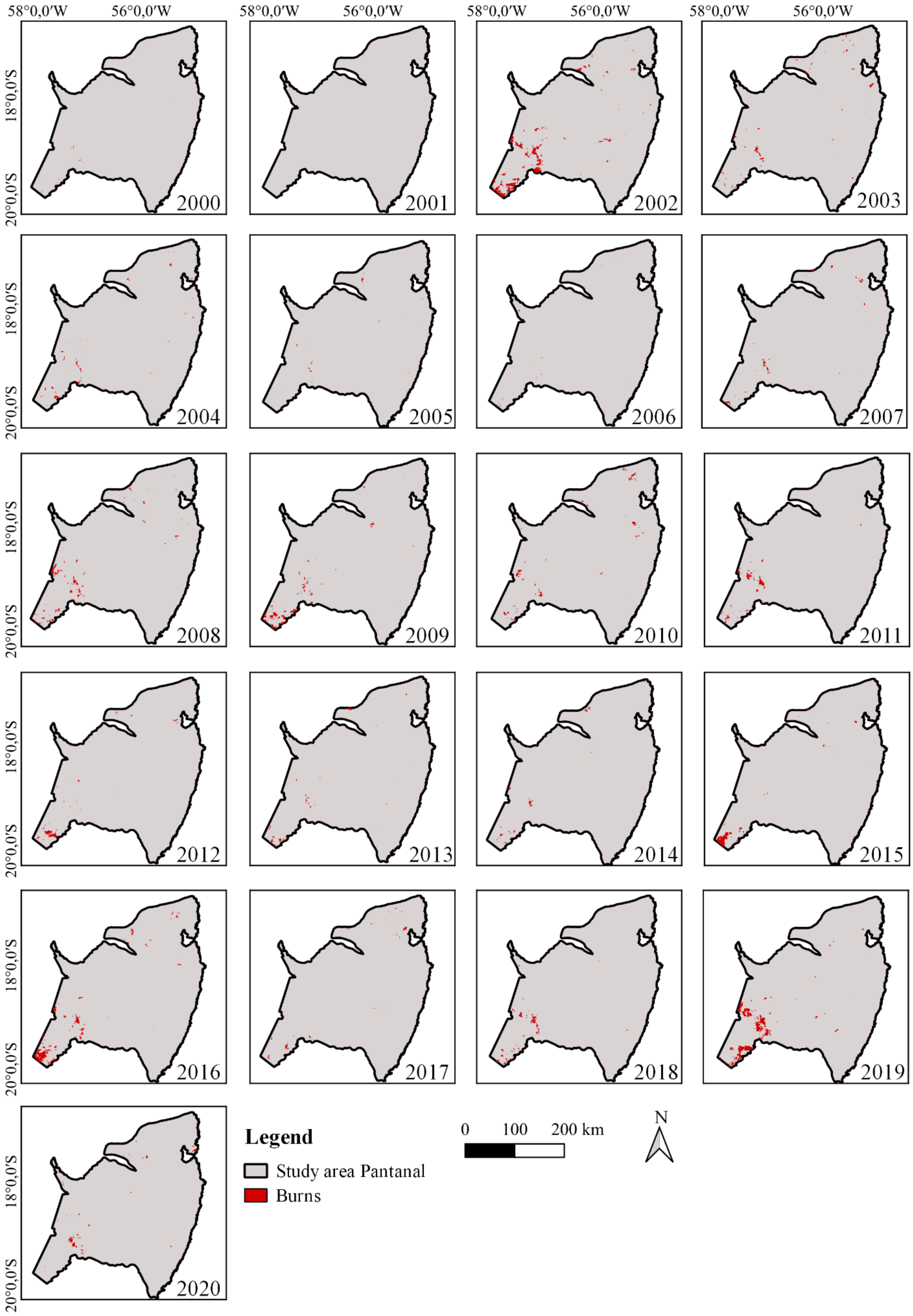


Fig. 6 - Quantified burned areas portion Pantanal wet period (2000-2020)



3 CONSIDERAÇÕES FINAIS

A utilização de dados obtidos por meio do Sensoriamento Remoto, análises de tendência e modelos de regressão foram consistentes para identificar as relações entre os eventos do Cerrado e do Pantanal, evidenciando o impacto das mudanças nas áreas queimadas no Pantanal.

A partir destas análises, observou-se que o uso e cobertura do solo apresentaram comportamento similar nos biomas, com diminuição da classe floresta e aumento das classes agropecuária e área não vegetada. Além disso, por meio do Teste de Mann-Kendall foi possível comprovar a conversão de áreas naturais em áreas antrópicas, bem como a tendência decrescente de corpos hídricos no Cerrado e a ausência de tendência no Pantanal. Em relação às áreas atingidas por queimadas, foram identificadas flutuações ao longo do tempo.

O uso de modelos de regressão, como ferramenta para identificação de fatores relevantes, permitiu destacar que as queimadas no Pantanal estão sob influência direta da concentração de áreas florestais e extensão dos corpos hídricos no Pantanal, e agropecuária no Cerrado. Por sua vez, seguindo um esquema recorrente, foram identificados os fatores relevantes que descrevem os elementos mencionados.

Nestas condições, concluímos que ao passo que as áreas naturais diminuíram, as áreas sob influência antrópica aumentaram. Além disso, o comportamento dos corpos hídricos e dos eventos de queimada são dinâmicos em relação ao período analisado. Ainda, foram verificadas interações mútuas entre as componentes dos biomas analisados, confirmando assim a relação direta entre alterações no Pantanal com as dinâmicas no Cerrado.

Para trabalhos futuros são sugeridos: a inclusão das relações entre as queimadas e outras variáveis, tanto climáticas como ambientais, tais como precipitação, temperatura e umidade do solo, a avaliação da mesma metodologia em outras áreas de estudo, e ampliação do período de análise.

REFERÊNCIAS

ALHO, C. J. R.; MAMEDE, S. B.; BENITES, M.; ANDRADE, B. S.; SEPÚLVEDA, J. J.O. Ameaças à biodiversidade do pantanal brasileiro pelo uso e ocupação da terra. **Ambiente & Sociedade**, v. 22, n. 1, p. 1-22, 2019.

ALHO, C. J. R. The pantanal. In: FRASER, L. H.; KEDDY, P. A. **The world's largest wetlands ecology and conservation**. Nova Iorque: Cambridge University, 2005. p. 203-271.

BERGIER, I. Effects of highland land-use over lowlands of the brazilian pantanal. **Science of the Total Environment**, v. 463, n. 1, p. 1060-1066, 2013.

GUERRA, A.; ROQUE, F. O.; GARCIA, L. C.; OCHAO-QUINTERO, J. M. O.; OLIVEIRA, P. T. S.; GUARIENTO, R. D. ROSA, I. M. D. Drivers and projections of vegetation loss in the pantanal and surrounding ecosystems. **Land Use Policy**, v. 91, n. 1, p. 104388, 2020.

HARDESTY, J.; MYERS, R.; FULKS, W. Fire, ecosystems, and people: a preliminary assessment of fire as a global conservation issue. **The George Wright Forum**, v. 22, n. 4, p. 78-87, 2005.

HARRIS, M. B.; TOMAS, W.; MOURÃO, G.; SILVA, C. J.; GUIMARÃES, E.; SONODA, F.; FACHIM, E. . Safeguarding the pantanal wetlands: threats and conservation initiatives. **Conservation Biology**, v. 19, n. 3, p. 714-720, 2005.

IVORY, S. J.; MCGLUE, M. M.; SPERA, S.; SILVA, A.; BERGIER, I. Vegetation, rainfall, and pulsing hydrology in the pantanal, the world's largest tropical wetland. **Environmental Research Letters**, v. 14, n. 12, p. 124017, 2019.

JUNK, W. J.; CUNHA, C. N. Pantanal: a large South American wetland at a crossroads. **Ecological Engineering**, v. 24, n. 4, p. 391-401, 2005.

KLINK, C. A.; MACHADO, R. B. A conservação do cerrado brasileiro. **Megadiversidade**, v. 1, n. 1, p. 147-155, 2005.

LEAL FILHO, W. ; AZEITEIRO, U. M.; SALVIA, A. L.; FRITZEN, B.; LIBONATI, R. Fire in paradise: why the pantanal is burning. **Environmental Science & Policy**, v. 123, n.1, p. 31-34, 2021.

MAPBIOMAS. **Estatísticas**. 2022. Disponível em: https://mapbiomas.org/estatisticas. Acesso em: 03 abr. 2023.

MMA. **Cadastro Nacional de Unidades de Conservação**. 2023. Disponível em: https://antigo.mma.gov.br/areas-protegidas/cadastro-nacional-de-ucs. Acesso em: 25 abr. 2023.

OLIVEIRA, P. T. S.; NEARING, M. A.; MORAN, M. S.; GOODRICH, D. C.; WENDLAND, E.; GUPTA, H. V. Trends in water balance components across the brazilian cerrado. **Water Resources Research**, v. 50, n. 9, p. 7100-7114, 2014.

PIVELLO, V. R. The use of fire in the cerrado and amazonian rainforests of Brazil: past and present. **Fire Ecology**, v. 7, n.1, p. 24-39, 2011.

SCHULZ, C.; WHITNEY, B. S.; ROSSETTO, O. C.; NEVES, D. M.; CRABB, L.; OLIVEIRA, E. C.; LIMA, P. L. T.; AFZAL, M.; LAING, A. F.; FERNANDES, L. C. S.; SILVA, C. A.; STEINKE, V. A.; STEINKE, E. T.; SAITO, C. H. Physical, ecological and human dimensions of environmental change in Brazil's pantanal wetland: synthesis and research agenda. **Science of the Total Environment**, v. 687, n.1, p. 1011-1027, 2019.