Wetlands (2024) 44:45
https://doi.org/10.1007/s13157-024-01800-z

WETLAND CONSERVATION AND RESTORATION

When Drought Matters: Changes Within and Outside Protected Areas from the Pantanal Ecoregion

Natália P. Smaniotto[1,2] · Leonardo F. B. Moreira[1,2] · Thiago B.F. Semedo[3,4,5] · Fernando Carvalho[1,2] · Fernando M. Quintela[1,2] · André V. Nunes[6,7] · Yulie Shimano[1]

Received: 3 May 2023 / Accepted: 1 April 2024 / Published online: 11 April 2024
© The Author(s), under exclusive licence to Society of Wetland Scientists 2024

Abstract
Protected areas (PA) are being stifled by human land uses, jeopardizing their integrity and ecosystem services. Therefore, we searched for human land use within 19 PAs of the Pantanal ecoregion. We assessed changes in land cover from protected areas' creation year up to 2021. In addition, we established a 10 km buffer from each PA limit to compare trends in the landscape inside and outside PAs. Our results indicated the presence of pasture fields in eight PAs analyzed. We also detected a decrease in open water areas and a slight variation in native vegetation over the years. There was an increase in grassland and savanna areas, while forest, wetland, and pasture fields did not change over the years. Of all 19 buffer zones, 15 had human land uses. In addition to an increase in the human land use area, buffer zones showed an increase in grassland cover and a decrease in the open water cover. Terrestrial environments within most Pantanal PAs still stand to human interventions. Still, the human land use in reserves where it is not allowed indicates management issues and low law enforcement. Unfortunately, aquatic environments' protection is more challenging, depending on actions at lowlands and surrounding plateaus that harbor the headwaters. There is a clear need to integrate warming and drying impacts in the protected areas management plans. Since we have no control over large-scale climate, we must focus more on mitigating regional climate from a land use perspective.

Keywords Wetland · Biodiversity · Climate change · Land use · Agricultural intensification

Introduction

It is becoming increasingly clear that land cover changes pose significant risks to biodiversity, primarily through habitat loss and fragmentation (McDonald et al. 2019). Wetland areas are replaced mainly by crops aligned with the current expansion of agro-industrial and food production (Ballut-Dajud et al. 2022; Fluet-Chouinard et al. 2023). Today, the potential harms of such conversion for essential regulating services, such as water purification or climate regulation, are considerable. Additionally, climate change impacts natural systems and human infrastructure (i.e., changes in fire regimes and intensity, heatwaves, and crop failures; Goulart et al. 2021; Fowler et al. 2021; Carnicer et

✉ Natália P. Smaniotto
npsmaniotto@gmail.com

1 Instituto Nacional de Pesquisa do Pantanal, Avenida Fernando Corrêa da Costa, 2367, Boa Esperança, Cuiabá, Mato Grosso 78060-900, Brazil

2 Museu Paraense Emílio Goeldi, Avenida Governador Magalhães Barata, 376, São Braz, Belém, Pará 66040-170, Brazil

3 Centro de Investigação em Biodiversidade e Recursos Genéticos, CIBIO, InBIO Laboratório Associado, Universidade do Porto, Campus de Vairão, Vairão 4485-661, Portugal

4 BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, Campus de Vairão, Vairão 4485-661, Portugal

5 Departamento de Biologia, Faculdade de Ciências, Universidade do Porto, Porto 4099-002, Portugal

6 Knowledge Centre on Biodiversity - Brazil, Belo Horizonte, Minas Gerais 31270-010, Brazil

7 Programa de Pós-Graduação em Ecologia e Conservação, Instituto de Biociências, Universidade Federal de Mato Grosso do Sul, Cidade Universitária, Mato Grosso do Sul, Campo Grande, Mato Grosso do Sul 79070-900, Brazil

al. 2022). Thus, there is a demand for coherent management of protected areas, including networks to safeguard biodiversity and ecosystem services.

In the last three decades, about 11% of natural vegetation in Brazil has been converted to human land use (Gonçalves-Souza et al. 2021), and projections indicate a massive expansion of cultivated area (> 75%) until 2050 (Molotoks et al. 2018). The situation is dire for savanna-like environments (> 10% are protected, MMA 2022), as current land use policies promote grassland/savanna loss (Bonanomi et al. 2019). Meanwhile, protected areas occupy only 19% of Brazil's continental territory (MMA 2022). The Brazilian National Protected Areas System Law (Portuguese acronym: SNUC) divides protected areas (PAs) into two groups based on the restrictions on activities allowed: (1) integral protection PAs, defined as a territory where no alterations caused by human interference are allowed, and the natural attributes can be only indirectly explored; (2) sustainable use PAs, were the collection and use of natural resources (with or without commercial purposes) are allowed depending on the category (Brasil 2000). Such networks benefit natural environments and local populations (indigenous or non-indigenous) through tourism and other cultural ecosystem services (Ferreira and Freire 2009; Gonçalves-Souza et al. 2021). Still, many integral protection PAs present activities incompatible with conservation purposes, and they also face common problems of mismanagement (e.g., funding, equipment, infrastructure, and inadequate oversight; ICMBio and WWF-Brasil 2011; Garcia et al. 2017; Ribeiro et al. 2021). These issues affect mainly the wetlands because policy directives often exclude them.

The Pantanal ecoregion—near the Brazil, Bolivia, and Paraguay border— is the broadest floodplain in the world. Most of the ecoregion is located on Brazilian territory around the Paraguay River (~ 150,000 km^2) and is affected by seasonal floods from river overflow and rainfall in the region. This seasonality is responsible for a complex of brackish and freshwater ponds, extensive flooded grasslands, savannas, and dry forests. Such habitat mosaic plays a central role in the species' natural history (e.g., population densities, home range, habitat preferences). Many threatened animal species benefit from this mosaic, such as jaguar *Panthera onca* (Linneus, 1758), white-lipped peccary *Tayassu pecari* Link, 1795, black howler monkey *Alouatta caraya* (Humboldt, 1812), giant anteater *Myrmecophaga tridactyla* Linneus, 1758, maned wolf *Chrysocyon brachyurus* (Illiger, 1815) (ICMBio 2018; MMA 2022; Rodrigues et al. 2002; Quigley and Crawshaw 1992; Tomas et al. 2022). The presence of these species in the Pantanal confirms the importance of these areas in safeguarding essential environments for the conservation of endangered species populations. Unfortunately, while private areas are under land use intensification, only 5% of the Brazilian Pantanal is within PAs (MMA 2022).

Between 1985 and 2021, the area under human land use almost tripled in the Brazilian Pantanal, reaching 2.2 million hectares. Although temporary crops still respond to a tiny amount of such conversion, the area destined for agriculture increased six times in the same interval (Project MapBiomas 2022). Cattle grazing has shaped the Pantanal landscape for more than 200 years due to the region's climate and soil that contribute to the production (Dick et al. 2021). However, since 1980, the agro and productive sectors have led to the intensification of pastures (Girardi and Rossetto 2011), which today cover around 15% of the Pantanal. At the same time, native land cover showed different losses (forest 14%, savanna 18%, wetlands 72%; Project MapBiomas 2022). Variations in land cover involve multiple combinations of factors, but a federal environmental regulation centered on the habitat mosaics of the Pantanal could aid in regional conservation. Although federal legislation provides some direction for the protection of protected areas (SNUC, Brasil 2000), legislation at the state level continues to soften regulations on land use that include the Pantanal region (PL nº 561/2022, PL nº 45/2022, Mato Grosso 2022; DL nº 14,273, Mato Grosso do Sul 2015).

Changes in the landscape outside protected areas play a crucial role in maintaining the interior of these areas (Laurance et al. 2012). In the Pantanal, the increasing advancement of human use of land and the construction of river dams are also seen as a concern for the natural landscape. In addition to direct human modifications, the Pantanal suffers from periods of more severe drought, favoring fires (Marengo et al. 2021). These changes to the natural landscape raise a warning about the health of the region's protected areas and might have negative consequences for the Pantanal's biodiversity. In this sense, land cover trajectories are valuable tools for evaluating the impacts of landscape changes and improving knowledge of the effectiveness of protected areas and management actions (Camana et al. 2020).

Here, we used a 30-year series of land cover changes to assess the extent to which the Brazilian Pantanal PAs are effective in conserving samples of the natural environment of the Pantanal. We focused on PAs where human land use is not allowed within the reserve. So, we included all four categories under integral protection plus one category for sustainable use (Natural Heritage Private Reserve). Explicitly, we examined (a) whether human-land use occurs within legally defined PAs, (b) how land cover has changed since PAs creation, and (c) compared land cover changes within PAs with outside areas. We hypothesize that there is an increase in the conversion of natural areas to anthropogenic land use because of farming expansion. In addition, wet environments would shrink because of the ongoing climate crisis and weaker environmental controls.

Materials and Methods

Data Compilation

We searched for polygon limits and management information for all Pantanal PAs, available on the Brazilian Environment Ministry website (MMA 2022; see Table S1). We restrained our search to the Brazilian portion of the Pantanal ecoregion because of the availability of land use trajectories. In addition, different legislations cover Bolivian and Paraguayan areas. Our focus was the PAs in which human land use is not allowed. However, there are distinct objectives regarding the administrative categories to which the Pantanal PAs belong. The SNUC classified Brazilian PAs into two main groups: Integral Protection (IPPAs) and Sustainable Use (SUPAs). The IPPA aims to maintain ecosystems free from human interference. So, they are devoted to biodiversity protection, scientific research, and regulated visitation related to tourism or environmental education. By contrast, SUPA aims to explore natural resources, maintaining biodiversity and ecological processes. In practice, land use change and human activities inside SUPAs are very diverse, depending on administrative categories (Brasil 2000). Specifically, the Natural Heritage Private Reserve (Portuguese acronym: RPPN) allows only research, recreational, and tourism activities. As we deal with land use and landscape modification, IPPAs and RPPNs were jointly considered, excluding one SUPA (Baía Negra Environmental Protection Area). Polygon limits were not readily available for some RPPNs, so our final data included 19 PAs (Fig. 1).

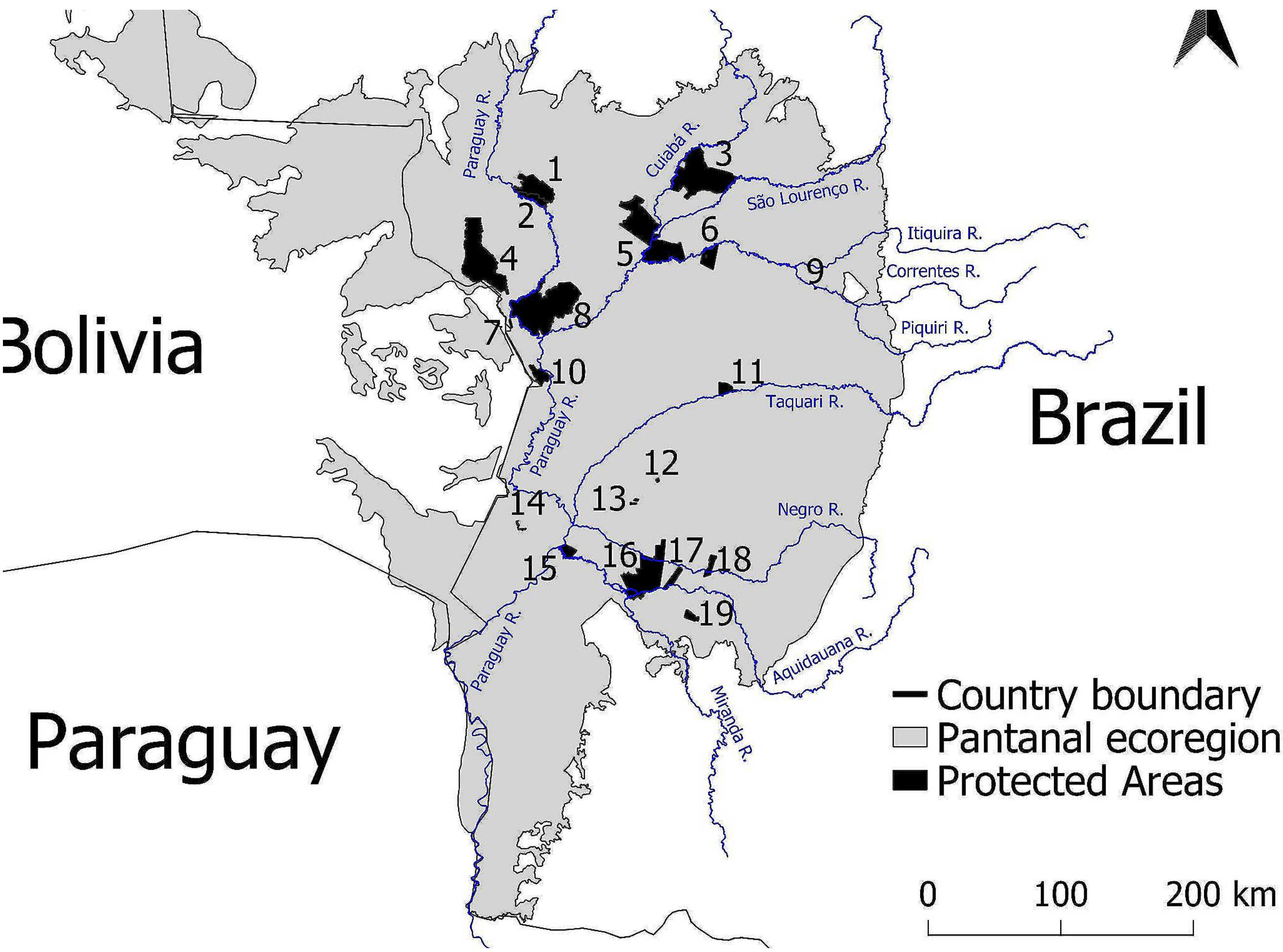

Fig. 1 Limits of the Pantanal ecorregion (light grey) and the location of the Brazilian Protected Areas (black). RPPN: Natural Heritage Private Reserve. 1- RPPN Jubran; 2- Taiamã Ecological Station; 3- RPPN Sesc Pantanal; 4- Guirá State Park; 5- Encontro das Águas State Park; 6- RPPN Poleiro Grande; 7- RPPN Rumo ao Oeste; 8- Pantanal Matogrossense National Park; 9- RPPN Pioneira da Rio Piquiri; 10- RPPN Engenheiro Eliezer Batista; 11- RPPN Fazenda Santa Cecília II; 12- RPPN Fazenda Nhumirim; 13- RPPN Alegria; 14- Piraputangas Municipal Park; 15- RPPN Paculândia; 16- Pantanal do Rio Negro State Park; 17- RPPN Fazenda Santa Sofia; 18- RPPN Fazenda Rio Negro; 19- RPPN Estância Caiman

We used land cover/use maps to evaluate landscape changes between PAs' creation year and the present state. In addition, we established a 10 km buffer from each PA limit to compare trends in the landscape inside and outside PAs. For each PA polygon available and buffer zone, we extracted cover data four times since the creation of the PAs, using Qgis (ver. 3.24). We used five-year intervals for most PAs and ten years for two PAs created before 1990. We did this combination because there was considerable variation among the PAs' creations (1981–2013). Still, three RPPNs (Pioneira do Rio Piquiri, Engenheiro Eliezer Batista, and Alegria) were not evaluated concerning landscape changes because they had less than 15 years. Landscape data were obtained from the MapBiomas Project, collection 7.0 (Project MapBiomas 2022) and corresponded to seven classes (forest, savanna, grassland, wetland, pasture fields, crop/pasture mosaic, and open water). Periodic floods influenced the land cover in the region. So, MapBiomas classified annual mosaics for Pantanal using images in the driest period (May to August). We reclassified the original MapBiomas land cover and land use into three categories: native vegetation cover, human-land use, and open water (river, river channels, lakes, dams, and reservoirs).

Data Analysis

To test landscape changes over the last decades, we used linear mixed-effect models (LMM). We analyzed PAs and buffer zones separately. Models included time-lapse (four levels: creation, T1, T2, and T3) as a fixed effect. As the protected areas differed in size and management, we included the identity of PA as a random effect. So, our model effect included 16 levels of random effect (one for each PA with more than 15 years). We used the Anova function to assess the models' statistical significance and conducted a posthoc test when applicable (Tukey's test with Bonferroni correction). Although we focused on overall native vegetation cover change, we also investigated the temporal variation of each land cover separately (forest, savanna, grassland, and wetland). Analyses were performed in the environment R (R Core Team 2021) using nlme, multcomp, and ggplot2 packages (Hothorn et al. 2008; Pinheiro et al. 2020; Wickham 2016).

Results

Of all 19 analyzed PAs, six belong to the integral protection group and 13 to the sustainable use. Despite being the most frequent PAs in the Pantanal, RPPNs corresponded only to one-third of the total protected areas. Pantanal Matogrossense National Park was the widest PA (136,000 ha), and RPPN Pioneira do Rio Piquiri was the smallest (199 ha). We found only six PAs with management plans (Table S1). Most PAs had more than 80% of the legal area covered by native vegetation between the creation year and 2021 (Table 1). Sixteen PAs gained native vegetation over time, while only three had a decrease. Pantanal Matogrossense National Park

Table 1 Landscape composition recorded within the legal area of 19 Protected Areas in the Brazilian portion of the Pantanal ecoregion. RPPN: Natural Heritage Private Reserve

Protected Area	Native vegetation (%)		Land use (%)		Open Water (%)	
	Creation year	2021	Creation year	2021	Creation year	2021
Taiamã Ecological Station	81.81	94.88			18.17	5.09
Pantanal Matogrossense National Park	46.03	78.32			53.93	21.63
Pantanal do Rio Negro State Park	77.94	98.55			22.06	1.45
Guirá State Park	52.38	81.19			47.62	18.81
Piraputangas Municipal Park	99.37	99.58	0.63	0.42		
Encontro das Águas State Park	98.21	98.27	0.38	0.31	1.41	1.42
RPPN Poleiro Grande	98.88	99.09	0.02	0.06	1.10	0.85
RPPN Rumo ao Oeste	99.98	99.92	0.02	0.08		
RPPN Pioneira do Rio Piquiri	93.61	88.10	0.26	2.71	6.13	9.19
RPPN Engenheiro Eliezer Batista	79.98	84.77			20.02	15.23
RPPN Fazenda Santa Cecília II	85.55	92.67		0.03	14.45	7.30
RPPN Fazenda Nhumirim	87.67	98.20			12.33	1.80
RPPN Fazenda Santa Sofia	93.85	98.75			6.15	1.25
RPPN Fazenda Rio Negro	85.36	95.35			14.64	4.65
RPPN Estância Caiman	99.80	99.72	0.14	0.23	0.06	0.05
RPPN Alegria	99.94	100			0.06	
RPPN Sesc Pantanal	97.98	98.31	0.29	0.06	1.73	1.58
RPPN Jubran	79.53	85.19			20.47	14.10
RPPN Paculândia	97.89	99.18			2.11	0.82

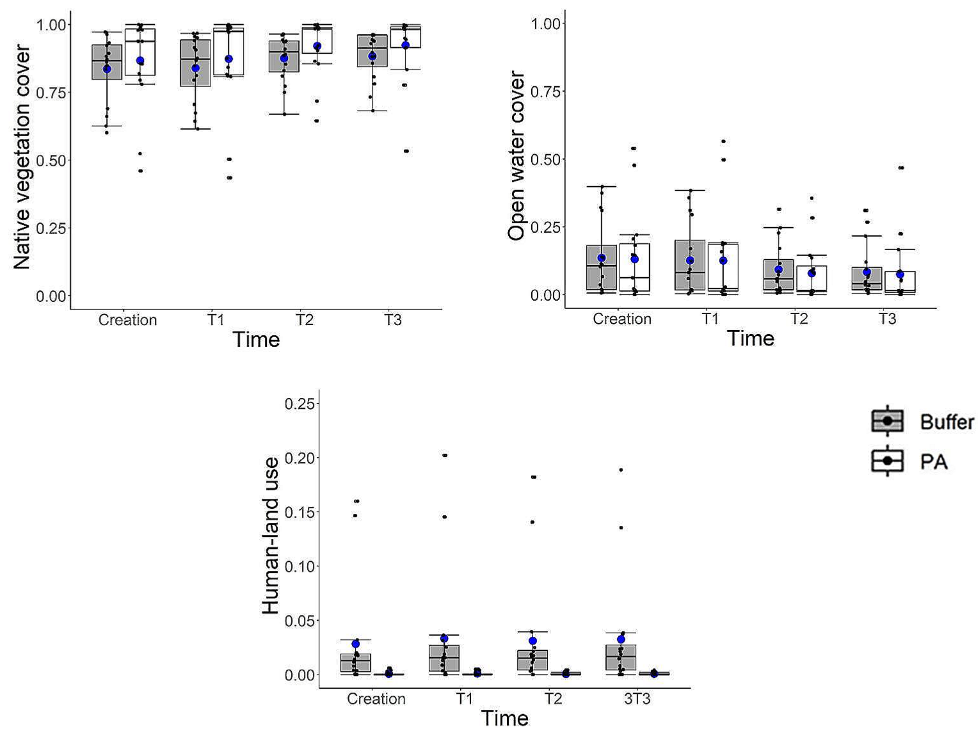

Fig. 2 Temporal changes in land use and land cover in 16 Protected Areas of Brazilian Pantanal and their buffer zones (10 km) in the reserve creation year and three different intervals (see data compilation for details). Blue dots represent mean values

Table 2 Summary of analysis of variance for temporal changes within four land cover from 16 Protected Areas of the Pantanal. See data compilation for details about time intervals

Native cover	Degree of freedom	F-statistic	P value	Significant Pair wise comparisons
Forest	3,45	2.710	0.060	
Savanna	3,45	3.423	0.025	T2- Creation*
Grassland	3,45	5.936	0.002	T2-Creation* T3-Creation** T1-T2* T1-T3**
Wetland	3,45	1.458	0.239	

* $p<0.05$; ** $p<0.01$; *** $p<0.001$

and Guirá State Park exhibited higher increases (33% and 29%, respectively), while RPPN Pioneira do Rio Piquiri exhibited a higher loss (5%). Eight PAs showed human land uses in the legally defined area in 2021 (Table 1). Conversion to pasture fields was the most common land use overall (Figure S1). Most exhibited small land use values (~0.5%, $N=8$) that remained similar since the PA creation.

Three PAs had a decrease in the human land use area over time: Piraputangas Municipal Park, Encontro das Águas State Park, and RPPN SESC Pantanal. Still, reductions were tiny in all three (Table 1). On the other hand, pasture fields increased ten times in the RPPN Pioneira do Rio Piquiri (PA with the higher increase; Table 1). Fifteen PAs had a reduction in the open water cover between the creation year and 2021, with eight of them with values higher than 50%. Encontro das Águas State Park and RPPN Pioneira do Rio Piquiri had a tiny increase in open water cover (Table 1).

Concerning landscape changes inside the PAs, we found temporal variations for native vegetation cover ($F_{3,45}$= 12.63; $p<0.001$) and open water cover ($F_{3,45}$ = 11.94; $p<0.001$). Overall, human land use did not differ across time ($F_{3,45}$ = 1.25; $p=0.302$). We found significantly more native cover vegetation (T2 and T3; pairwise comparison: $p<0.001$) than in the creation year (Fig. 2; see Table S2). Forest and wetland covers did not show temporal changes (Table 2; Fig. 3). Grassland cover increased in the recent period (Fig. 3), while savanna cover showed a modest variation in interval T2 (Table 2). Open water cover decreased in the intervals T2 and T3 compared to the creation year (Fig. 2; Table S2).

We found human land uses in the buffer zone of 15 PAs (Table S3). Concerning landscape changes outside PAs, we found significant variations for native vegetation ($F_{3,45}$= 6.87; $p<0.001$), open water cover ($F_{3,45}=9.102$; $p<0.001$), and human-land use ($F_{3,45}=3.36$; $p=0.03$). Pair-wise differences indicated increases in the native vegetation cover and human-land use (Fig. 2, Table S4). Significant differences were detected only for grassland cover (Table 3; Fig. 3), while the other native covers did not change outside PAs. Open water cover also shrank outside PAs (Fig. 2), where eight areas showed a decrease higher than 50% (Table S4).

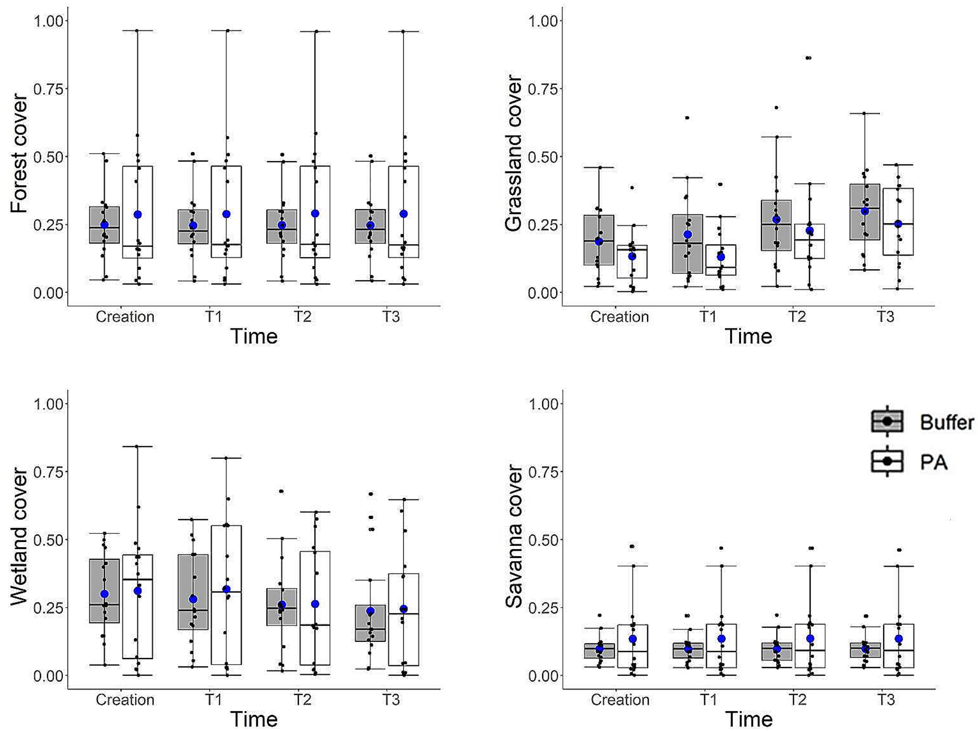

Fig. 3 Temporal changes in native cover in 16 Protected Areas of Brazilian Pantanal and their buffer zones (10 km) in the reserve creation year and three different intervals (see data compilation for details). Blue dots represent mean values

Table 3 Summary of analysis of variance for temporal changes within four land cover from buffer zones (10 km) of 16 Protected Areas of the Pantanal

Native cover	Degree of freedom	F-statistic	P value	Significant Pair wise comparisons
Forest	3,45	2.420	0.08	
Savanna	3,45	0.774	0.51	
Grassland	3,45	5.926	0.002	T3-Creation** T1-T3**
Wetland	3,45	1.525	0.220	

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Discussion

In line with evidence for protected areas (Maiorano et al. 2008; Nagendra 2008; Bailey et al. 2016), our results showed that most Pantanal PAs are effective at safeguarding natural environments from intensive land use. Although there was little human land use within the protected area, the land cover trajectories did not indicate trends similar to landscape conversion outside the PA. Still, the human land use in reserves where it is not allowed indicates management issues and low law enforcement. We also detected a significant shrinking of the open-water cover within and around the legally protected areas. The SNUC law establishes that PAs must have a management plan within five years of their creation. However, our results show that less than half of PAs in the Pantanal have management plans. Therefore, we should take drying conditions and the presence of livestock pastures as warning signs for current and future issues.

We now recognize that human pressures on PAs depend on the regional context, with PA size and land-use intensification in the non-protected landscape playing major roles (e.g., Maiorano et al. 2008; Nagendra 2008; Ribeiro et al. 2021). Concerning Brazilian PAs, managers often overlook objectives related to conservation in the Sustainable-Use PAs (ICMBio and WWF-Brasil 2011). Here, we found degraded areas within Private and Public reserves that did not show cover changes in at least 20 years. One can argue that such areas might be pastures abandoned by landowners for conservation purposes. Natural regeneration occurs in some areas, even though abandoned pasture fields might not return to an old-growth savanna state or native grassland (Cava et al. 2018). Either abandoned ones or currently in use, our result highlights a need for active restoration of these pasture fields that conflict with the main objectives of PAs. Indeed, a focus is needed on specific activities to manage and monitor each different protected area. Assessments of landscape restoration in PAs and the effects of protected area systems on ecosystem restoration are scarce and often focused on forest environments (Andam et al. 2013; De Matos et al. 2021). Grassy ecosystems, the dominant vegetation type in the Pantanal, have historically been neglected in conservation and restoration agendas (Török et al. 2021; Overbeck et al. 2022). Still, grassland cover showed the most pronounced increase (in the PAs polygons and buffer zones) among the native cover investigated. Although we found small portions of pasture fields in PAs, our results may be conservative because native grassland areas also harbor extensive cattle farming in the Pantanal. So, the pressure of cattle farming on Pantanal PAs might be the lower bound of the current reality.

Our study evidenced that forest, savanna, and wetland covers have remained relatively stable since the PA creation. Such a trend was not different from the land-cover change surrounding PAs. That is a positive aspect considering some ecosystem services related to habitat mosaics (e.g., climate regulation, carbon capture and storage, erosion control, nutrient cycling, and soil formation; Costanza et al. 2014). In addition, such wet-dry mosaics favor distinct elements of the Pantanal fauna, such as the lowland tapir, marsh deer, and yellow anaconda (Tomas et al. 2001; Trolle et al. 2008; Smaniotto et al. 2020). However, the mosaic balance would be compromised in the following decades with the shrinking of rivers and other water bodies. There is a growing consensus that a protection network must include management actions in the non-protected surroundings of the PAs (Maiorano et al. 2008; Acreman et al. 2020). Such an integrated network is of paramount importance, mainly for freshwater biodiversity, because pressures on aquatic habitats (water abstraction, river regulation, pollution, exploitation of species) are symptoms of a vast dendritic network outside PA boundaries (Azevedo-Santos et al. 2019; Acreman et al. 2020). Identifying weak points in the Pantanal network is tough because drought events result from regional climate changes and human land use in the Pantanal and surrounding plateaus (Marengo et al. 2021; Hofmann et al. 2021).

Recurrent events of drought and heatwaves have captured the public's attention in central-eastern Europe (Drumond et al. 2017), central South America (Arias et al. 2024), and South Asia (Aadhar and Mishra 2023). Although these climate extremes pose severe environmental and economic challenges, regional climate is critically affected by land use type (Foley et al. 2005; Jia et al. 2022). Since we have no control over large-scale climate, we must focus more on mitigating regional climate from a land use perspective. Highland land uses in the Upper Paraguay River Basin influence Pantanal aquatic habitats (Roque et al. 2016). At the same time, river fragmentation by dams has shown synergetic effects with climate change in the region (Peluso et al. 2022). To address the relative impact of different factors (land use, extreme climate, hydropower dams) is beyond the scope of the present study. However, our results for the water cover and the human-land use in the buffer zones reinforced the need to pay more attention to processes operating at regional scales.

Our research showed that human use remained constant within the PAs. In addition, of all eight PAs with human land use, only two had a management plan, and data on another eight private PAs were unavailable. Terrestrial environments within most Pantanal PAs still stand to human interventions. Unfortunately, aquatic environments' protection is more challenging, depending on actions at lowlands and surrounding plateaus that harbor the headwaters. In the case of Pantanal, legislation at the state level still has limited reach in safeguarding entire river basins. In addition, the regulation of artificial drainage of wetlands is under discussion in the Mato Grosso. After drainage liberation at the end of 2022, further debate on the controversial aspects led the State Public Ministry to request the bill annulment. Since then, the State Public Ministry has already expressed concern about hydric security in the version presented by the State Environmental Council. Wetland drainage is discouraged on a technical and scientific basis (Nunes da Cunha et al. 2018). Brazil is one of the countries that committed to elaborating a Strategic Plan for Biodiversity and among the goals are: (i) to reduce deforestation in the Pantanal, (ii) increase the protected territory by PAs to 17%, and (iii) manage effectively 100% of the PAs (Aichi Targets; UICN 2011). So, we strongly advocate a Pantanal federal legislation that focuses not only on regulating economic activities but also on safeguarding local and regional habitat mosaics within and around PAs to connect the diverse elements of the waterscape and maintain their biodiversity. Ideally, these regulations should also avoid social impacts related to indigenous and traditional populations.

Several interests are at stake, so the first step should be planning the management of all current PAs. After that, unquestionably, Pantanal needs more PAs (both public and private). It would be instructive to focus on the freshwater environments of surrounding plateaus and unique mosaics in the lowlands. Because forecasts indicate an even dryer Pantanal, the creation and management of protected areas need to be well integrated– ideally in networks–in the regional planning of Midwestern Brazil.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13157-024-01800-z.

Acknowledgements NPS, FC, FMQ and LFBM are supported by a fellowship from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (PCI-DC # 301284/2023-7; PCI-DA # 301260/2023-0; PCI-DA # 301265/2023-2; PCI-DB # 300912/2022-6). TBFS is supported by fellowship from the Portuguese Foundation for Science and Technology (FCT), under scholarship number 202210212BD.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Natália P. Smaniotto, Leonardo F.B. Moreira, Fernando Carvalho, Yulie Shimano, Thiago B.F. Semedo, Fernando M. Quintela, and Andre V. Nunes. The first draft of the manuscript was written by Natália P. Smaniotto, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding NPS, FC, FMQ and LFBM are supported by a fellowship from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) (PCI-DC # 301284/2023-7; PCI-DA # 301260/2023-0; PCI-DA # 301265/2023-2; PCI-DB # 300912/2022-6). TBFS is supported by fellowship from the Portuguese Foundation for Science and Technology (FCT), under scholarship number 202210212BD.

Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

References

Aadhar S, Mishra V (2023) The 2022 mega heatwave in South Asia in the observed and projected future climate. Environ Res Lett. https://doi.org/10.1088/1748-9326/acf778

Acreman M, Hughes KA, Arthington AH et al (2020) Protected areas and freshwater biodiversity: a novel systematic review distils eight lessons for effective conservation. Conserv Lett 13:1–14. https://doi.org/10.1111/conl.12684

Andam KS, Ferraro PJ, Hanauer MM (2013) The effects of protected area systems on ecosystem restoration: a quasi-experimental design to estimate the impact of Costa Rica's protected area system on forest regrowth. Conserv Lett 6:317–323. https://doi.org/10.1111/conl.12004

Arias PA, Rivera JA, Sörensson AA et al (2024) Interplay between climate change and climate variability: the 2022 drought in Central South America. Clim Change 177:1–22. https://doi.org/10.1007/s10584-023-03664-4

Azevedo-Santos VM, Frederico RG, Fagundes CK et al (2019) Protected areas: a focus on Brazilian freshwater biodiversity. Divers Distrib 25:442–448. https://doi.org/10.1111/ddi.12871

Bailey KM, McCleery RA, Binford MW, Zweig C (2016) Land-cover change within and around protected areas in a biodiversity hotspot. J Land Use Sci 11:154–176. https://doi.org/10.1080/1747423X.2015.1086905

Ballut-Dajud GA, Herazo LCS, Fernández-Lambert G et al (2022) Factors affecting wetland loss: a review. Land 11:434. https://doi.org/10.3390/land11030434

Bonanomi J, Tortato FR, Gomes R, de SR et al (2019) Protecting forests at the expense of native grasslands: land-use policy encourages open-habitat loss in the Brazilian cerrado biome. Perspect Ecol Conserv 17:26–31. https://doi.org/10.1016/j.pecon.2018.12.002

Brasil (2000) Lei Federal N° 9985. Regulamenta o art. 225, § 1°, incisos I, II, III e VII Da Constituição Federal, institui o Sistema Nacional De Unidades De Conservação Da Natureza E dá outras providências. Ministério do Meio Ambiente

Camana M, Dala-Corte RB, Collar FC, Becker FG (2020) Assessing the legacy of land use trajectories on stream fish communities of southern Brazil. Hydrobiologia 839:441–446. https://doi.org/10.1007/s10750-020-04347-2

Carnicer J, Alegria A, Giannakopoulos C et al (2022) Global warming is shifting the relationships between fire weather and realized fire-induced CO_2 emissions in Europe. Sci Rep 12:8–13. https://doi.org/10.1038/s41598-022-14480-8

Cava MGB, Pilon NAL, Ribeiro MC, Durigan G (2018) Abandoned pastures cannot spontaneously recover the attributes of old-growth savannas. J Appl Ecol 55:1164–1172

Costanza R, de Groot R, Sutton P et al (2014) Changes in the global value of ecosystem services. Glob Environ Chang 26:152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

De Matos TPV, De Matos VPV, De Mello K, Valente RA (2021) Protected areas and forest fragmentation: sustainability index for prioritizing fragments for landscape restoration. Geol Ecol Landscapes 5:19–31. https://doi.org/10.1080/24749508.2019.1696266

Dick M, Silva MA, Silva RRF et al (2021) Environmental impacts of Brazilian beef cattle production in the Amazon, Cerrado, Pampa, and Pantanal. J Clean Prod 311:127750

Drumond A, Gimeno L, Nieto R et al (2017) Drought episodes in the climatological sinks of the Mediterranean moisture source: the role of moisture transport. Glob Planet Change 151:4–14. https://doi.org/10.1016/j.gloplacha.2016.12.004

Ferreira MN, Freire N (2009) Community perceptions of four protected areas in the Northern portion of the Cerrado hotspot, Brazil. Environ Conserv 36:129–138

Fluet-Chouinard E, Stocker BD, Zhang Z et al (2023) Extensive global wetland loss over the past three centuries. Nature 614:281–286. https://doi.org/10.1038/s41586-022-05572-6

Foley JA, DeFries R, Asner GP et al (2005) Global consequences of land use. Science 309:570–574. https://doi.org/10.1126/science.1111772

Fowler HJ, Wasko C, Prein AF (2021) Intensification of short-duration rainfall extremes and implication for flood risk: current state of the art and future directions. Philos Trans R Soc Math 379:2195. https://doi.org/10.1098/rsta.2019.0541

Garcia AS, Sawakuchi HO, Ferreira ME, Ballester MVR (2017) Landscape changes in a neotropical forest-savanna ecotone zone in central Brazil: the role of protected areas in the maintenance of native vegetation. J Environ Manage 187:16–23. https://doi.org/10.1016/J.JENVMAN.2016.11.010

Girardi EP, Rossetto OC (2011) Análise Da pecuária no Pantanal Mato-Grossense. Rev Geográfica América Cent 47:1–16

Gonçalves-Souza D, Vilela B, Phalan B, Dobrovolski R (2021) The role of protected areas in maintaining natural vegetation in Brazil. Sci Adv 7:2932–2949

Goulart HMD, Wiel K, Folberth C et al (2021) Weather-induced crop failure events under climate change: a storyline approach. Earth Syst Dyn 12:1503–1527. https://doi.org/10.5194/esd-12-1503-2021

Hofmann GS, Cardoso MF, Alves RJV et al (2021) The Brazilian Cerrado is becoming hotter and drier. Glob Chang Biol 27:4060–4073. https://doi.org/10.1111/gcb.15712

Hothorn T, Bretz F, Westfall P (2008) Simultaneous inference in general parametric models. Biometrical J 50:346–363

ICMBio WWF-B (2011) Efetividade De gestão as unidades de conservação federais: Avaliação comparada das aplicações do método Rappam Nas unidades de conservação federais, nos ciclos 2005-06 e 2010. ICMBio, Brasília

ICMBio (2018) Livro Vermelho Da Fauna Brasileira Ameaçada De Extinção. Volume II - Mamíferos

Jia S, Yang C, Wang M, Failler P (2022) Heterogeneous impact of land-use on climate change: study from a spatial perspective. Front Environ Sci 10:1–17. https://doi.org/10.3389/fenvs.2022.840603

Laurance WF, Carolina Useche D, Rendeiro J et al (2012) Averting biodiversity collapse in tropical forest protected areas. Nature 489:290–293. https://doi.org/10.1038/nature11318

Maiorano L, Falcucci A, Boitani L (2008) Size-dependent resistance of protected areas to land-use change. Procedings R Soc B 275:1297–1304. https://doi.org/10.1098/rspb.2007.1756

Marengo JA, Cunha AP, Cuartas LA et al (2021) Extreme drought in the Brazilian pantanal in 2019–2020: characterization, causes,

and impacts. Front Water 3:639204. https://doi.org/10.3389/frwa.2021.639204
Mato Grosso do Sul (2015) DL 14273. http://www.imasul.ms.gov.br
Mato Grosso (2022) PL #561/2022. http://www.al.mt.gov.br
McDonald RI, Mansur AV, Ascensão F et al (2019) Research gaps in knowledge of the impact of urban growth on biodiversity. Nat Sustain 2019 31 3:16–24. https://doi.org/10.1038/s41893-019-0436-6
MMA (2022) Ministério do Meio Ambiente - Departamento de Áreas Protegidas. https://dados.mma.gov.br/dataset/unidadesdeconservacao. Accessed 10 Aug 2022
Molotoks A, Stehfest E, Doelman J et al (2018) Global projections of future cropland expansion to 2050 and direct impacts on biodiversity and carbon storage. Glob Chang Biol 24:5895–5908. https://doi.org/10.1111/GCB.14459
Nagendra H (2008) Do parks work? Impact of protected areas on land cover clearing. Ambio 37:330–337. https://doi.org/10.1579/06-R-184.1
Nunes da Cunha C, Junk WJ, Paixão E, Arruda EC (2018) Recomendação técnica n°01/2018/INCT-INAU. Cuiab&#225
Overbeck GE, Vélez-Martin E, Menezes LS et al (2022) Placing Brazil's grasslands and savannas on the map of science and conservation. Perspect Plant Ecol Evol Syst 56:125687. https://doi.org/10.1016/j.ppees.2022.125687
Peluso LM, Mateus L, Penha J et al (2022) Climate change negative effects on the neotropical fishery resources may be exacerbated by hydroelectric dams. Sci Total Environ 828:154485. https://doi.org/10.1016/j.scitotenv.2022.154485
Pinheiro J, Bates D, DebRoy S, Sarkar D (2020) nlme: Linear and Nonlinear Mixed Effects Models
Project MapBiomas (2022) Collection 7 of Brazilian Land Cover & Use Map Series. mapbiomas.org. Accessed 24 Sep 2022
Quigley HB, Crawshaw PG (1992) A conservation plan for the jaguar *Panthera onca* in the Pantanal region of Brazil. Biol Conserv 61:149–157. https://doi.org/10.1016/0006-3207(92)91111-5
R Core Team (2021) R: a language and environment for statistical computing. R Found Stat Comput 1
Ribeiro S, Moreira LFB, Overbeck GE, Maltchik L (2021) Protected areas of the Pampa biome presented land use incompatible with conservation purposes. J Land Use Sci 16:260–272. https://doi.org/10.1080/1747423X.2021.1934134
Rodrigues FHG, Medri ÍM, Tomas WM, de Mourão G M (2002) Revisão do conhecimento sobre ocorrência e distribuição de Mamíferos do Pantanal. Embrapa, Corumbá
Roque FO, Ochoa-Quintero J, Ribeiro DB et al (2016) Upland habitat loss as a threat to Pantanal wetlands. Conserv Biol 30:1131–1134. https://doi.org/10.1111/cobi.12713
Smaniotto NP, Moreira LFB, Rivas JA, Strüssmann C (2020) Home range size, movement, and habitat use of yellow anacondas. Salamandra 56:159–167
Tomas WM, Salis SM, Silva MP, Miranda Mourão G (2001) Marsh deer (*Blastocerus dichotomus*) distribution as a function of floods in the Pantanal wetland, Brazil. Stud Neotrop Fauna Environ 36:9–13. https://doi.org/10.1076/snfe.36.1.9.887
Tomas WM, Timo TPDC, Camilo AR et al (2022) Primatas ocorrentes na Bacia do Alto Paraguai E Pantanal, Brasil. Bol do Mus Para Emílio. Goeldi - Ciências Nat 17:701–724. https://doi.org/10.46357/bcnaturais.v17i3.882
Török P, Brudvig LA, Kollmann J et al (2021) The present and future of grassland restoration. Restor Ecol 29:1–6. https://doi.org/10.1111/rec.13378
Trolle M, Noss AJ, Cordeiro JLP, Oliveira LFB (2008) Brazilian tapir density in the Pantanal: a comparison of systematic camera-trapping and line-transect surveys. Biotropica 40:211–217. https://doi.org/10.1111/j.1744-7429.2007.00350.x
UICN WWF-BRASIL, IPÊ (2011) Metas De Aichi. Situação atual no Brasil
Wickham H (2016) ggplot2: elegant graphics for data analysis. Springer-, New York

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.