Vol. 66, p. 243-265, jul./dec. 2025. DOI: 10.5380/dma.v66i.95152 e-ISSN 2176-9109

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Landscape transition predictive model: Piraputanga River Watershed

Modelo preditivo de transição da paisagem: bacia hidrográfica do Piraputanga

Thiago Ferreira PEREIRA[1*], Beatriz Ferraz BUHLER[2], Sandra Mara Alves da Silva NEVES[1], Wilkinson Lázaro LOPES[1], Claumir Cesar MUNIZ[1], Ernandes Sobreira OLIVEIRA JUNIOR[1]

[1] Universidade Estadual de Mato Grosso (UNEMAT), Cáceres, MT, Brasil.

[2] Secretaria de Estado da Educação de Mato Grosso (SEDUC – MT), Cáceres, MT, Brasil.

[*] Contact e-mail: thiago.ferreira@unemat.br

Article received on April 11, 2024; final version accepted on March 31, 2025, published on September 23, 2025.

ABSTRACT The theme of Ecosystem Services (ES) has been the focus of several authors and is conceptualized as the processes through which natural ecosystems sustain human life. ES are divided into four classes: provisioning, regulating, supporting, and cultural. Environmental transformations, such as deforestation or degradation, directly compromise ES. Therefore, the main objective of this study was to analyze the impact of environmental transformations on changes in the natural landscapes of the Piraputanga River Watershed (PRW). Data related to land use and land cover, deforestation, and loss of water surface were obtained from the MapBiomas project, and fire data were obtained from the INPE platform. To classify the degree of landscape transformation, the degree of hemeroby was used in conjunction with a model based on linear trend analysis with Monte Carlo simulations. The analyses show trends in the conversion of natural areas, such as forest and savanna formations, to agricultural and pasture uses, which in 2022 represented 40.51% of the area, equivalent to 67.74 km². There was a 40% decline in water surface area. In contrast, there was an increase in pasture areas (155%) and the number of fires (163%). The projections showed a decrease in water availability, an increase in deforestation, and expansion of pasture areas. Estimates indicate that water resources in the region will disappear by 2067, a period during which the forest will be almost completely extinct due to increased agricultural activity. It is important to highlight the need for public policies to mitigate these impacts. This work highlights the landscape transition process, which is still classified as mesohemerobiotic hemerobiosis. However, all results indicate a marked process of change, and measures must be taken to prevent the situation from worsening. The transition process in the region involves trends that affect biodiversity and the capacity of ecosystems to provide essential environmental services. Finally, future projections raise concerns regarding the loss of water resources as a crucial factor.

Keywords: ecosystem services; landscape transformation; environmental impact.

RESUMO

A temática Serviços Ecossistêmicos (SE) tem sido alvo de diversos autores, sendo conceituado como os processos em que os ecossistemas naturais sustentam a vida humana. Os SE são divididos em quatro classes: provisão, regulação, suporte e cultural. As transformações ambientais, como o desmatamento ou a degradação, comprometem diretamente os SE. Diante disso, o objetivo central deste trabalho foi analisar o impacto das transformações ambientais na mudança das paisagens naturais da Bacia Hidrográfica do Córrego Piraputanga (BHCP). Dados referentes ao uso e à cobertura da terra, ao desmatamento e à perda de superfície de água disponíveis foram tomados no MapBiomas, e dados de queimadas disponíveis na plataforma INPE. Para classificação do grau de transformação da paisagem utilizou-se o grau de hemerobia em conjunto com modelo baseado na tendência linear com simulações Monte-Carlo. As análises evidenciam tendências de conversão de áreas naturais, como formações florestais e savânicas, para usos agrícolas e de pastagem, que em 2022 representaram 40,51 % da área equivalente a 67,74 km². Houve queda na superfície de água em 40%, contrastando o aumento de áreas de pastagem (155 %) e número de queimadas 163 %. As projeções realizadas demonstraram diminuição na quantidade de água, aumento do desmatamento e de áreas de pastagem. Isso indica que a quantidade de água na região chegará a desaparecer em 2067, período em que a floresta estará quase toda extinta devido ao aumento da atividade agropecuária. É importante destacar a necessidade de políticas públicas para a atenuação dessas observações. Este trabalho evidencia o processo de transição da paisagem, que ainda está classificado como grau de hemerobia mesohemerobiótico. Entretanto, todos os resultados indicam que há um processo de alteração acentuado, e que medidas devem ser tomadas para que a situação não se agrave. O processo de transição na região são tendências que afetam a biodiversidade e a capacidade dos ecossistemas de fornecer serviços ambientais essenciais. Por fim, as projeções futuras elevam preocupações considerando a perda dos recursos hídricos como fator crucial.

Palavras-chave: serviços ecossistêmicos; transformação da paisagem; impacto ambiental.

1. Introduction

The concept of ecosystem services is based on the processes by which ecosystems sustain human life, ensuring well-being while maintaining biodiversity and the production of ecosystem goods (Daily *et al.*, 1997). The human population can benefit directly or indirectly from ecosystem services and functions, such as food (ecosystem goods) and waste assimilation (service) (Costanza *et al.*, 1997). In addition to these, another 17 renewable ecosystem functions and services are described by these authors. However, Groot *et al.* (2002) reformulated the framework of ecosystem functions and services by classifying them according to ecosystem functions, goods, and services assigned to natural systems in a renewable manner.

Over the past two decades, ecosystem services have been the focus of numerous studies. Since then, various authors have addressed different concepts of services provided by ecosystems. All these concepts converge on a central point: natural ecosystems are fundamental in supporting and promoting human well-being (Mengist *et al.*, 2020; Torres *et al.*, 2021; Aryal *et al.*, 2022). Between 2001 and 2005, the

Millennium Ecosystem Assessment was conducted with the main objective of evaluating changes in services provided by the environment/ecosystem for human well-being, considering conservation and sustainable use actions (MEA, 2005).

Human activities are not dissociated from the natural resources provided by nature; on the contrary, according to the report *The Economics of Ecosystems & Biodiversity* (TEEB, 2010), they are increasingly dependent on ecosystem services such as energy, raw materials, housing, food, among other services. According to MEA (2005), ecosystem services are divided into four classes:

i. provisioning services, which include those directly related to benefits for the population, such as food, timber, water, and fibers;

ii. regulating services, which influence the natural regulation of the environment, such as the hydrological cycle, air and climate quality, flood and disease control, among other aspects;

iii. cultural services, such as tourism, spiritual, and educational values;

supporting services, which refer to services that support other ecosystem services, mostly contributing indirectly and in the long term to society, including nutrient cycling, photosynthesis, soil maintenance, and fertilization (Parron *et al.*, 2015).

In TEEB (2010), there is a valuation assigned to tropical forest ecosystem services for timber provision in Cameroon, for example, amounting to US$ 560 per ha/year, while climate regulation was valued between US$ 842–2,265 per ha/year and hydrological regulation at US$ 24 per ha/year. In this context, the estimated valuation through the conservation of protected areas in the Amazon would be US$ 46 per ha/year, according to the report.

Within the category of ecosystem services, there are water-related ecosystem services, which are responsible for maintaining and ensuring water security for society (Schuler *et al.*, 2017; Sharma *et al.*, 2024). Since the 1990s, various authors, including educational institutions, government organizations, and national agendas, have defined the concept of water security as access to and availability of water to support both human health and the environment (Cook & Bakker, 2012), as evidenced by Ruscheinsky *et al.* (2018), who showed the chronological evolution of the concept between 1999 and 2013. In 2000, a notable highlight was the Global Water Partnership (GWP, 2000), which defined water security as the sustainable use and protection of water resources to ensure people's health and well-being. UN-WATER (2013) defines water security as the population's capacity to safeguard the quantity and quality of water for sustenance, well-being, and socioeconomic development, while ensuring ecosystem preservation against water pollution.

According to the classification of ecosystem service functions, water provisioning in streams, lakes, and aquifers occurs naturally in ecosystems with regular water distribution, such as maintaining irrigation and drainage, where vegetation cover plays an important role in water filtration, and water retention and storage also occur through the soil surface (Groot *et al.*, 2002; Costa *et al.*, 2022). Water supply contributes to society's quality of life, encompassing benefits such as water provisioning for extractive activities, mitigation of water-related damage, cultural services, and ecosystem support services (Brauman *et al.*, 2007; Chen & Vardon, 2024). Another important factor regarding hydrological services provided by ecosystems is their contribution to biological balance and the conservation of living species in the environment (Machado & Pacheco, 2010; Chaiyarat *et al.*, 2024).

The preservation of riparian forests plays a significant role in water contribution within a watershed (Aguiar *et al.*, 2024). Additionally, the conservation of riparian vegetation helps mitigate pollution in headwater rivers (Turunen *et al.*, 2021). Forest systems are essential for the provision of ecosystem services in supporting and maintaining forest structure, such as species richness within forest and aquatic ecosystems (Azevedo, 2012; Pessoa *et al.*, 2025).

When an environment is degraded or deforested, the ecosystem services provided by the environment are compromised, such as the reduction in carbon storage (Eguiguren *et al.*, 2019; Qu *et al.*, 2024). According to the report published by TEEB (2010), the accumulated estimated value of reducing greenhouse gas (GHG) emissions through the conservation of global forests by 2030 amounts to US$ 3.7 billion. It is important to emphasize that forests, from the perspective of ecosystem services, also stand out for their cultural services, being non-material benefits linked to society, where forest biodiversity is associated with social and economic services, such as assigning natural heritage value, among other factors (Azevedo, 2012; Derek *et al.*, 2025).

A robust methodology to compare the effect of the degree of human impact on landscape change at both national and regional levels over time is through hemeroby indicators (Walz & Stein, 2014). The authors highlight the use of hemeroby to assess the state of the landscape (natural ecosystems) as a function of human impacts (anthropogenic activities) across different periods. Other studies highlight the use of hemeroby to assess the impacts of anthropogenic actions on landscape change and the loss of environmental quality in watersheds (Freitas & Carvalho, 2008; Gusmão *et al.*, 2021). The classification of the degree of human impact based on hemeroby indices is presented in Table 1.

The loss of forest systems contributes to the reduction of environmental quality in watersheds, consequently leading to the reduction of ecosystem services (Trevisan, 2020). Thus, the Piraputanga River Watershed (PRW) in Cáceres - MT plays an essential role in the provision of ecosystem services, standing out for its rich environmental diversity, covering the Cerrado biome with forest, grassland, and savanna formations (Ribeiro & Valter, 1998). Beyond its ecological importance, the PRW region contributes significantly to cultural services, promoting tourism and recreational activities. Sustainable management and preservation are imperative to ensure the vitality of this ecosystem (Souza & Sousa, 2014; Tavares *et al.*, 2021).

Given this scenario, the present study aims to analyze the impact of environmental transformations on the natural landscape changes of the Piraputanga River Watershed from 1985 to 2022. This work is aligned with the Sustainable Development Goals (SDGs) (UN, 2015), particularly SDG 15 – Life on Land, which seeks to protect, restore, and promote the sustainable use of terrestrial ecosystems, manage forests sustainably, combat desertification, halt and reverse land degradation, and halt biodiversity loss. The hypothesis suggests that anthropogenic alterations in the watershed have increased over time (deforestation and fires), resulting in the loss of surface water area, leading

TABLE 1 – Classification system for the degree of hemeroby.

Hemerobic Classification	Land use and land cover classes	Numerical scale	Human Impact
Ahemerobiotic	Rocks, glaciers and perpetual snow	1	Almost none
Oligohemero-biotic	Broadleaf, coniferous and mixed forests, beaches, dunes, sand, Inland wetlands, peat bogs, salt pans, coastal lagoon, intertidal flats, estuaries, sea and ocean	2	Low
Mesohemero-biotic	Natural pastures, shrubland, sparse vegetation area, and burned area	3	Moderate
β - euhemero-biotic	Urban green area, pastures, agriculture, watercourses and water bodies	4	Moderately Strong
α - euhemero-biotic	Sports and leisure facilities, non-irrigated arable land, vine-yards, fruit trees and berry plantations, and complex cultiva-tion patterns	5	Strong
Polihemero-biotic	Discontinuous urban fabric, extraction sites, dump sites, and construction sites	6	Very Strong
Metahemero-biotic	Continuous urban fabric, industrial or commercial units, highways, railways, port zones, and airports	7	Excessively Strong

SOURCE: Walz & Stein, 2014.

to a greater degree of hemeroby due to reduced environmental quality. Furthermore, it is believed that changes in this watershed could lead to drastic alterations over the next 40 years, with increased deforestation and agricultural activities and the depletion of water resources if no environmental action is taken.

2. *Methodology*

2.1. Study area

The PRW (Piraputanga River Watershed) is located in the municipality of Cáceres, state of Mato Grosso, situated at coordinates 16° 3’ 41.904” S and 57° 34’ 35.436” W, covering an area of 170 km². The watershed comprises 96.22% Cerrado phytophysiognomies and 3.78% Pantanal (Ramos

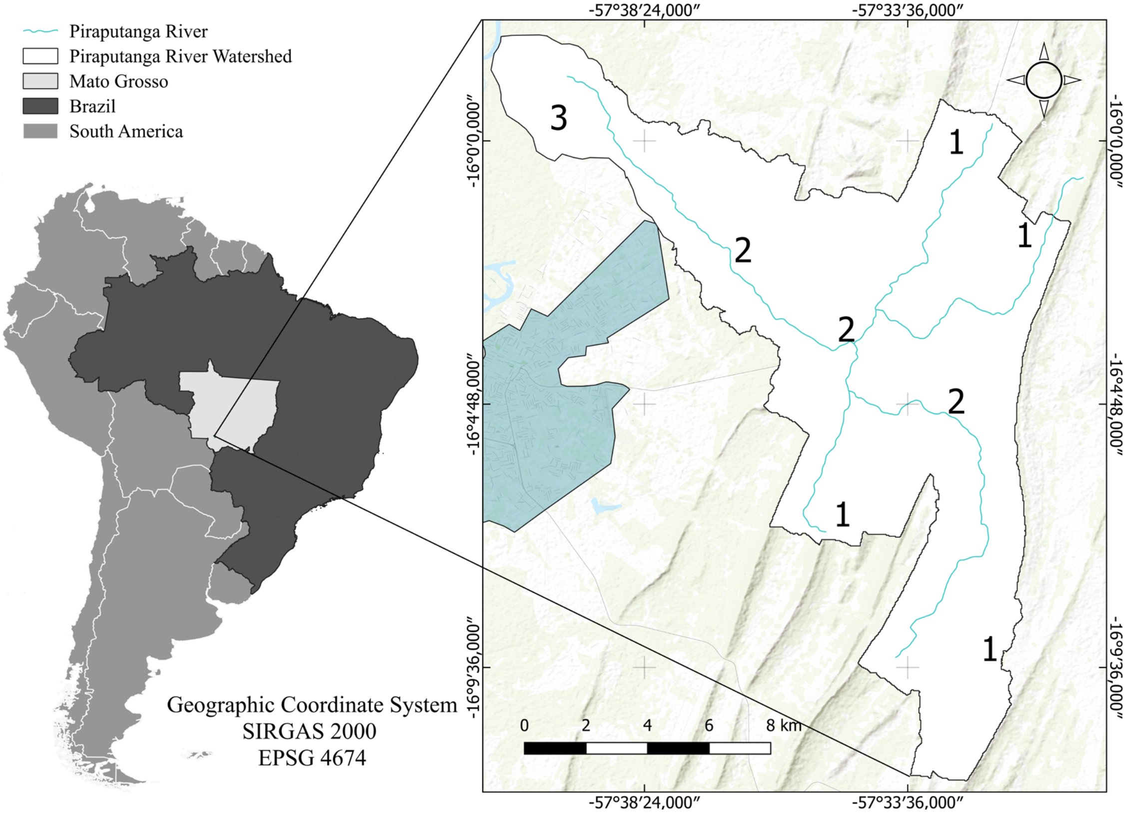

FIGURE 1 – Piraputanga river Watershed, Cáceres-MT. Data collection sites distributed along the river, where the sampling points are divided into Headwaters (1), Course (2), and Mouth (3).

SOURCE: Authors (2024).

et al., 2018) (Figure 1). Its headwaters are diffuse and located in the mountainous province (headwater 1 – 16° 8' 13.58" S and 57° 32' 12.81" W; headwater 2 – 16° 4' 55.09" S and 57° 33' 57.04" W), and its waters flow into the left bank of the Paraguay River (16° 1' 33.69" S and 57° 37' 30.68" W) (Rodrigues *et al.*, 2021). The predominant soil is red-yellow argisol, with texture ranging from fine to coarse sand. Fluvial dynamics are influenced by bank erosion processes, resulting in heterogeneous watercourses, which can be perennial or intermittent (Souza & Sousa, 2014).

2.2. Environmental transformations

To better understand the effects of environmental transformations within the PRW, the data were divided into four main topics. In this sense, data were gathered regarding:

i. land use and land cover,
ii. deforestation,
iii. surface water, and
iv. wildfires.

These topics aimed to assess the degree of impact in the region caused by environmental transformations.

The database related to vegetation cover and land use, deforestation, and surface water was provided by the MapBiomas project platform (MapBiomas, ©2024) and served as the foundation for this research. Accordingly, a 37-year historical series (1985–2022) was generated using collection 08 of vegetation cover and land use data to analyze the reduction in ecosystem services within the watershed and to demonstrate environmental transformations and natural landscape conservation status. The raster images used to generate maps and hierarchical legend were obtained from Landsat 8 satellite imagery (OLI sensor) with a spatial resolution of 30 m. These data were acquired and processed through the Google Earth Engine® platform, made available by MapBiomas. The cartographic representation scale adopted in this study was 1:200,000.

Watershed maps and spatial analyses were elaborated using Quantum GIS (QGIS©). The land cover and land use legend was defined according to the fourth categorical level provided by the MapBiomas project, which incorporates classification classes from other systems (FAO, IBGE, and GEE).

Graphs were created to explore data related to deforestation, surface water area, and wildfires. Deforestation and water surface data were acquired through the MapBiomas platform, which utilizes Google Earth Engine technology. Wildfire data were retrieved from the National Institute for Space Research (INPE) platform. For wildfire and surface water analyses, the historical series from 1987 to 2021 was considered.

Wildfire data from 2020 differed significantly from previous years and were considered outliers; therefore, these data were excluded from statistical analyses following removal through the Dixon test. Fire occurrence records were available only from 1998 to 2022 due to limited data availability for earlier years.

To complement land use and land cover data and assess impacts within the watershed, the hemeroby index was employed to quantify the extent of landscape transformation. This methodology assesses the degree of environmental impact in the study area and was defined based on Walz & Stein (2014), with adaptations. Table 1 provides a detailed overview of the landscape hemeroby scale system from the literature.

Scale 1 is defined by regions of glaciers, rocks, and snow. These environments have virtually no human impact. In this study, the Ahemerobiotic classification (Scale 1) was not observed. Scale 2 is characterized by a low degree of human impact, in which the following land cover and land use classes were included: Forest Formation, Savanna Formation, Grassland Formation, Flooded or Swampy Field, and River; scale 3, corresponding to a moderate degree of human impact, included the following classes: Pasture, Silviculture, and Mosaic of Uses. Scales 4 and 5 proposed by Walz & Stein (2014) were adapted by merging both into a single hemeroby class (Euhemerobiotic), due to the similarity of characteristics identified in the study area, and were classified as having a strong degree of hemeroby. This scale encompassed the Soybean and Temporary Crops classes. Scales 6 and 7 were also adapted and grouped into the same hemeroby class (Metahemerobiotic), as they presented similarities between classes and were defined as having an excessively strong degree of human impact. Thus, they were consolidated as Class 6, encompassing the following land use classes: Urbanized Area and Non-vegetated Areas.

For statistical analysis, regression analyses were conducted based on the nature of the data, aiming to compare the effects of environmental transformations over time, considering deforestation (km²), wildfires (number of fire occurrences), and surface water area (km²). When comparing variables over time (1985–2022), periods with the greatest number of available paired data for the variables were utilized. Dixon's test was applied to identify data outliers using the following calculation:

$$Q = \frac{(x_a - x_b)}{R}$$

Where x_a is the outlier value, x_b represents the data point closest to x_a, and R is the range of the data set. In all cases, a 95% confidence interval was considered ($p<0.05$).

The forecasting analysis was based on a Generalized Linear Model (GLM), which was fitted to the data to predict future values of the dependent variable — in this case, data related to surface water area, accumulated deforestation area, and pasture area over a period of 80 years. The extrapolated data were then tested using Monte Carlo analyses with 1,000 repetitions, considering confidence intervals of 95% and 80%.

The linear regression model was defined by Equation 1:

$$Y = \beta_0 + \beta_n X_n + €$$

Where Y represents the dependent variable (in this case, the one to be predicted), β_0 is the intercept, $\beta_n X_n$ correspond to the coefficients of each independent variable, and finally, ε represents the model error.

3. Results

3.1. Environmental Transformations

In the temporal analysis over a 37-year period (1985 to 2022) regarding land use and land cover in the PRW, a 26% reduction in vegetation cover was observed, attributed to the forest formation class, along with a 30% decrease in savanna formation (Figure 2). Pasture areas experienced a 155% increase during the same period, indicating the conversion of natural systems to livestock use. In other words, it is clearly observed that areas of forest and savanna formations have been transformed into pasturelands.

In situ observational analyses were not carried out, only through satellite images. In this sense, between the years 1985 to 2005, there was an increase in urbanized areas, while from 2005 to 2022 they remained stable (Table 2). Additionally, over the 37 years, the class of Non-vegetated Areas (attributed to Bare Soil) decreased by 31%.

The detailed information on the dynamics of vegetation cover and land use that occurred in the PRW during the analyzed period is presented in Table 2.

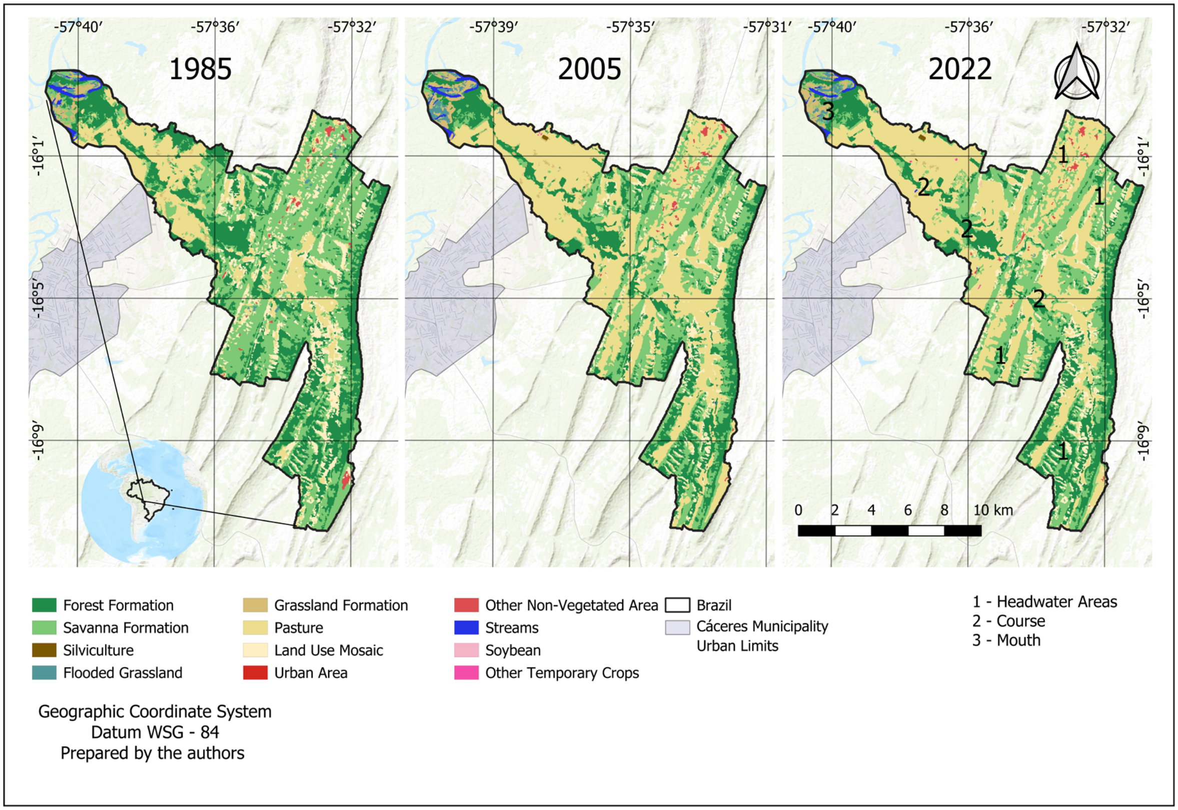

FIGURE 2 – Dynamics of land use and land cover within the study area (Piraputanga River Watershed) between 1985 and 2022.
SOURCE: the authors (2024).

Grassland formation had a reduction of 5.3% from 1985 to 2022. It was observed that in the period from 2005 to 2022, there was an increase in temporary crops and silviculture, indicating growth in agriculture and tree planting. Soybean cultivation in the PRW is considered a singular event, given that it occurred only in 2022 (Table 2 and Figure 4).

Figure 3-A shows that in 1985, the PRW contained natural forest and savanna formations classified as Oligohemerobiotic, indicating a low degree of environmental impact and demonstrating that the landscape remained well-conserved at this time. Twenty years later, however, the PRW area began entering a transitional phase (Figure 3-B), with landscapes now classified as Mesohemerobiotic, reflecting a moderate degree of impact. This shift from low to moderate impact levels resulted from increased anthropogenic activities, particularly construction developments during this period.

TABLE 2 – Dynamics of vegetation cover and land use classes, and classification of hemeroby degrees by vegetation cover and land use classes in the Piraputanga River Watershed, Mato Grosso (MT).

Land Cover and Land Use Classes	Hemeroby Degree	Human Impact	Impact Level	Annual percentages (%)		
				1985	2005	2022
Forest Formation	Oligohemerobic	Low	2	27,42	21,35	20,10
Savanna Formation	Oligohemerobic	Low	2	41,35	27,93	28,81
Flooded Fields and Wetlands	Oligohemerobic	Low	2	0,60	0,83	0,75
Grassland Formation	Oligohemerobic	Low	2	1,33	1,81	1,40
Streams	Oligohemerobic	Low	2	0,79	0,70	0,57
Silviculture	Mesohemerobic	Moderate	3	0,00	0,04	0,06
Pasture	Mesohemerobic	Moderate	3	15,82	40,97	40,45
Mosaic of Uses	Mesohemerobic	Moderate	3	12,09	5,91	7,38
Soybean	Euhemerobic	Strong	5	0,00	0,00	0,01
Other Temporary Crops	Euhemerobic	Strong	5	0,00	0,01	0,04
Urban Area	Metahemerobic	Excessively Strong	7	0,00	0,01	0,01
Other Non-Vegetated Areas	Metahemerobic	Excessively Strong	7	0,61	0,44	0,42

SOURCE: the authors, 2024.

In the PRW, the territorial portions of the landscape that underwent the most changes are those found in the lower areas (depression) of the Piraputanga River Watershed (Figure 3 – B area outlined in red), whose degree of impact was characterized as moderate, while the areas that suffered less impact were found in the mountainous province.

The landscape underwent its most significant alterations between 1985 and 2005, marking the beginning of the transitional phase for the region. From 2005 to 2022, however, the rate of landscape change decreased substantially. The historical deforestation data for the PRW (Figure 4-A) reveals notable temporal variations. Peak deforestation occurred in 1987, when 1.31 km² of the watershed was deforested. The lowest deforestation rate was recorded in 2011, with only 0.07 km² affected. By 2021, deforested area had decreased to 0.25 km² of the region. Despite this overall declining trend, the final years of the study period show a concerning reversal: from 2017 onwards (Figure 4-A), deforested area extent began increasing again.

Given this, it was observed that fires occurring in the region had significant temporal trends (linear regression, $R^2 = 0.26$; $p < 0.05$), with the highest fire outbreaks recorded in the last decade, particularly in

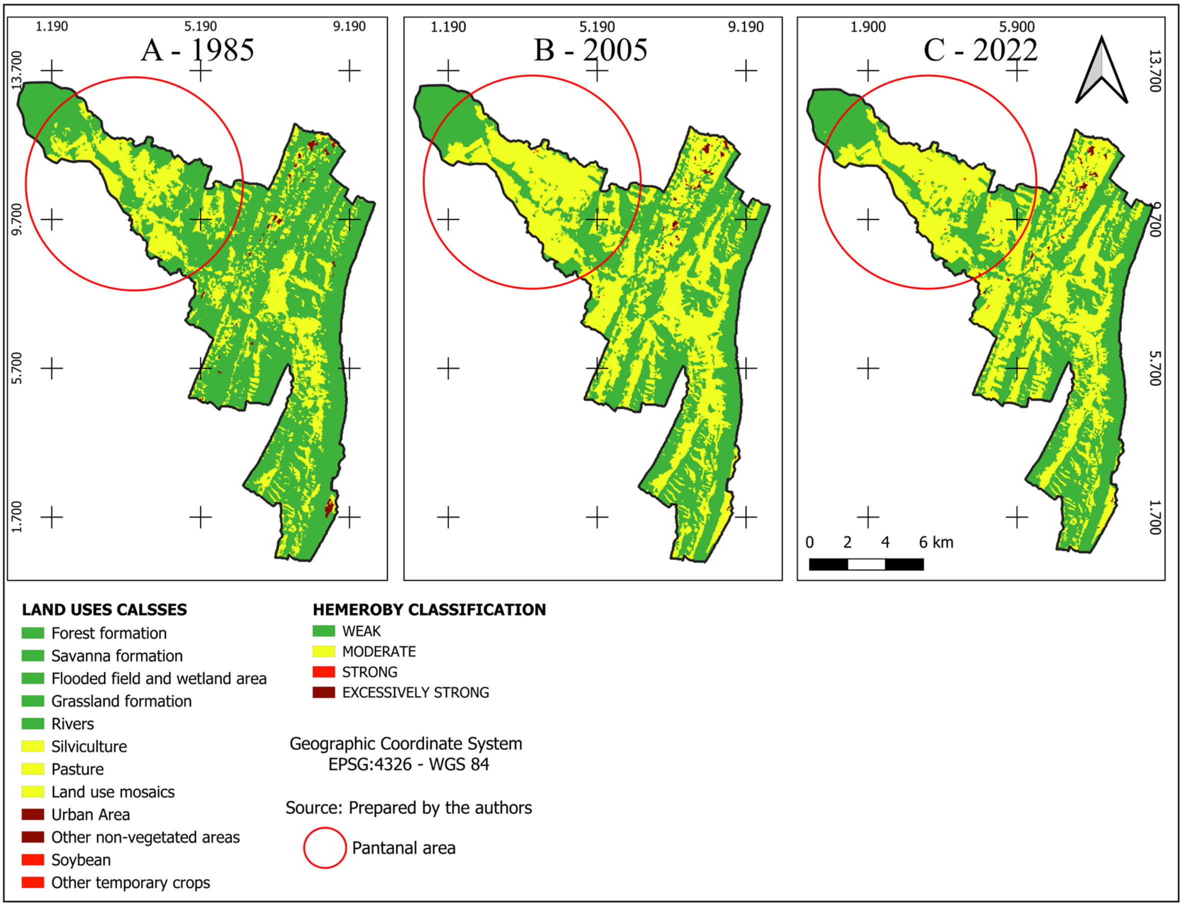

FIGURE 3 – Spatial and temporal distribution of the hemeroby degree of human impacts on land use and land cover in the Piraputanga River Watershed region. Red circles indicate depression areas (floodplain) within the Piraputanga River Watershed.
SOURCE: the authors (2024).

2018 (Figure 4 – B). However, 2020 exhibited the highest number of fire outbreaks in the watershed (1,086), but these data were not presented due to their identification as outliers. Thus, in 2020, recorded outbreaks were seven times higher than in 2018, which represented the second-highest occurrence with 154 fire outbreaks. The year 1998 was the only year with no recorded fire outbreaks in the region.

Given this scenario, significant effects of landscape change on ecosystem services provided within the Piraputanga River Watershed were evidenced. For example, a 40% reduction in surface water area was recorded over the 37-year period. In

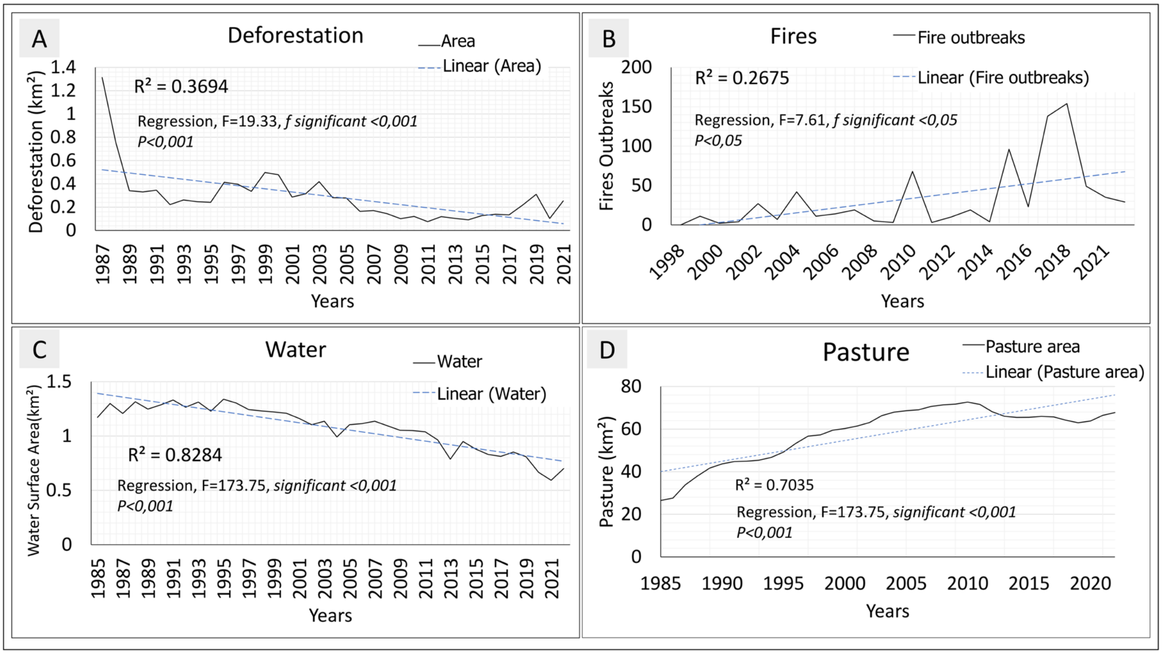

FIGURE 4 – Effect of environmental transformations over the years within the Piraputanga River Watershed: A - Deforestation levels in the region from 1987 to 2020; B - Number of fire outbreaks from 1998 to 2021; C – Loss of water surface for the years 1985 to 2021; D – Increase in pasture areas for the years 1985 to 2020.

SOURCE: the authors (2024).

1985, the water surface occupied 1.17 km², equivalent to 0.70% of the total watershed area. After 20 years, in 2005, it occupied 1.10 km², and by the end of the study period, it had decreased to 0.70 km².

As previously mentioned, pastureland increased significantly (linear regression, $R^2 = 0.70$, $F = 85.41$, $p < 0.05$). From 1985 to 2010, a 2.74-fold increase in pasture areas was observed. From 2010 to 2020, pasture areas showed a slight reduction of 6.8% (Figure 4 – D).

When analyzing the relationships between deforested areas and fire outbreaks relative to water surface in the PRW system (Figure 5), no significant logarithmic relationship was observed between deforestation and fire outbreaks (Figure 5 – A). Given the low coefficient of determination ($r^2 = 0.0317$), deforestation does not appear to be the primary driver of fire outbreak frequency. However, although not statistically significant, a trend was observed whereby greater deforested area coverage corresponded to lower numbers of fire outbreaks.

Regarding the relationship between deforestation and water surface in the system, results are presented in Figure 5 – B. A positive relationship between these variables was observed, suggesting that years with larger water surface areas correspond to increased deforested area coverage. In 2021, the lowest deforestation rate occurred, with only 0.25

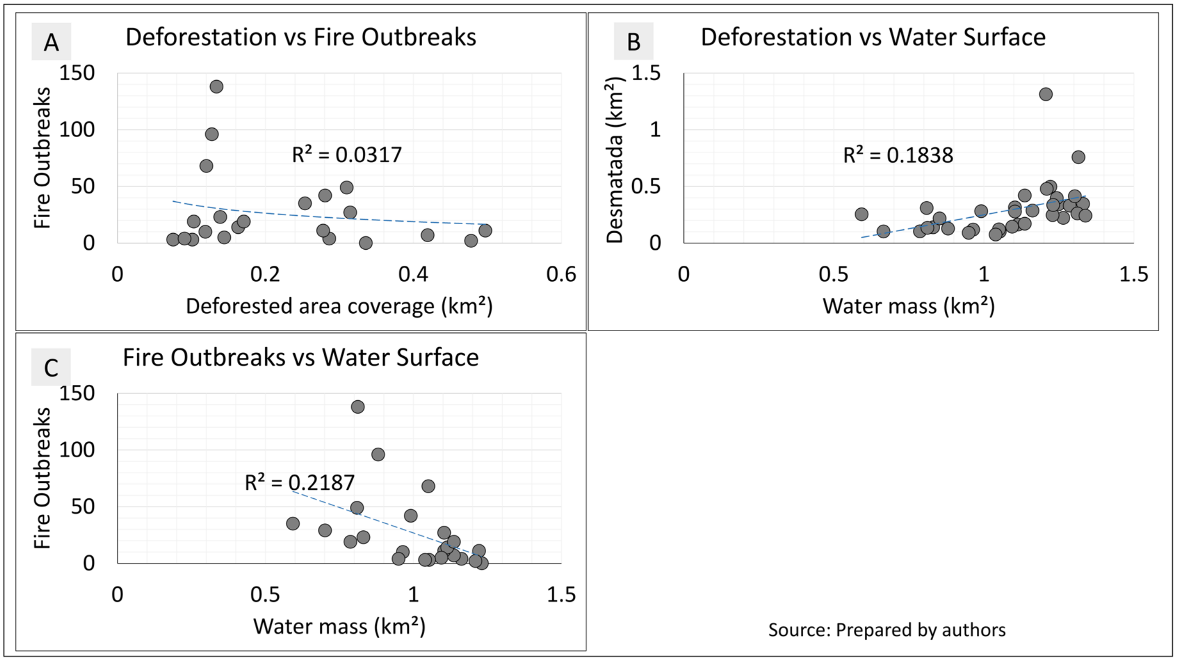

FIGURE 5 – Effect of annual cover: A. of burned areas in relation to water loss in the Piraputanga River Watershed (ANOVA, F=14.72, P<0.05); B. Impact of deforestation on water loss in the Piraputanga River Watershed system (ANOVA, F=236.80, P<0.01).
SOURCE: the authors (2024).

km² deforested, while the water surface in the system occupied 0.59 km² in the same year. According to the analyses (Figure 5 – C), years with the highest water amounts corresponded to the lowest rates of fire outbreaks.

The predictive statistical analysis demonstrated a substantial decline in water surface area, with projections indicating that by 2067, water scarcity in the PRW will be severe, with water mass potentially reduced to zero (Figure 6). It is important to note that projections were generated with 95% and 80% confidence intervals, enhancing the robustness and reliability of the results. Thus, from 2022 onwards, intense transformations are anticipated, including progressive water loss in the PRW extending through 2067.

Projections for accumulated deforested areas indicate a linear increase in deforestation (Figure 7), implying serious losses of natural ecosystem services. It is noteworthy that the 95% and 80% confidence intervals are closely aligned with the projections. Projections indicate that pasture areas will expand to nearly double by 2067, reaching slightly over 130 km² (Figure 8). This expansion may result from continued deforestation or water surface loss, indicating that livestock farming will continue to predominate in this region over the coming decades.

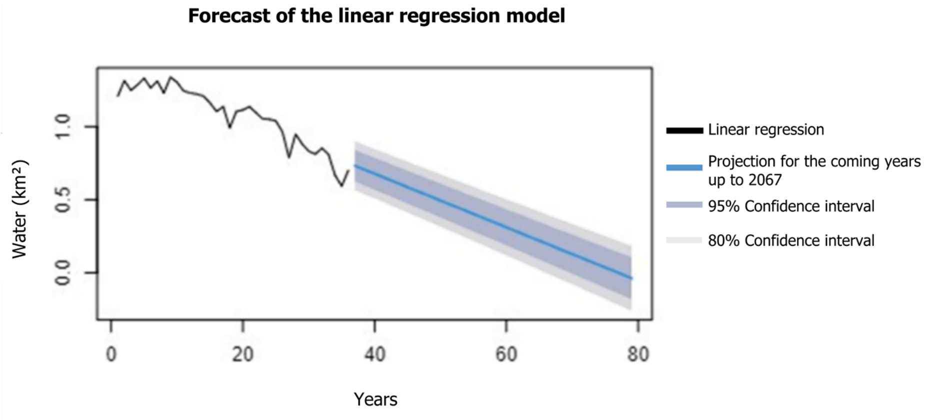

FIGURE 6 – Predictive analysis of water surface loss up to the year 2067 according to the FORECAST prediction model.
SOURCE: the authors (2024).

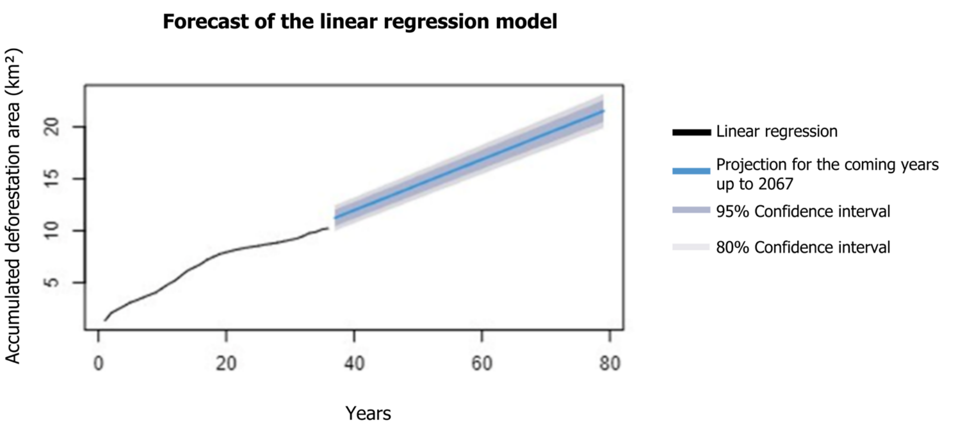

FIGURE 7 – Predictive analysis of the increase in accumulated deforested areas up to the year 2067 according to the FORECAST prediction model.
SOURCE: prepared by the authors (2024).

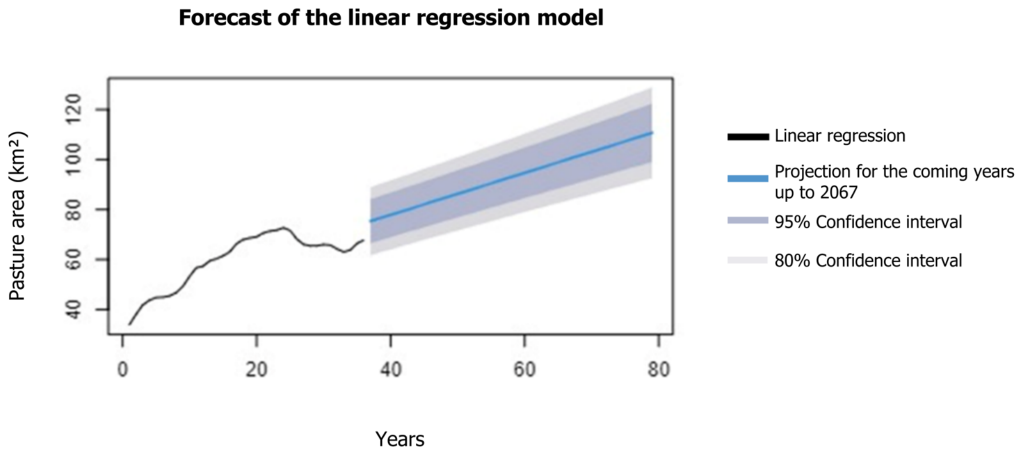

FIGURE 8 – Predictive analysis of the increase in pasture areas up to the year 2067 according to the FORECAST prediction model.
SOURCE: the authors (2024).

4. Discussion

Landscape changes can be attributed to the growth and development of urban areas near the region (Dos Santos Funaro *et al.*, 2022). Accumulated deforestation indices increased progressively over time. Thus, although annual deforestation rates showed a decreasing trend, cumulative deforestation continued to increase. From 1985 to 2005, the highest degree of landscape transformation was observed. This phenomenon can be explained by the cumulative nature of deforestation impacts, indicating that despite reductions in annual deforestation rates, the total environmental impact continues to increase over time. In subsequent years (2005–2022), less landscape transformation was observed in the watershed, indicating stabilization in deforestation rates. This decrease in exploitation of vegetated areas suggests that the environment has already undergone intense pressure from landscape transformation, and areas previously available for deforestation have been largely exploited, leaving fewer areas available for deforestation under the current scenario.

The areas least affected by landscape transformation occurred in the mountainous province regions. These regions are Permanent Preservation Areas (APPs); therefore, the lowest deforestation indices in these regions can be attributed to Law No. 12.651/2012, which prohibits APP exploitation for deforestation. Moreover, these areas present challenging conditions for agricultural use.

This work supports the raised hypotheses, with analyses showing conversion trends of natural areas, such as the reduction of forest and savanna formations, into agricultural and pasture uses. This has environmental implications including biodiversity loss, climate change, and impacts on water resources regarding both quantity and quality (Alho *et al.*, 2019; Feng *et al.*, 2021).

The observation of the transitional phase characterized by increased agricultural and livestock activities and significant vegetation cover loss in the PRW was corroborated by previous studies. Souza & Sousa (2014) and Rodrigues *et al.* (2021) had already documented the influence of anthropogenic actions in the region, highlighting that landscape transformations are occurring under considerable pressures. This phenomenon may also reflect the rapid demographic growth of the Cáceres region, which strongly impacted land use and occupation from the 1960s onwards (Santos & Zamparoni, 2012). The reduction in landscape change observed between 2005 and 2022 may reflect the implementation of the State Forest Code, Complementary Law No. 233 of 2005, which regulates forest management in Mato Grosso State. Article 1 establishes the following legal principles:

1 – Protection of natural resources: flora, fauna, atmosphere, soil, and water;

2 – Recovery of degraded areas and legal reserve; and

3 – Sustainability of forest activity (Brazil, 2005).

For the PRW, this population growth impact is evidenced by Dos Santos Funaro *et al.* (2022), who highlight that rural expansion in the region has exerted pressure on ecosystem services, primarily through economic activities involving the replacement of native vegetation areas with grasslands. This aligns with the Millennium Ecosystem Assessment (2005), which emphasizes that system pressures result from population growth driving high consumption demands. From 1988 to 2018, the most prominent production activities in Mato Grosso were livestock and agriculture, with cattle production expanding by 384.7% (Capoane, 2022). Landscape change in the PRW is particularly attributed to livestock activity expansion through increased pasture areas, which is corroborated by previous studies (Ramos *et al.*, 2018; Rodrigues *et al.*, 2021).

The PRW exhibits Cerrado characteristics with diverse phytophysiognomies, including gallery and riparian forests, grasslands, and cerrado sensu stricto (Ribeiro & Walter, 1998; Sousa & Souza, 2014; Paiva, 2023). Given this diversity, the literature demonstrates that environmental changes have negative impacts on both faunal (Rurangwa *et al.*, 2021) and floral (Araújo *et al.*, 2023; Shaheen *et al.*, 2024) biodiversity. These implications raise concerns about biodiversity threats resulting from landscape alteration and degradation (Dudgeon *et al.*, 2005; Pérez-Cárdenas *et al.*, 2021), which limit ecosystem functioning by impairing the ability to provide ecosystem services (Tylianakis, 2007; Aquino *et al.*, 2012; Araújo *et al.*, 2023). Forest system degradation, beyond contributing to reduced environmental quality, compromises human well-being, as these systems, characterized as "public goods," are essential for rural family subsistence, making resource conservation fundamental for poverty reduction (TEEB, 2010).

However, studies indicate that the optimal approach to maintaining ecosystem service balance in agricultural land systems is the conservation of 50% of natural landscapes (Araújo *et al.*, 2021). In this context, landscape preservation becomes a crucial priority. In certain dry environments, for example, vegetation plays a fundamental role in accelerating vegetation regeneration processes (Pérez-Cárdenas *et al.*, 2021). Another example involves the positive effects that habitats have on insect diversity by providing better survival conditions, as movement in open areas, such as pastures, is hindered. Moreover, these species exhibit preferences for native habitats that provide shelter, food availability, and suitable nesting sites (Salomão *et al.*, 2023).

Another significant impact involves climate changes resulting from landscape modification. Forest conversion to pasture, for example, contributes to carbon stock loss within ecosystems (Menezes *et al.*, 2021). In the 1990s and 2010s, Dale (1997) and Pielke & Roger (2005) documented the effects of relationships between land use and land cover changes and climate change. Recently, this issue continues to be discussed and projected for future scenarios (Pereira *et al.*, 2004; Sinha *et al.*, 2020; Gurara *et al.*, 2021).

The findings of this research corroborate results from the Alto Paraguai region, where studies have identified the greatest water surface reduction experienced by the Pantanal region (Lázaro *et al.*, 2020), into which the Piraputanga River Watershed drains. The authors also emphasize that any landscape alterations result in ecosystem service losses. Other historical drought events have been documented in the literature (Trenberth *et al.*, 2014; Gunacti *et al.*, 2023; Yuan *et al.*, 2023), demonstrating that extreme droughts also have implications for climate change.

The decrease in water surface area has consequences for the loss of this important ecosystem service due to landscape changes. The decline in water surface area appeared to coincide with increased accumulated deforestation, demonstrating that maintaining the original landscape contributes to water flow maintenance. This highlights the importance of deforestation impacts on a watershed's water body, where deforestation can influence hydrological processes (Kong *et al.*, 2022). In this case, the landscape deforestation index appeared to correlate with water availability. For example, during periods when water availability decreased, there was a parallel increase in regional deforestation. Regional studies connecting deforestation to watercourses still lack political attention and research investment, as many regions remain neglected (Fugère *et al.*, 2016).

In 2020, the Pantanal biome became the focus of global attention due to the high number of fire outbreaks in the region (Pelissari *et al.*, 2020). This event contributed to substantial plant and animal life losses and affected human health (Caumo *et al.*, 2022). Fire impacts on biodiversity directly affect aquatic communities (Robson *et al.*, 2018; Gomez *et al.*, 2022), as evidenced in other Brazilian regions such as the Amazon, highlighting the need to implement existing policies aimed at minimizing impacts (Feng *et al.*, 2021). A positive relationship was observed between fires and landscape changes. As mentioned, areas with greater water coverage present lower fire risks, as water serves as a natural resource and acts as a means of fire control and prevention (Češljar & Stevović, 2015). Thus, water resource management is fundamental for maintaining environmental conservation in a sustainable manner (Kalogiannidis *et al.*, 2023).

The presented projections indicate reductions in water surface levels and increases in pasture and accumulated deforested areas. These trends are concerning, resulting in ecosystem service losses. Water is a key element sustaining life within ecosystems (Lázaro *et al.*, 2020), and water loss results in biogeochemical cycle imbalances (Keller *et al.*, 2020), habitat reduction for fish and bird species (Alho *et al.*, 2019), macroinvertebrates (Oliveira Junior *et al.*, 2013), and aquatic plants (Oliveira Junior *et al.*, 2020; Thomaz, 2023).

5. Conclusion

The evidence demonstrates that the PRW underwent a landscape transition process from 1985 to 2005, characterized by decreased forest and savanna formations and increased pasture areas, reflecting the expansion of agricultural grazing activities, fires, and deforestation. However, from 2005 to 2022, deforestation rates stabilized. Regarding water surface area, significant losses were documented over the 37-year period. The loss of vegetation and water combined with increased pasture areas represent trends that affect biodiversity and particularly the capacity of ecosystems to provide essential environmental services.

According to hemeroby degree analysis, the 37-year transition phase evidenced for the PRW indicates that the region is in a state of moderate impact. Landscape change impacts were greater in floodplain areas (Pantanal region). Predictive analyses indicate that the watershed will continue losing water over the next 40 years, while pasture areas are projected to increase. Predictive analysis for deforestation indicated that accumulated deforestation rates will increase by 2065. However, it is noteworthy that previously available areas have already been deforested, reinforcing the need to maintain conservation of permanent preservation areas and reduce environmental quality impacts.

In conclusion, this diagnosis aligns with Sustainable Development Goal 15 (Life on Land), which aims to combat deforestation and land degradation while promoting restoration and conservation measures for ecosystems degraded by drought or desertification events. The observed extreme events, such as increased pastures and reduced water availability in the Pantanal, emphasize the relevance of this work's alignment with the Sustainable Development Goals and its contribution to regional and local populations.

Therefore, it is recommended that conservation and sustainable management policies be implemented to mitigate land use change impacts in the PRW and ensure ecosystem service sustainability in the region. Integration of ecological processes and continuous monitoring are essential for decision-making, with these results serving as a reminder of the necessary balance between human development and nature conservation, particularly considering current global challenges regarding climate change and biodiversity loss.

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