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Vulnerability of Rural Properties in the Pantanal Amid Recent Exceptional Environmental Changes

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Summary

Abstract

This study analyzed recent exceptional environmental changes (REECs) in the Pantanal, focusing on rural properties of various sizes affected. The results highlight that REECs do not occur uniformly in space and disproportionately affect properties of different sizes. Small properties were particularly impacted by exceptional fires, which has significant implications as these areas house communities with limited resources and rely on subsistence agriculture. Strategies for fire prevention and control, income source diversification, and strengthening the adaptive capacity of these communities are recommended to reduce vulnerability to these changes. Our study underscores the importance of targeted interventions tailored to local needs and collaboration to promote the resilience of communities affected by REECs in the Pantanal.

Resumo

Este trabalho analisou as mudanças ambientais excepcionais recentes (REECs) no Pantanal, com foco nas propriedades rurais de diferentes tamanhos afetadas. Os resultados destacam que as REECs não ocorrem uniformemente no espaço e afetam propriedades de diferentes tamanhos de maneira desigual. Propriedades pequenas foram particularmente atingidas por incêndios excepcionais, o que tem implicações significativas, pois essas áreas abrigam comunidades com recursos limitados e dependem da agricultura de subsistência. Estratégias de prevenção e combate a incêndios, diversificação de fontes de renda e fortalecimento da capacidade adaptativa dessas comunidades são recomendadas para redução da vulnerabilidade frente a essas mudanças. Nosso estudo ressalta a importância de intervenções direcionadas de acordo com a necessidade local e colaboração para promover a resiliência das comunidades afetadas por REECs no Pantanal.

Introduction

In a constantly changing world, humanity's vulnerability to environmental changes has become increasingly evident (IPCC 2021). Climate change, natural disasters, and rapid environmental changes are among the factors that have significant impacts on human communities (Moritz et al. 2014, Bowman et al. 2020). As we navigate these rapidly changing times, it is crucial to understand the intricate network of factors that make us susceptible to these environmental changes (Ma et al. 2019, Rana et al. 2022) and explore ways to mitigate their impact (Füssel, 2007, Bodin et al. 2019). Human vulnerability to environmental changes is a complex interaction of social, economic, and environmental factors (O'Brien et al. 2004, Schelhas et al. 2012, Holme & Rocha 2021). These vulnerabilities are not distributed equitably, with communities with fewer financial resources often being more vulnerable to the burden of environmental changes (Hsiang et al. 2017), particularly exceptional environmental events. Exceptionalities can be understood as unique vulnerabilities or exceptional challenges faced by specific groups or individuals in the context of environmental changes (Birkmann et al. 2013). These human vulnerabilities to environmental changes are an urgent concern that requires strategies and action, including transformative and disruptive forms of adaptation and mitigation (Mc Wethy et al. 2019, IPCC 2014). Due to their disproportionate nature (Eriksen et al., 2015), there is a clear need for a fair and inclusive approach to adaptation and mitigation efforts (O'Brien et al. 2018, Ranganathan & Bratman 2019, IPCC 2021).

Ranchers are on the front lines of rapid environmental changes (Khan et al. 2020), and their vulnerability is a pressing concern not only for their own communities but also for global food security (Nelson et al. 2007, Kerr et al. 2022). As we face the challenges of climate change and other environmental changes, it is essential to recognize the critical role that ranchers play in the sustainability of our societies (Leichenko & O'Brien 2002, Tomas et al. 2019).

Wetlands are vital ecosystems that provide a range of ecological services, including food, water purification, flood control, and habitat for diverse flora and fauna (Mitsch & Gosselink 2015, de Groot et al. 2018). However, these ecosystems face unprecedented challenges due to rapid environmental changes driven by human activities and climate change (Davidson 2014). In the past 10 years, these areas have decreased by 16% (Lázaro et al. 2020). These rapid wetland changes can have disproportionate consequences for vulnerable communities, such as traditional ranchers, who rely heavily on the dynamics of these areas and their resources (Ghermandi et al. 2015). This environmental instability caused by climate change can disrupt production (Dang et al. 2020) and significantly impact the local economy.

An excellent example of wetlands undergoing rapid changes is the Pantanal, the largest continuous wetland area in South America (Junk et al. 2006). Over the last 50 years, the region has seen accelerated land use changes (Roque et al. 2021), changes in fire regimes (Filho et al. 2021, Garcia et al. 2021, Libonati et al. 2022), and large-scale avulsive processes (Assine et al. 2015) that require special attention in certain areas (Louzada et al. 2022, Martins et al. 2022).

In this study, we assess how rural properties in the Pantanal can be differently affected by a set of recent exceptional environmental changes (REECs) that the region has been experiencing. We evaluate environmental exceptionalities related to land use changes, fire, and flooding, as they are among the drivers that can have significant consequences for the region's socioeconomy and biodiversity (Damasceno-Junior et al. 2004, Damasceno-Junior et al. 2021). We use property size as a surrogate for socio-environmental vulnerability and resilience to changes, as ranch size can be an indicator of resource availability, technology adoption, access to information, and community support (Derbile et al. 2019). Generally, larger ranches are expected to have more resources, both in terms of land and capital, allowing them to invest in technologies (Stefanes et al. 2018). In the case of the Pantanal, large ranches may even have more land to manage cattle in the face of floods, fires, and other adversities (Araujo et al. 2018), thereby increasing their resilience to environmental changes (Silveira et al. 2012).

Methods

Study Area

The Pantanal Plain, located in the heart of South America, is one of the world's largest floodplains and spans three countries: Brazil, Paraguay, and Bolivia. In Brazil, it covers the states of Mato Grosso do Sul and Mato Grosso, totaling an area of approximately 140,000 km^2 (Silva & Abdon 1998, Alho 2008). This unique biome is characterized by its diverse landscapes and influences from surrounding biomes, such as the Amazon, Cerrado, and Atlantic Forest (Figure 1), resulting in a varied distribution of plant species and a landscape that forms a mosaic of vegetation types.

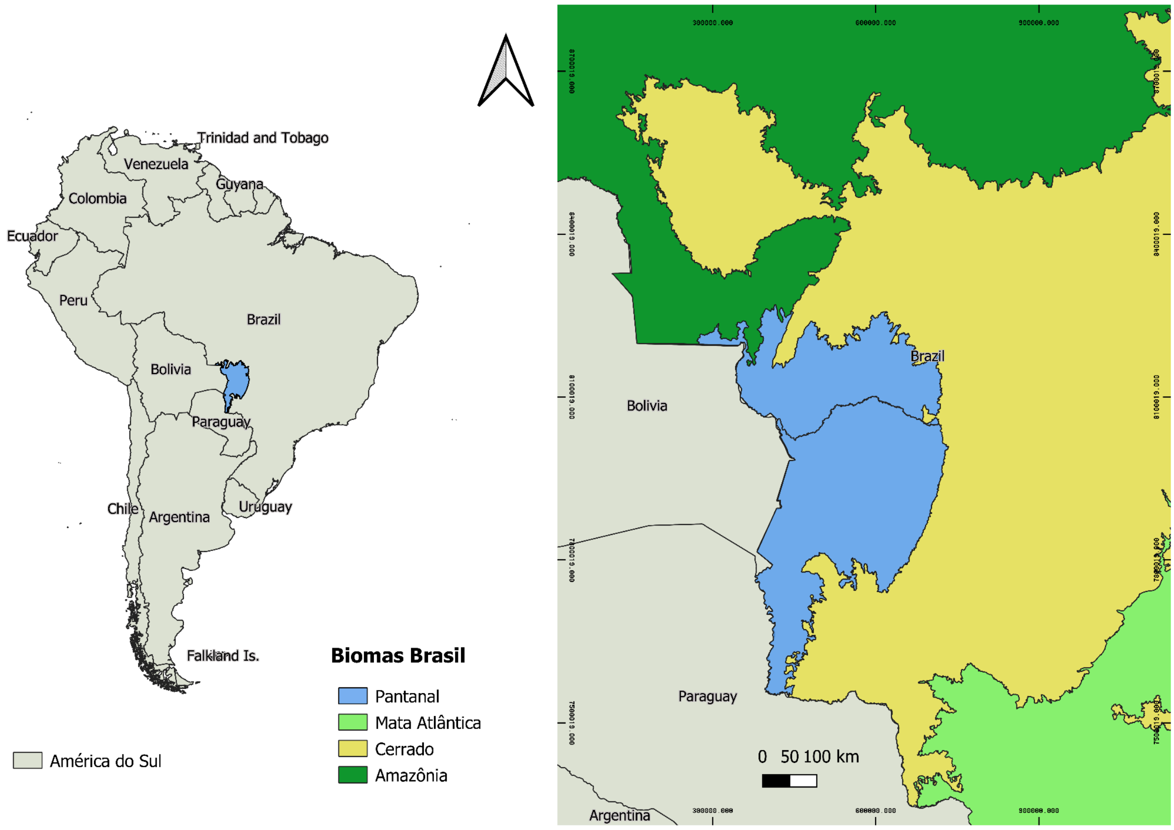

Figure 1. Location of the study area and visualization of the centralization of the Pantanal on the South American continent and Brazilian biomes surrounding the Pantanal.

The Pantanal landscapes are dominated by lagoons and small watercourses ("corixos"), which harbor a rich diversity of aquatic plant species (Junk et al. 2006). Additionally, in the lower parts of the Pantanal, where seasonal flooding occurs, native grasslands are common and strongly influenced by the seasonal flood regime (Assine et al. 2015). In the higher areas of the Pantanal, tree vegetation predominates, and many tree species are shared with the Cerrado biome (Silveira et al. 2012). These higher areas are less influenced by flooding and give rise to vegetation formations known as "capões" and "cordilheiras" (IMASUL 2008, Damasceno-Junior et al. 2021). The Pantanal's vegetation types are often highly heterogeneous, except for monodominant formations that exhibit more uniform characteristics and are dominated by a single abundant species (Souza et al. 2021).

This diversity of landscapes and the influence of different adjacent biomes result in the occupancy of a wide variety of animals, many of which are also found in neighboring biomes. This uniqueness makes Pantanal's biodiversity of great importance for both nature conservation and scientific research (Junk et al. 2006).

The biome, of significant ecological importance, has its economic base centered on traditional extensive cattle ranching. In this model, pasture cleaning is predominantly done through the use of fire to remove unwanted woody and herbaceous vegetation (Silveira et al. 2012, Santos et al. 2021). Besides livestock, agriculture is also present in the Pantanal, although it is more concentrated in the higher parts of the biome, where the influence of flooding is lower (Roque et al. 2021). The variation in economic activities among rural properties also contributes to a mosaic of land uses in the Pantanal landscape.

Data provided by MapBiomas (2023) on land use and occupation reveal that in 2022, more than 14,000 hectares of the Pantanal region were exclusively allocated for agricultural activities. These agricultural areas may include crops such as soybeans, sugarcane, or other seasonal crops. Livestock farming occupies the largest share of land cover in the Pantanal, with 2,244,684.9 hectares of pasture dedicated to cattle farming.

Other activities present in the Pantanal include fishing and extractive activities, such as the harvest of native fruits and the medicinal use of plants in traditional and riverine communities (Bortolotto et al. 2017). These activities are directly related to the biome's hydrological cycle (Hamilton et al. 2019). The Pantanal is renowned for its rich fish diversity and is an important fishing area for local communities (Silva et al. 2019).

Seasonal variations in water levels and seasonal floods in the Pantanal play a fundamental role in regulating these extractive activities (Hamilton et al. 2019). The availability of natural resources necessary for extractive activities, such as fish and fruits, is intricately linked to the flooding and drying patterns that occur throughout the Pantanal's hydrological cycle (Silva et al. 2019).

Main Data Collection Procedures and Definitions of Exceptionalities

The challenges posed by climate change require us to understand how rapid environmental changes impact socioecological systems (IPCC 2014). The increase in global temperatures and intensification of dry periods directly affect wetlands such as the Pantanal (Libonati et al. 2020, Teodoro et al. 2022). Inherent characteristics of this biome include the presence of fire, seasonal flooding, and drought cycles (Damasceno-Junior et al. 2021), as well as human occupation through rural activities (Guerra et al. 2021). Thus, we define exceptional change in land use, exceptional fire, exceptional flooding, and exceptional change in aquatic/terrestrial landscape as possible variables that may exhibit recent effects on the biome in a heterogeneous way (time/space) using data available in geoprocessing systems, in order to understand how properties of different sizes throughout the Pantanal are affected.

1. *Exceptional Land Use Change (ELUC)*

Using data from the MapBiomas Collection 7 database, we reclassified the categories present in the Pantanal into two classes. The resulting classes from the previous process were "Native Vegetation" and "Other Types of Use." This allowed us to identify areas where there was an exceptional conversion from native vegetation to some type of anthropogenic use. The data used covered the period from 2000 to 2021 with a spatial resolution of 30 meters. To select areas with the desired conditions, we identified areas that remained with native vegetation until 2019 and subsequently cross-referenced them with data on areas that showed conversion from native to another type of use into 2020 and 2021.

2. *Exceptional Fire (EF)*

The burned area was obtained from the MCD64A1 burned area product from Collection 6 through MODIS sensor with a spatial resolution of 500 meters and images provided by the ALARMES system (LASA - https://alarmes.lasa.ufrj.br/) captured by the Visible Infrared Imaging Radiometer Suite (VIIRS), also with a resolution of 500 meters (Pinto et al. 2020). To calculate exceptional fire activity, we used the model already developed by Libonati et al. (2022), which consists of the ratio of the burned area in 2020 to the average burned area between 2001-2019.As a product, values from 0 to 2 were generated, where 2 and 1 are considered low frequency and 0 as no fire frequency. Subsequently, we selected areas with the selection criterion of areas without fire (=0). The calculation result identifies areas where fire was a recent occurrence.

3. *Exceptional Flooding (EFL)*

We used data from the MapBiomas Water Collection 1 database (2023), which provides information on the frequency of flooding from 1985 to 2020, with a resolution of 30 meters. The classification of the water surface made by MapBiomas was performed using the Spectral Mixture Model (MEM) applied to Landsat scenes from the following sensors: Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM), and Landsat 8 Operational Land Imager (OLI). This approach allowed us to eliminate 70% of cloud cover. After blending scenes, using Fuzzy logic, we could assign conditions to identify and classify pixels corresponding to water (for better understanding, please refer to: mapbiomas.org). For our study, we used the total frequency of the water surface (in the historical series). We considered areas with exceptional flooding as those that had a frequency value of 1 within a 36-year interval.

4. *Exceptional Aquatic/Land Change (EALC)*

The Modified Normalized Difference Water Index (MNDWI) was used to understand the variation in aquatic/terrestrial coverage of the Pantanal over the past 23 years. The index ranges from -1 to 1, with negative values indicating wet environments and positive values indicating terrestrial environments (Gil et al. 2019, Asokan & Anitha 2019, Louzada et al. 2020). We used annual images from July to August in the range from 2000 to 2022, captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor with a spatial resolution of 250 meters. After obtaining the MNDWI for all images, we isolated areas that remained wet 2000 until 2018 and crossed them with terrestrial areas from 2019 to 2022. This allowed us to identify areas that recently transitioned to terrestrial and highlight an exception in the Pantanal's seasonal cycle.

The images were processed using Q.GIS 3.16 software for spatial distribution analysis. After obtaining the spatial distribution of exceptionalities, we extracted the percentage of land coverage by private properties. We used data from the Rural Environmental Registry provided by the National Rural Environmental Registry System, which allowed us to identify each property within the biome and its total area. Based on the premises of Law No. 8,629/1993 (Art. 4, II and III), properties were classified into three categories: small, medium, and large. The variables were analyzed independently and through spatial overlap. Thus, we were able to identify areas that underwent independent rapid changes and also verify if there is a spatial distribution correlation through Pearson correlation.

Results

The distribution of exceptionalities showed a higher concentration in distinct regions within the biome. The landscape change through the conversion of native vegetation to other uses highlights the arc of deforestation, located near the biome's edge, bordering the Cerrado and Amazon. Exceptional fires found in 2020 were concentrated in northern regions of the biome, mostly in the state of Mato Grosso (MT) and the municipality of Corumbá in the state of Mato Grosso do Sul (MS). The exceptional flood pulse was not evident in a recent period but demonstrates the water's reach in the floodplain during an extreme event. The environments with recent conversion from aquatic to terrestrial were distributed along the Paraguay River, the largest watercourse in the biome, which plays a crucial role in the flood pulse (Figure 2).

We identified 4,390 private properties that underwent recent land use changes in the biome, with 2,743 in MT and 2,297 in MS. For the occurrence of exceptional fires, there were 4,900 properties, with 2,107 in MT and 2,793 in MS. Exceptional flooding had the widest distribution, affecting 5,421 properties, with 2,907 in MT and 2,514 in MS. Exceptional landscape change (Aquatic/Terrestrial) had the smallest distribution, affecting a total of 21 properties, with 9 in MT and 12 in MS.


0 50 100 km
ELUC
EF
EFI
EALC

Figure 2. Visual results of the spatial distribution of exceptional variables: (ELUC) Exceptional Land Use Change; (EFl) Exceptional Flooding; (EF) Exceptional Fire; and (EALC) Exceptional Aquatic/Land Change.

The exceptional fire proved to be the variable with the greatest impact on private properties, totaling 1,231,479 hectares of coverage. In Mato Grosso, the properties affected by the fire had average values for each class, with 41.37% on large properties, 49.34% on medium-sized properties, and 57.79% on small properties (Figure 3).

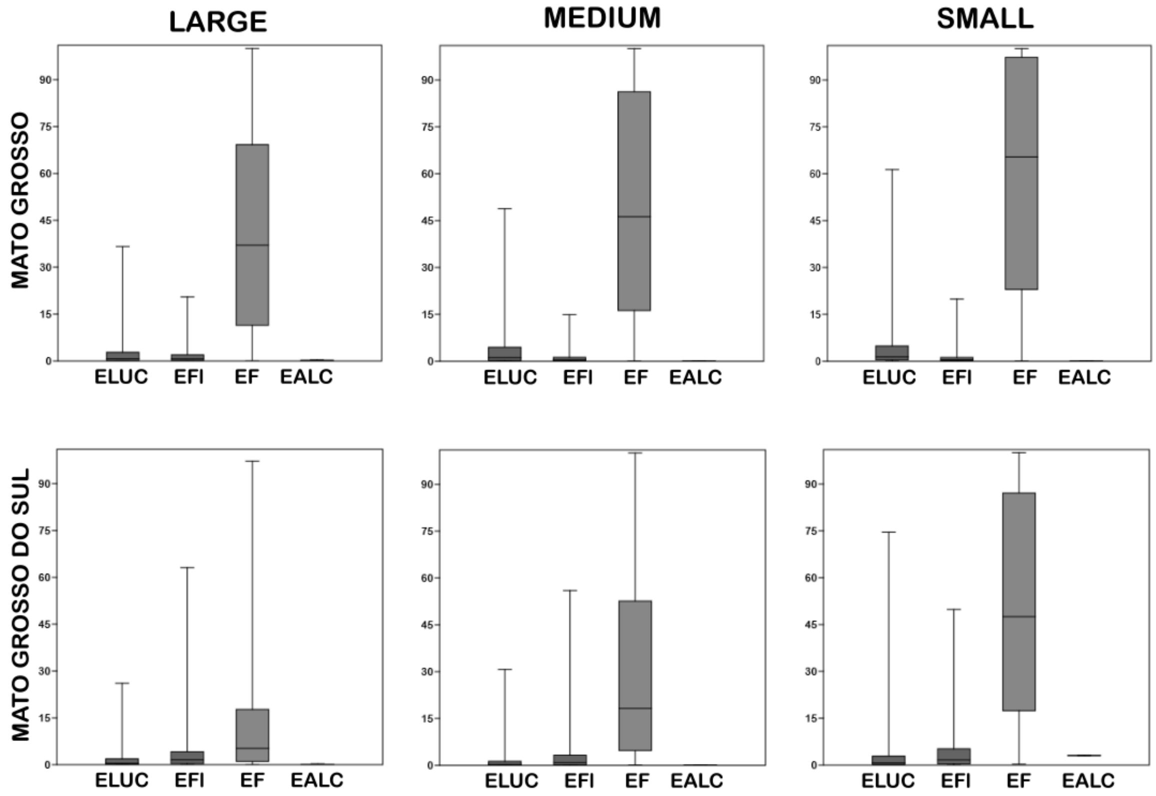

Figure 3. Percentages of the spatial distribution of exceptional variables by size class of rural properties present in the Pantanal of Mato Grosso and Mato Grosso do Sul, Brazil. (ELUC) Exceptional Land Use Change; (EFl) Exceptional Flooding; (EF) Exceptional Fire; and (EALC) Exceptional Aquatic/Land Change.

The peak area affected per property for each class (large, medium, and small) ranged from 321,409 to 91,624.55 hectares. In the state of Mato Grosso do Sul, the fire was also variable with the highest impact, but with lower values than the neighboring state, except for small properties, which showed that an average of 53% of each property was affected by the fire. Although they have average percentage values, we can observe significant impacts with peak areas ranging from 321,409 to 33,311.76 hectares. The other variables had an average coverage of less than 10% for the three property classes defined in this study. ELUC ranged from 0.001 hectares to 5269.308 hectares; EFl ranged from 0.01 to 7951.63 hectares, and EALC ranged from 0.093 to 28.851 hectares (Table 1). None of the exceptional changes showed spatial distribution correlation by area or percentage of coverage (Figure 4).

Table 1. Presentation of the results extracted from the variables (ELUC) Exceptional Land Use Change; (EFl) Exceptional Flooding; (EF) Exceptional Fire; e (EALC) Exceptional Aquatic/Land Change for the Pantanal in the states of Mato Grosso (MT) and Mato Grosso do Sul (MS), Brazil. (PNA) Properties Not Affected; (PA) Properties Affected.

Variables	Classes	PNA	PA	Average (%)	Min (ha)	Max (ha)
ELUC_MT	**LARGE**	248	593	2,32	0.001	133.745
	MEDIUM	205	590	4,19	0.002	481.965
	SMALL	1844	1560	4,7	0.001	2941.341
EF_MT	**LARGE**	358	483	41,37	0.054	91624.55
	MEDIUM	555	240	49,34	0.168	1193.805
	SMALL	2813	591	57,79	0.003	321.409
EFl_MT	**LARGE**	26	815	1,68	0.035	4345.902
	MEDIUM	94	701	1,24	0.001	114.657
	SMALL	2013	1391	1,29	0.001	33.499
EALC_MT	**LARGE**	832	9	0,13	0.142	28.851
	MEDIUM	795	-	-	-	-
	SMALL	3404	-	-	-	-
ELC_MS	**LARGE**	512	1006	1,85	0.002	5269.308
	MEDIUM	291	397	2	0.003	278.206
	SMALL	1107	244	3,5	0.001	51.484
EF_MS	**LARGE**	993	525	13,76	0.01	33311.76
	MEDIUM	564	124	29,6	0.362	1285.636

	SMALL	1236	115	53	0.025	321.409
EFl_MS	**LARGE**	43	1475	4,3	0.01	7951.63
	MEDIUM	99	589	0,35	0.002	882.114
	SMALL	901	450	4,43	0.001	144.184
EALC_MS	**LARGE**	1507	11	0,07	0.093	20.608
	MEDIUM	688	-	-	-	-
	SMALL	1350	1	3,06	8.243	8.243

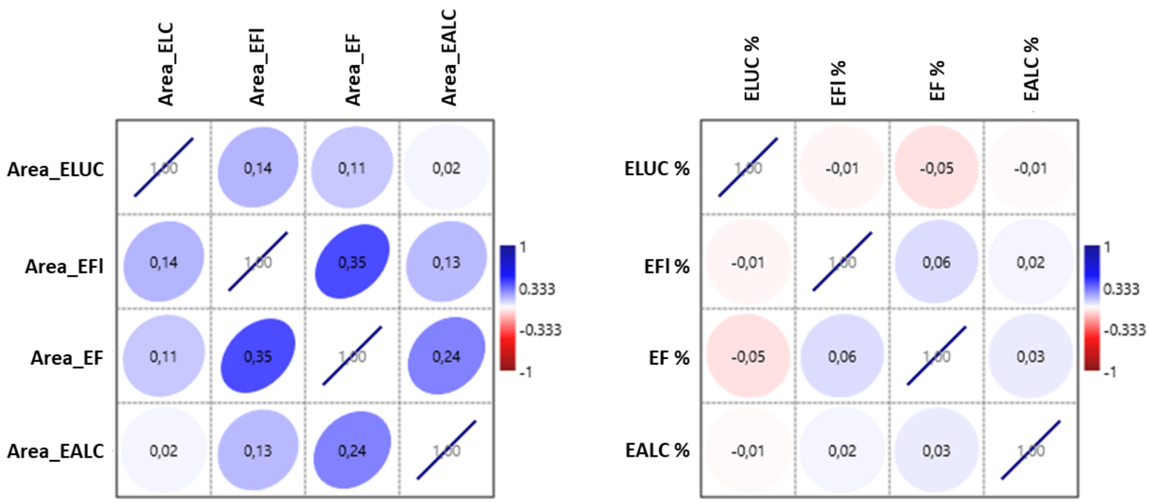

Figure 4. Correlation of the spatial distribution of variables (ELUC) Exceptional Land Use Change; (EFl) Exceptional Flooding; (EF) Exceptional Fire; and (EALC) Exceptional Aquatic/Land Change.

Discussion

The vulnerability of ranchers to Recent Exceptional Environmental Changes (REECs) is a complex issue influenced by various factors, including property size. Our study revealed that REECs in the Pantanal do not occur uniformly in space, meaning they do not overlap and affect properties of different sizes unevenly. One of the most significant findings of our study was the discovery that smaller rural properties, which we refer to as "small properties," were particularly affected by recent fires in the Pantanal of Mato Grosso and Mato Grosso do Sul. In contrast, "large properties" have experienced the majority of exceptional floods in the region. These results have crucial implications and open new perspectives for the development of socioecological resilience strategies and the reduction of vulnerability of rural properties in the Pantanal, considering the multiple REECs expected to intensify in the coming decades.

The low correlation between the different types of REECs analyzed can be attributed to several interconnected factors (Teodoro et al. 2022). Some of these exceptionalities have contrasting relationships with climatic factors that occur at different times and locations. For example, the increase in fire rates is associated with areas with high primary vegetation production, low precipitation, and prolonged drought events, along with rising temperatures (Libonati et al. 2022, Mataveli et al. 2021, Teodoro et al. 2022). In contrast, flooding in the Pantanal requires heavy rainfall in the headwaters of rivers to raise their levels to the point of overflow (Damasceno-Junior et al. 2021, Pereira et al. 2021). This dependence on opposing climatic conditions suggests that these events are distributed heterogeneously in different areas of the Pantanal, presenting distinct challenges for rural properties and biodiversity.

Furthermore, the vulnerability of properties is intrinsically linked to socioecological adaptive capacity, sensitivity, and exposure, which are the three main factors determining susceptibility or resistance to the effects of climate change (O'Brien et al. 2004, IPCC 2021). Adaptive capacity refers to the ability of the socioecological system to adjust to potential harm, create opportunities in the face of adversity, or respond to consequences (IPCC, 2014). Smaller properties with less financial and geotechnological resources (Stefanes et al. 2018) have demonstrated lower adaptive capacity compared to larger properties. This may hinder their ability to implement preparedness and recovery measures in the face of extreme events such as fires and floods.

The pressure exerted by deforestation for the expansion of agricultural areas on smaller properties (Stefanes et al. 2018, Yang et al. 2022) are activities that impact seasonal processes (Alho & Silva 2012) and can favor the occurrence of REECs. Deforestation for the conversion of native forests leads to the degradation of various biological processes and contributes to increased temperatures and dry periods in the Pantanal (Alho et al. 2019), altering the dynamics of ecosystem services provided in these areas (Jin et al. 2022). Furthermore, the high percentage of small properties affected by EF highlighted in our study and their lower adaptive response capacity compared to larger properties (Stefanes et al. 2018) make them more susceptible to REECs.

In this context, changes in rural policies can play a fundamental role in mitigating these damages (Louzada et al. 2021). Targeted interventions are needed, including the provision of accessible agricultural credit, training in sustainable and resilient ranching practices, investment in rural infrastructure (Brown et al. 2017, Strassburg et al. 2017), incentives for the creation of protected areas, and awareness-raising about future scenarios (Colman et al. 2022) that amplify the risks of REECs. Additionally, collaboration between ranchers, local governments, non-governmental organizations, and research institutions is essential to develop specific adaptive strategies for each region and community, considering the unique characteristics of each property and local environmental threats (Singh et al. 2022).

It is interesting to note that on a large scale, we can think of two major areas of change: the land-use change arc (second arc, Guerra et al. 2020), mainly in the east-west direction and bordering the Cerrado, and the corridor of changes along the Paraguay River, which spread mainly in the north-south direction along the western edge. Much of the EF occurred in sensitive vegetation (Garcia et al. 2021, Silgueiro et al. 2021, Libonati et al. 2022) and had a catastrophic impact on the biodiversity of the Pantanal (Tomas et al. 2021), highlighting the need for more attention to the direction of mitigation and adaptation actions.

Implications of Our Findings for Public Policies and Socioecological Resilience Strategies in the Pantanal

The results of our study on Recent Exceptional Environmental Changes (REECs) in the Pantanal highlight the complexity of the relationship between the size of rural properties and the vulnerability of ranchers to different types of extreme events. This differentiated approach is essential to understanding how different REECs affect agricultural properties non-uniformly and, therefore, how resilience strategies need to be adapted to meet the specific needs of each context.

1. Small Properties and Wildfires: The discovery that small properties in the Pantanal, located in the states of Mato Grosso and Mato Grosso do Sul, have been particularly affected by recent wildfires suggests the need for targeted interventions for these communities. These areas often house communities with limited resources, where

subsistence ranching is a common practice. Exceptional wildfires have devastating consequences for these families and communities as they directly impact their subsistence and food security. This conclusion is supported by various scientific studies. Research such as Teodoro et al. (2022) and Libonati et al. (2020) highlight the increasing occurrence of exceptional wildfires in the Pantanal and their possible relationship with climate change, reduced precipitation, and rising temperatures. Furthermore, studies by Stefanes et al. (2018) emphasize the vulnerabilities of small properties due to a lack of financial and technological resources.

To address these challenges, fire prevention and combat strategies, such as the creation of community brigades and training in integrated fire management, are recommended based on studies like Picos et al. (2019), Rocha (2020), and Pivello et al. (2021). Adopting adaptive actions like these can enhance the response capacity of these properties. Diversifying income sources, including sustainable activities and ecotourism, is also supported by research such as that of Bodin et al. (2019) and Walker et al. (2004).

2. Large Properties and Floods: The observation that large properties experienced most of the EFl highlights the importance of water resource management and proper infrastructure to deal with these events. Recurrent socio-economic activities in the Pantanal can favor environmental imbalance that causes severe floods (Alho & Silva 2012). The location of properties in relation to the flood pulse is an important aspect for prioritizing adaptive actions since the spatial distribution of flooding tends to affect lower-lying areas more frequently (Roque et al. 2021). Diversifying the productive matrix for the Pantanal is a favorable adaptation for properties, considering species that benefit from flooding (Bertazzoni & Damasceno-Junior 2011).

3. Resilience Strategies: The study's conclusions suggest that socioecological resilience strategies need to be adapted to address the specific characteristics of each REEC and the needs of affected rural properties. Identifying REECs is the first step in creating dynamic strategies that can enhance adaptive capacity, transforming a vulnerable system into a resilient one (Nelson et al. 2007). This may include the creation of customized management plans for different types of events, as well as strengthening community response capacity (Walker et al. 2004).
4. Collaboration and Experience Sharing: Property owners, regardless of size, can benefit from collaboration and experience sharing. This may involve the creation of local or regional networks integrated into the system that connects the social and ecological aspects (Bodin et al. 2019), where ranchers can exchange information about their resilience strategies and learn from each other's best practices (Garcia et al. 2021). The communication network is considered an important tool for the protection of valuable resources by Sakellariou (2021). Thus, more effective strategies can be defined on a dynamic scale with a focus on more susceptible areas, reducing overall impact.
5. Monitoring and Early Warning: Continuous monitoring of environmental conditions and early warning systems can be vital in helping rural properties prepare for imminent REECs by identifying areas with a higher likelihood of occurrence (Kaur & Sood 2019, Sakellariou 2021). This allows for targeted preventive and mitigation actions to reduce severe events (Picos et al. 2019, Libonati et al. 2022).
6. Government Support: It is important for the government and relevant agencies to consider the results of this study when developing policies and support programs for vulnerable rural areas (Martin et al. 2022). This may include subsidies for the implementation of resilience measures and investment in critical infrastructure.

7. Management Plans Considering Compound Impacts on the Territory: In summary, our study provides valuable information to guide the formulation of policies and resilience strategies that address the different needs of rural properties in the Pantanal in the face of ongoing environmental changes. Pursuing socially focused pathways with climate justice as a guiding principle for vulnerable groups due to adaptation limitations is the main challenge in achieving socioecological resilience for all (Barnes et al. 2020, Martin et al. 2022). The differentiated approach based on property size can be an important step toward building more resilient and adaptable agricultural communities in the face of increasing environmental challenges.

Conclusions

The rapid and exceptional environmental changes pose distinct yet complementary challenges for rural producers, necessitating the adoption of tailored resilience strategies and actions for each local need. The discovery that the impact of fires is greater on small properties directs us towards the creation of resilience strategies and actions that address the needs of small-scale producers, who have limited resources and lack government support, increasing their vulnerability.

Establishing communication networks for sharing knowledge (ideas, challenges, and solutions) that integrate communities, research, and governance is one of the main pathways to achieving socioecological resilience in the face of new challenges.

We emphasize the need for targeted interventions for small properties in the Pantanal affected by exceptional wildfires, recognizing the socio-economic challenges and emphasizing the importance of collaboration to enhance the resilience of these communities.

Rethinking ways to reduce the impact of REECs (Recent Exceptional Environmental Changes) can also lead to a reduction in the impact caused by agricultural producers in the Pantanal. Changing the way we approach a problem provides more holistic and necessary solutions to address initially uncertain and high socioecological impact challenges. It is of utmost importance to adopt strategies that rethink action plans to ensure the continued vitality of the biome.

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