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Landscape of the Tocantins-Araguaia Basin: challenges, dynamics, and future prospect for conservation

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Tese apresentada ao Programa de Pós-Graduação em Ecologia de Ambientes Aquáticos Continentais do Departamento de Biologia, Centro de Ciências Biológicas da Universidade Estadual de Maringá, como requisito parcial para obtenção do título de Doutor em Ecologia e Limnologia.
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Orientador: Prof. Dr. Angelo Antonio Agostinho
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Paisagem da bacia Tocantins-Araguaia: desafios, dinâmicas e perspectivas futuras para a conservação

RESUMO

O desmatamento tropical e políticas insustentáveis são desafios atuais na bacia hidrográfica do Tocantins-Araguaia (TOAR), localizada no coração do bioma Cerrado. Analisou-se a dinâmica do uso da terra em um período de 35 anos (1985-2020). Os resultados mostraram mudanças antropogênicas relevantes impulsionadas por atividades agrícolas, resultando em grandes perdas de vegetação, especialmente em florestas naturais, savanas e pastagens. Nesse período constatou-se um crescimento exponencial de pastagens e agricultura em detrimento de categorias naturais. Parte das áreas estáveis da TOAR correspondeu a áreas legalmente protegidas. Considerando os desafios destacados, analisou-se também cenários futuros de uso e cobertura da terra (2015-2045) sob três cenários de demanda de área: "*Business-as-usual*" (BAUS), "*Conservation-based*" (CONS) e "*Production-based*" (PROD). A análise das projeções futuras indicou a persistência de padrões de desmatamento e fragmentação, especialmente no cenário PROD. A notável perda prevista em Floresta Natural e Savana, mesmo no cenário conservacionista, evidencia a necessidade urgente de esforços proativos de conservação, regulamentações mais rigorosas e considerações ambientais aprimoradas nos planos de desenvolvimento. Considerando o contexto explorado e discutido mediante os dados obtidos, este estudo não apenas destaca as complexidades da dinâmica passada do uso da terra na TOAR, mas também aponta para a urgência de ações coordenadas para garantir um futuro sustentável. A persistência do desmatamento mesmo em cenários orientados para a conservação levanta questões sobre a eficácia das atuais medidas de proteção, enfatizando a necessidade de reavaliação e fortalecimento das estratégias de conservação. A TOAR está em uma encruzilhada ecológica, exigindo esforços concretos e direcionados por parte de tomadores de decisão, pesquisadores e população para garantir sua gestão sustentável e a preservação de seus ecossistemas únicos, biodiversidade e patrimônio cultural em meio às crescentes pressões antropogênicas.

Palavras-chave: desmatamento tropical; manejo de bacias hidrográficas; dinâmica do uso da terra; cenários de conservação; preservação da biodiversidade; segurança hídrica.

Landscape of the Tocantins-Araguaia Basin: challenges, dynamics, and future prospect for conservation

ABSTRACT

Tropical deforestation and unsustainable policies are current challenges in the Tocantins-Araguaia River basin (TOAR), located in the heart of the Cerrado biome. In the first article, the dynamics of land use were analyzed over a period of 35 years (1985-2020). The results showed relevant anthropogenic changes driven by agricultural activities, resulting in major vegetation losses, especially in natural forests, savannas and pastures. During this period, there was an exponential growth in pastures and agriculture to the detriment of natural categories. Part of TOAR's stable areas corresponded to legally protected areas. Considering the challenges highlighted in the first article, in the second, future scenarios of land use and cover (2015-2045) were analyzed under three area demand scenarios: "Business-as-usual" (BAUS), "Conservation-based" (CONS) and "Production-based" (PROD). Analysis of future projections indicated the persistence of deforestation and fragmentation patterns, especially in the PROD scenario. The notable predicted loss in Natural Forest and Savanna, even in the conservation scenario, highlights the urgent need for proactive conservation efforts, stricter regulations, and enhanced environmental considerations in development plans. Considering the context explored and discussed in the articles presented, this study not only highlights the complexities of the past dynamics of land use in TOAR, but also points to the urgency of coordinated actions to ensure a sustainable future. The persistence of deforestation even in conservation-oriented scenarios raises questions about the effectiveness of current protection measures, emphasizing the need to re-evaluate and strengthen conservation strategies. The TOAR is at an ecological crossroads, requiring concrete and targeted efforts on the part of decision makers, researchers and the population to ensure its sustainable management and the preservation of its unique ecosystems, biodiversity and cultural heritage amidst increasing anthropogenic pressures.

***Keywords*:** tropical deforestation; watershed management; land use dynamics; conservation scenarios; biodiversity preservation; water security.

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SUMMARY

1 GENERAL INTRODUCTION

The intricate relationships between tropical deforestation, climate concerns, and environmental sustainability has been a longstanding global focus for scientists, governments, and environmental organizations. In the Brazilian context, decades of conservation efforts have resulted in notable achievements, such as a significant reduction in Amazon deforestation during the 2010s (Nepstad et al., 2014; Reydon et al., 2020). Despite these successes, Brazil grapples with ongoing environmental challenges, including setbacks in environmental policy and escalating deforestation rates in many biomes, especially in the Brazilian Savanna (Cerrado), home of the Tocantins-Araguaia basin (Pelicice et al., 2021; Polizel et al., 2021; Alerta MapBiomas, 2023).

The Tocantins-Araguaia hydrographic basin (TOAR) emerges as a pivotal case study. Positioned in the ecotone between the Brazilian Cerrado and the Amazon, the basin encapsulates the environmental complexities of the MATOPIBA region. The MATOPIBA is a Brazilian region comprehending the states of Maranhão, Tocantins, Piauí and Bahia, in which agricultural development is encouraged and receive direct governmental subsidies, being nowadays considered the country’s main agricultural frontier (Pelicice et al., 2021; Bispo et al., 2023). This basin covers 11% of Brazil's total area, so it is crucial for its freshwater systems, navigable rivers, and unique biodiversity (Latrubesse et al. 2019; Ribeiro et al., 1995; Coelho et al., 2012). Despite its environmental relevance, the TOAR faces several anthropogenic pressures, from deforestation and farming expansions to mining operations and transportation infrastructure development (Latrubesse et al., 2019; Pelicice et al., 2021; Bispo et al., 2023).

Linking environmental health to human well-being, the TOAR's freshwater ecosystems play vital roles in biodiversity preservation, water purification, and flood control. However, unregulated land use practices and the alarming rise in deforestation pose significant threats to this region (Alerta Mapbiomas, 2023). The basin's rich biodiversity, including endangered species and the expansive floodplains, faces jeopardy from ongoing anthropogenic activities (Pelicice et al., 2021; Chamon et al., 2022). Additionally, the threat becomes even more significant when we consider the gaps in our understanding of biodiversity and ecosystem functioning in the biomes encompassing the TOAR (Castro et al., 1999; Hopkins, 2007; Borges and Loyola, 2020).

Understanding the urgent need for basin-level analyses, the first chapter of this document embarks on a comprehensive assessment of the TOAR's land use dynamics over 35 years, critically assessing the main land use transitions and their intensities over time. Informed by the challenges highlighted in the first chapter, and recognizing the pivotal role of land use analysis in environmental planning, the second chapter extends beyond a retrospective examination and presents three distinct future land use scenarios for the TOAR, projecting from 2015 to 2045. These scenarios, ranging from "business-as-usual" to "conservation-based" and "production-based," aim to provide valuable insights for policymakers, researchers, and stakeholders. By exploring the potential consequences of different land use policies and conservation efforts, our study seeks to enhance the sustainable management of the TOAR basin, contributing to informed decision-making amid the expanding challenges of anthropogenic activities.

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2 CONSERVATION CHALLENGES AMIDST VEGETATION LOSS AND AGRICULTURAL EXPANSION: A COMPREHENSIVE ANALYSIS OF LAND USE DYNAMICS IN THE TOCANTINS-ARAGUAIA BASIN

ABSTRACT

Rapid tropical deforestation and unsustainable policies pose challenges to biodiversity conservation in Brazil, particularly in the Tocantins-Araguaia hydrographic basin (TOAR), a mega diverse region significantly impacted by agricultural expansion. This study investigates on land use dynamics in TOAR over a 35-year period (1985–2020). We aimed to evaluate how have land use practices changed over time within the TOAR, and what is the spatial distribution of stable areas. Moreover, we evaluated how the intensity of land use changes oscillated between the landscape and categories over the years, while applying the intensity analysis methodology to identify the most pervasive systematic transitions between natural and anthropogenic categories. Our findings reveal concentrated anthropic changes primarily driven by agricultural activities, leading to remarkable vegetation losses in natural forests, savannas, and grasslands. At the cost of natural vegetation, pastureland nearly doubled, and agriculture expanded by 1300%. The identification of stable areas exposed critical gaps in protection for wetlands, natural forests, and savannas, with only 17.08%, 11.89%, and 9.37% of their stable areas, respectively, falling within protected areas. The results also underscore the systematic conversion of natural landscapes into pastureland and agriculture, emphasizing the pressing need for basin management strategies. These findings offer crucial insights for stakeholders, guiding sustainable decision-making and fostering preservation efforts amid escalating anthropogenic pressures. This study presents the first broad-scale land use analysis on TOAR, underscoring the imperative for targeted conservation actions this understudied region, pivotal for biodiversity and cultural heritage preservation.

Keywords: Biodiversity; Anthropogenic Impact; Sustainable Development; Environmental Policy; Land Use Intensity; Hydrographic Basin Scale.

2.1 Introduction

Tropical deforestation intertwined with climate concerns has long brought together scientists, environmental organizations, and governments to pursue solutions towards conservation. In Brazil, conservation initiatives undertaken in recent decades have played a crucial role in establishing a range of environmental and social programs, policies, and international treaties to safeguard Brazil’s biodiversity and ecosystems (Capobianco, 2019; Pelicice and Castello, 2021). This long-standing effort has yielded positive outcomes; for example, during the 2010s, the Brazilian government developed a framework for conserving the Brazilian Amazon, resulting in a nearly 70% reduction in deforestation (Nepstad et al., 2014; Reydon et al., 2020). Nevertheless, some setbacks occurred with this decrease; for instance, in 2010, Brazil maintained its global leading position in deforestation rates, with nearly 55 million hectares deforested between 1990 and 2010 (FAO, 2010).

There has also been an escalation in deforestation rates in other biomes and ecosystems, notably in the Brazilian Savanna (Cerrado) (Alerta MapBiomas, 2023; Pelicice et al., 2021; Polizel et al., 2021). Additionally, Brazil has faced a significant number of setbacks in environmental policy over the past decade (Thomaz et al., 2020). These include the rampant construction of hydropower dams in the Amazon (Winemiller et al., 2016), proposals for the "naturalization" of non-native fish (Pelicice et al., 2014), the polemic review of the Brazilian Forest Code (Nazareno et al., 2012; Soares-Filho et al., 2014), the recurring downgrading, downsizing, and reclassification of protected areas (Azevedo-Santos et al., 2017; Conceição et al., 2022; Metzger et al., 2019), as well as consistent budget cuts, mainly from scientific and environmental agencies (Reydon et al., 2020). More recently, the last presidential administration (2019–2022) established a political agenda that negatively impacted various aspects of Brazil's environmental sector (Ferrante and Fearnside, 2019; Pelicice and Castello, 2021; Reydon et al., 2020; Siqueira-Gay et al., 2020; Thomaz et al., 2020; Trindade et al., 2022).

One significant consequence of specific unsustainable development practices and policy decisions in Brazil is the potential threats that impact both the Amazon and Cerrado biomes (Ferrante and Fearnside, 2019; Pelicice and Castello, 2021). These biomes are globally renowned for their numerous ecosystem services, including carbon storage (Bullock and Woodcock, 2020; Dionizio et al., 2020; Siqueira-Gay et al., 2020) and climate regulation

(Strand et al., 2018). They also provide a home to unique and sometimes isolated indigenous people and cultures (Bowman et al., 2021; Siqueira-Gay et al., 2020). Moreover, these biomes are recognized for their exceptional biodiversity, encompassing endemic and endangered species (Chamon et al., 2022; IUCN, 2023; Polizel et al., 2021). Despite its global ecological significance, Brazil has designated only 28.7% and 7.5% of the Amazon and Cerrado biomes as conservation units, respectively (Polizel et al., 2021). This scenario becomes even more concerning when we consider the gaps in our understanding of biodiversity and ecosystem functioning in these biomes (Borges and Loyola, 2020; Castro et al., 1999; Hopkins, 2007). Besides, in 2015, the government launched the MATOPIBA project in the region, encompassing the ecotone between the Amazon, Cerrado, and Caatinga biomes, with the aim of promoting agricultural practices linked to monocultures and cattle farming (Pelicice et al., 2021; Polizel et al., 2021). In fact, the extensive transformation of the Cerrado into soybean monoculture over recent decades has been a primary factor contributing to the expansion of total cropland in Brazil (Lapola et al., 2014). This has resulted in a 46% reduction in native Cerrado vegetation, with only 19.8% of its original area remaining undisturbed (Ferrante and Fearnside, 2019; Strassburg et al., 2014).

The Tocantins-Araguaia hydrographic basin (TOAR) represents a unique case in this context of environmental degradation since it encompasses the MATOPIBA region and other agricultural frontiers (Latrubesse et al., 2019; Pelicice et al., 2021). This basin covers nearly 11% of Brazil's total area and is one of the country's most significant freshwater systems (Coelho et al., 2012; Ribeiro et al., 1995). Most of the rivers within the TOAR are navigable, further increasing the economic significance of the basin, particularly for the transportation of agricultural products (Latrubesse et al., 2019; MMA, 2005). Concerning biodiversity, the TOAR is an ecotone bridging the megadiverse Amazon and Cerrado biomes, which is recognized as a global biodiversity hotspot (Mittermeier et al., 2004). Additionally, the TOAR exhibits latitudinal biodiversity gradients since it separates the Amazon from the southern Mata Atlântica and Pantanal biomes, as well as the eastern Caatinga. The basin is also known for its high levels of endemism, particularly within aquatic ecosystems (Chamon et al., 2022). In this regard, the Tocantins River has seven large hydroelectric dams and numerous smaller dams in its tributaries (Pelicice et al., 2021; Swanson and Bohlman, 2021). In contrast, the Araguaia River largely maintains its natural free-flowing regime, hosting the most geodiverse floodplain of the Cerrado (Martins et al., 2021; Pelicice et al., 2021), with a greater number of fish species than any other basin in this biome (Latrubesse et al., 2019). Furthermore, fish play a crucial role as both an economic resource and a food source for traditional communities. They also sustain the region's sport fishing tourism industry (Santana et al., 2021; Vasconcellos et al., 2022).

It is widely recognized that human-induced changes to the landscape are the primary drivers of deforestation, global biodiversity decline, and disruptions in ecosystem structure and function (Vitousek et al., 1997). These changes are characteristic of developing nations that persist in promoting unsustainable practices related to human consumption through the production and exportation of commodities such as soybeans and beef (Hughes et al., 2023). In this context, the TOAR has recently experienced anthropogenic changes, including the displacement of people, increased mining operations, and the development of transportation infrastructure (railways and roads) (Barros and Baggio, 2021; Ferrante et al., 2021; Queiroz et al., 2022). Moreover, in the past three decades, the agricultural frontier has extended into the Brazilian Cerrado and Amazon biomes (Alerta MapBiomas, 2023; Polizel et al., 2021), and The Tocantins and Araguaia basins have both undergone significant pressures driven by activities such as agriculture and cattle farming (Barros and Baggio, 2021; Pelicice et al., 2021; Polizel et al., 2021).

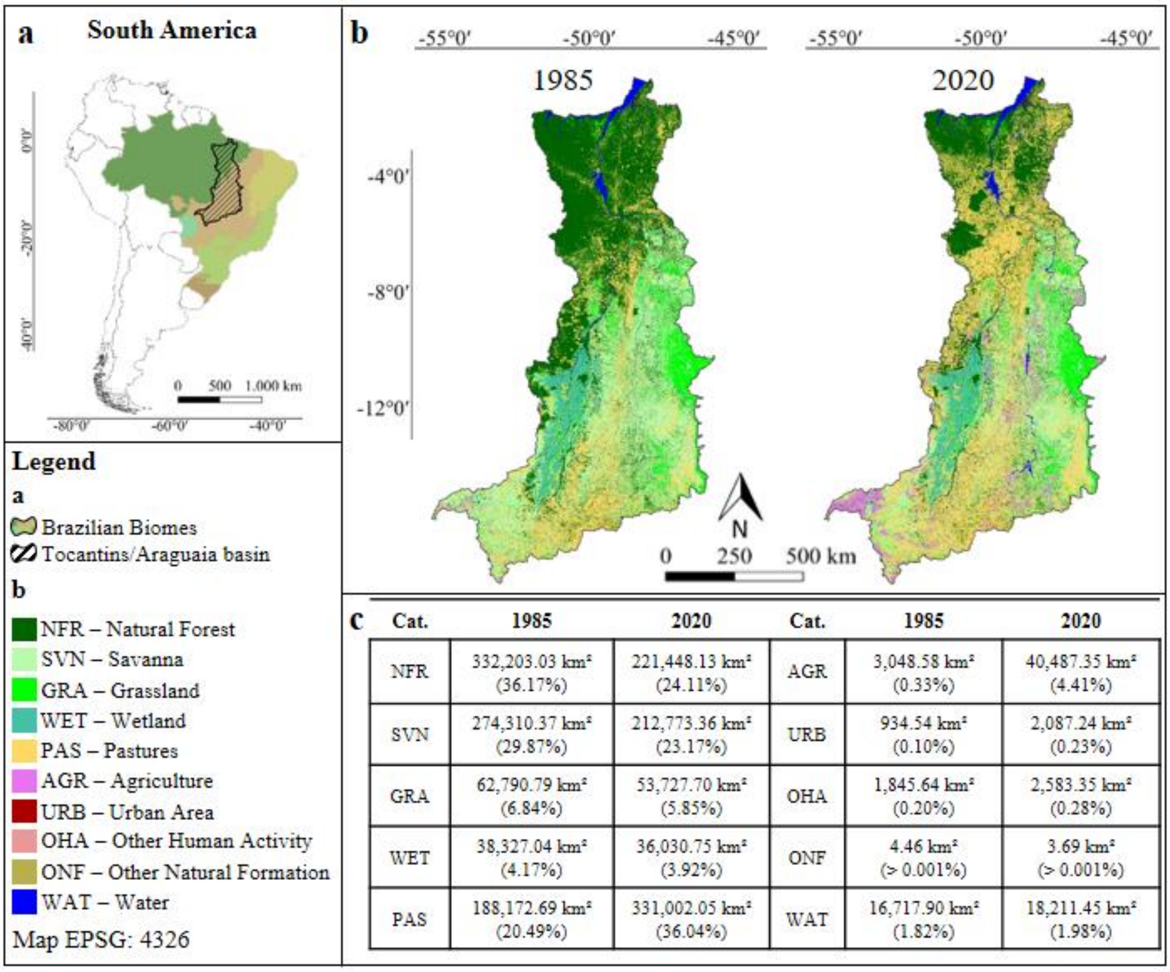
Thus, to assess the conservation status and plan for the sustainable development of TOAR, crucial information lies in data related to the current and historical land use and cover of the basin. However, few studies have examined land use changes in the TOAR, with most focusing on small areas (Santos et al., 2017; Vale et al., 2020) or solely on the Cerrado biome (Latrubesse et al., 2019; Silva et al., 2006). Furthermore, many of these studies have prioritized topics other than land use dynamics (Coelho et al., 2012; Serrão et al., 2020; Serrão et al., 2023). Notably, most studies have focused on the Araguaia Basin (Martins et al., 2021; Oliveira et al., 2020) and the Tocantins Basin (Martins et al., 2015; Swanson and Bohlman, 2021) individually. The present study represents the first comprehensive assessment of the TOAR. Pelicice et al. (2021) provided a comprehensive overview of the basin, emphasizing the primary environmental threats and challenges related to conservation and sustainability; however, the authors did not analyze the land use dynamics of the basin.

Therefore, this study investigates on land use dynamics in TOAR over a 35-year period (1985–2020). We aimed to evaluate how have land use practices changed over time within the TOAR, and what is the spatial distribution of stable areas. Moreover, we evaluated how the intensity of land use changes oscillated between the landscape and categories over the years, while extending the intensity analysis methodology (Aldwaik and Pontius, 2012) to identify the most pervasive systematic transitions between natural and anthropogenic categories. Specifically, our goals were as follows: 1) present the annual land use composition from 1985 to 2020; 2) identify the primary land use changes among categories; and 3) create a map of stable areas during the study period while considering protected areas in the TOAR. Moreover, regarding the intensity analysis, we aimed to: 4) assess the overall intensity of land use changes, including annual landscape intensity and category-level intensities of area gain and loss; and 5) analyze transitions among categories while focusing on identifying systematic land use transitions, i.e., that were either avoided or prioritized by categories.

2.2 Materials and Methods

2.2.1 Characterization of the study area

The TOAR encompasses the Tocantins and Araguaia River basins, draining an area of approximately 967,059 km², accounting for 10.8% of Brazil's territory (Fig. 1a). This basin is longitudinally oriented, with the river stretching nearly 2,600 km (Coelho et al., 2012). Thhere are approximately 409 municipalities within the TOAR drainage area. However, the human population density is relatively low at around 9.3 inhabitants/km², with most of the population concentrated in major urban centers (Latrubesse et al., 2019; MMA, 2005). The TOAR is primarily situated within the Cerrado biome, although it also encompasses a portion of the Amazon Forest in its northern region. In terms of river connectivity, the Tocantins River features numerous hydropower dams and reservoirs along its course. In contrast, the Araguaia River maintains its free-flowing nature, conserving one of the world's largest floodplain systems (Ilha do Bananal). Consequently, compared to the Tocantins River, the natural flow regime of the Araguaia River is better preserved (Latrubesse et al., 2019). This hydrographic basin serves as an extensive and vital ecological corridor for numerous species, connecting the Pantanal in the south to the Amazon Forest in the north.



Cat.	1985	2020	Cat.	1985	2020
NFR	332,203.03 km² (36.17%)	221,448.13 km² (24.11%)	AGR	3,048.58 km² (0.33%)	40,487.35 km² (4.41%)
SVN	274,310.37 km² (29.87%)	212,773.36 km² (23.17%)	URB	934.54 km² (0.10%)	2,087.24 km² (0.23%)
GRA	62,790.79 km² (6.84%)	53,727.70 km² (5.85%)	OHA	1,845.64 km² (0.20%)	2,583.35 km² (0.28%)
WET	38,327.04 km² (4.17%)	36,030.75 km² (3.92%)	ONF	4.46 km² (> 0.001%)	3.69 km² (> 0.001%)
PAS	188,172.69 km² (20.49%)	331,002.05 km² (36.04%)	WAT	16,717.90 km² (1.82%)	18,211.45 km² (1.98%)

Fig. 1 a: Geographic location of the Tocantins-Araguaia hydrographic basin. b: Land use and land cover for the years 1985 and 2020 in the Tocantins-Araguaia hydrographic basin. c: Composition of land use and land cover in the Tocantins-Araguaia hydrographic basin for the years 1985 and 2020, categorized as follows: NFR – Natural forest; SVN – Savanna formation; GRA – Grassland; WET – Wetland; PAS – Pastures; AGR – Agriculture; URB – Urban infrastructure; OHA – Other human activity; ONF – Other natural formation; WAT – Water. Refer to Table 1 for additional details on land use categories

Two significant federal protected areas encompass the TOAR: the Estação Ecológica Serra Geral do Tocantins, situated in the eastern part of the TOAR; the Parque Nacional do Araguaia, established to safeguard the river and floodplain ecosystems of the Araguaia River. Additionally, a portion of the Araguaia River's floodplain falls within one of Brazil's most significant protected areas, known as Área de Proteção Ambiental da Ilha do Bananal/Cantão. This protected area is legally classified as a sustainable use area, permitting the utilization of certain natural resources and controlled human occupation. Furthermore, additional smaller and geographically isolated areas are designated for full protection or sustainable use within the TOAR (INDE, 2023).

Despite the social, political, and environmental significance of the TOAR and its pronounced and escalating environmental degradation in recent years, scientific studies on the basin are scarce. To illustrate this point, we performed four database searches conducted on September 29, 2023, using the “Web of Science” platform with the name of the five major Brazilian basins as the search criteria (“AMAZON BASIN”, “PARANÁ BASIN”, “PARAGUAY BASIN”, “TOCANTINS BASIN”, and “ARAGUAIA BASIN”). For each resulting dataset, we counted the number of scientific papers published between 1940 and 2023 in peer-reviewed journals, which yielded 10,781 papers for the Amazon Basin, 3,903 papers for the Paraná Basin, 882 papers for the Paraguay Basin and only 606 and 353 papers for the Tocantins and Araguaia basins, respectively. In light of this, the TOAR stands as one of the most significant yet overlooked basins in Brazil. Unfortunately, this political and scientific neglect has ultimately contributed to biodiversity loss. Given the limited number of studies conducted in the TOAR over time, this loss may encompass a substantial portion of undocumented and undescribed biodiversity.

2.2.2 Data acquisition and preparation

Annual land use maps from 1985 to 2020 were acquired via the MapBiomas platform (MapBiomas, 2021; Souza et al., 2020). All rasters had a consistent matrix resolution of 30x30 meters, the same spatial extent, and utilized EPSG 6933 (WGS 84/NSIDC EASE-Grid 2.0 Global). The MapBiomas project is a collaborative, multi-institutional initiative aimed at producing land use and land cover (LULC) maps. Automated classification processes were applied to satellite imagery to generate annual and national LULC maps. MapBiomas collection 6 offers data spanning from 1985 to 2020 and classifies 34 LULC categories using an empirical decision tree classification algorithm relying on single-date spectral mixture analysis (MapBiomas, 2021; Souza et al., 2020).

The original 34 categories from the MapBiomas mapping were consolidated into 10 equivalent categories. This categorization was performed to ensure the highest possible consistency among the LULC categories. The categorization is presented in Table 1. MapBiomas category 25 (other non-vegetated areas) was grouped under the category “other human activity”. This decision aligns with MapBiomas' detailed methodology since category 25 pertains to non-permeable surfaces primarily associated with human infrastructure or mining, which are distinct from the designated categories (MapBiomas, 2021; Souza et al., 2020). The other human activity category also encompasses the Mapbiomas categories silviculture and mining, which represented about 28% and 60% of the OHA category in 2020, respectively.

Table 1. Categorization of the MapBiomas land use and land cover categories.

Name	Abbreviation	Type	MapBiomas Categories
Natural forest	NFR	Natural	Forest Formation, Mangrove, Wooden Restinga
Savanna formation	SVN	Natural	Savanna Formation
Grassland	GRA	Natural	Grassland
Wetland	WET	Natural	Wetlands
Pastures	PAS	Anthropic	Pasture, Mosaic Agriculture and Pasture
Agriculture	AGR	Anthropic	Sugar Cane, Soybean, Rice, Other Temporary Crops, Coffee, Citrus, Other Perennial Crops
Urban infrastructure	URB	Anthropic	Urban Area
Other human activity	OHA	Anthropic	Forest Plantation, Mining, Other non-Vegetated Areas
Other natural formation	ONF	Natural	Other non-Forest Formations, Beach, Dune and Sand Spot, Rocky Outcrop, Salt Flat
Water	WAT	Natural	River, Lake, and Ocean

To analyze the landscape composition and dynamics, we utilized all 36 rasters, year by year, to create three products: LULC composition tables displaying the annual area of each category (objective 1); a figure illustrating the net/gross losses and gains of all the LULC categories and line plots for quantifying the area dynamics of the categories over time (objective 2); a map indicating stable areas from 1985 to 2020, plotted alongside the TOAR protected areas (objective 3). The TOAR shapefile was identical to the one employed for representing the Tocantins Hydrographic Region in the MapBiomas platform. The shapefile for protected areas was obtained from the National Spatial Data Infrastructure of Brazil (INDE, 2023). We only considered the protected areas listed in the Brazilian National System of Conservation Units (SNUC in Portuguese). We utilized QGIS software (version 3.10) for LULC reclassifications, to produce the LULC thematic maps, and for the generation of the aforementioned products.

2.2.3 Intensity analysis

To identify systematic spatiotemporal patterns in land use, we conducted a full land use intensity analysis following the approach outlined in Aldwaik and Pontius (2012) using the R package OpenLand: Quantitative Analysis and Visualization of Land Use and Cover Changes (Exavier and Zeilhofer, 2020). This methodology assumes that you have maps of the identical area, depicting the same LULC categories, at a minimum of two different time points. Overlaying maps from any two distinct time points generates a cross-tabular matrix. In this matrix, rows represent categories from the initial time, columns represent categories from the subsequent time, and the entries quantify the area that has transitioned from the initial category to the subsequent category within the specified time frame (Aldwaik and Pontius, 2012).

The intensity analysis comprises three levels: interval; category; transition. The interval level concentrates on identifying time intervals during which the overall annual rate of change was either rapid or slow. The category level assesses fluctuations in both the magnitude and intensity of gross losses and gains within each category across different time intervals (Aldwaik and Pontius, 2012). To depict the intensity of land use changes in the TOAR, we generated maps illustrating the total number of LULC transitions for every pixel in the study area. Furthermore, by employing the interval and category levels of the intensity analysis, we created two figures elucidating the overall landscape and annual change intensities within categories (objective 4).

At the transition level, it also determines which transitions a particular category avoids and prioritizes within a given time period (Aldwaik and Pontius, 2012). Thus, at the transition level, the analysis is composed of a winning category (category *n*) and a losing category (category *m*), in which *n* prioritizes or avoids gaining area from *m* at a given intensity in a given time interval. The uniform intensity of transition from category *m* to all non-*m* categories at a given time interval is represented as Vtm. Meanwhile, Qtmj stands for the intensity of transition from category *m* to a specific category *n* during the same time interval. If Qtmj > Vtm, it signifies that category *m* is losing area to category *n* at a rate exceeding the uniform intensity for that time interval. Similarly, Wtn represents the uniform intensity of transition to category *n* from all non-*n* categories at a given time interval, while Rtin indicates the intensity of transition from a specific category *m* to category *n* during that time interval. Therefore, when Rtin > Wtn, it implies that category *n* is prioritizing the acquisition of area from the specific category *m* during that specific time interval (Aldwaik and Pontius, 2012). Consequently, we identified systematic transitions, which occur when category *n* consistently aims to acquire area from category *m* during a specific time interval. These transitions are characterized by the fulfillment of both the Qtmj > Vtm and Rtin > Wtn conditions.

We conducted the transition level analysis six times, altering the *m* category among NFR, SVN, GRA, WET, PAS, and AGR. If category *m* lost to another at a rate higher than the uniform loss rate within a specific interval (Qtmj > Vtm), we examined the Wtn and Rtin of that winning category to determine whether a systematic transition was present. Additionally, we opted to streamline the presentation of transition level results and created charts to emphasize the primary systematic transitions regarding occurrence, area, and intensity for all 35 years (objective 5). The occurrence output illustrates how frequently each *n* category appeared concerning the total count of systematic transitions involving the *m* category (Equation 1). The area output displays the percentage of area for each *n* category in relation to the total area of systematic transitions involving *m* (Equation 2). Lastly, the intensity output developed using Equations 3, 4, and 5 first calculates the total difference, representing the sum of the difference between the intensity of loss for *m* and the intensity of gain for *n*, relative to the respective uniform loss and gain values (Equation 3). Later, the same calculation is used to determine the *n* difference, albeit exclusively for systematic transitions involving the specific *n* category (Equation 4). Using the previously obtained values, the *n* intensity indicates the percentage that the *n* difference represents in the total difference (Equation 5).

Equation 1.

$$\boldsymbol{n}\ \textbf{Occurrence}\ (\%) = \frac{\boldsymbol{n}\ \textbf{Occurrences}}{\boldsymbol{m}\ \textbf{Total systematic transitions}}\ \textbf{x 100}$$

Equation 2. $$\boldsymbol{n}\ \textbf{Area}\ (\%) = \frac{\sum_{\mathbf{i}=\boldsymbol{n}} \textbf{Transition Area}}{\sum \textbf{Transition Area}}\ \textbf{x}\ \mathbf{100}$$

Equation 3. $$\textbf{Total Difference} = \sum(\mathbf{Qtmj} - \mathbf{Vtm}) + (\mathbf{Rtin} - \mathbf{Wtn})$$

Equation 4. $$\boldsymbol{n}\ \textbf{Difference} = \sum_{\mathbf{i}=\boldsymbol{n}}(\mathbf{Qtmj} - \mathbf{Vtm}) + (\mathbf{Rtin} - \mathbf{Wtn})$$

Equation 5. $$\boldsymbol{n}\ \textbf{Intensity}\ (\%) = \frac{\boldsymbol{n}\ \textbf{Difference}}{\textbf{Total Difference}}\ \textbf{x}\ \mathbf{100}$$

2.3 Results

2.3.1 Landscape land use: composition and changes

Changes in land use between 1985 and 2020 can be summarized into three primary patterns (Figs. 1b and 1c). First, there was a substantial loss in the natural forest, savanna, and grassland categories, amounting to approximately 110,000, 61,500, and 9,000 km², respectively. Second, remarkable stability was observed in wetland and water areas, with minimal changes in comparison to the other natural categories. Last, there was remarkable growth in pastures and agricultural areas. The pastures area nearly doubled in size, occupying significant portions of natural forests and savannas, while the agricultural area expanded by 13 times its original extension.

The initial observation from Fig. 2a reveals a net area loss in natural forests, savannas, and grasslands, accompanied by a net gain in pastures and agricultural areas. The substantial gain and loss area values shown in Figs. 2b and 2c corroborate that the pastures category experienced the most significant gross change. Conversely, agriculture experienced relatively modest gross changes over the study period, with a notable increase in area gain beginning around the year 2000. Pastures emerged as the primary category gaining area throughout most intervals, while natural forests consistently represented the primary category losing area, eventually surpassed by pastures in 2007/2008.

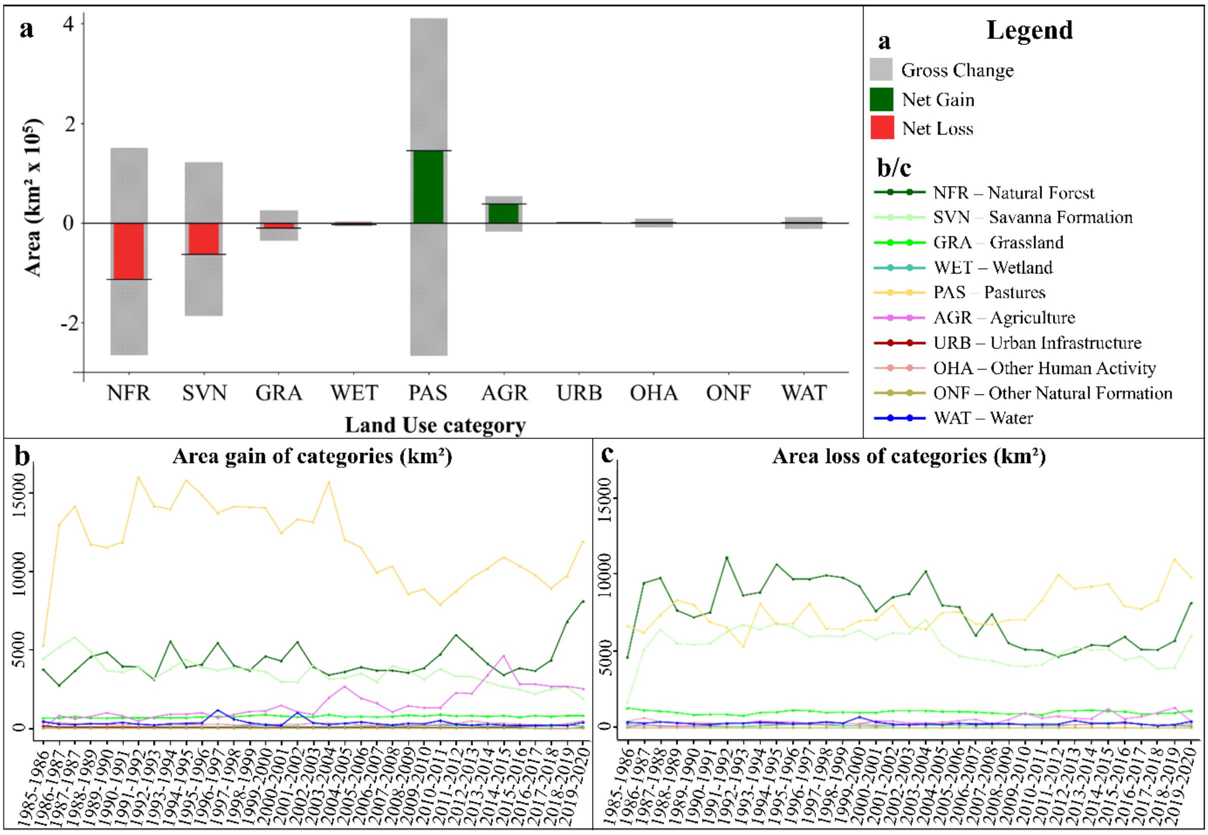


Fig. 2 a: Analysis of the net gains, losses, and gross changes in land use categories from 1985 to 2020. b: Timeline depicting area gains across the 10 land use categories analyzed from 1985 to 2020. c: Timeline illustrating area losses among the 10 analyzed land use categories from 1985 to 2020

2.3.2 Intensity analysis: landscape and category intensities

Nearly 61% of the pixels within the TOAR remained unchanged throughout the 35-year analysis (Fig. 3). These regions are further discussed as "stable areas." Pixels that underwent changes from 1 to 2 times accounted for 27.59% of the total, with a higher concentration observed in the western boundaries of the TOAR. Pixels that experienced 3–5 and 6–10 changes represented 9.66 and 1.75% of pixels, respectively, with a visual concentration primarily observed in the northeastern region of the TOAR.

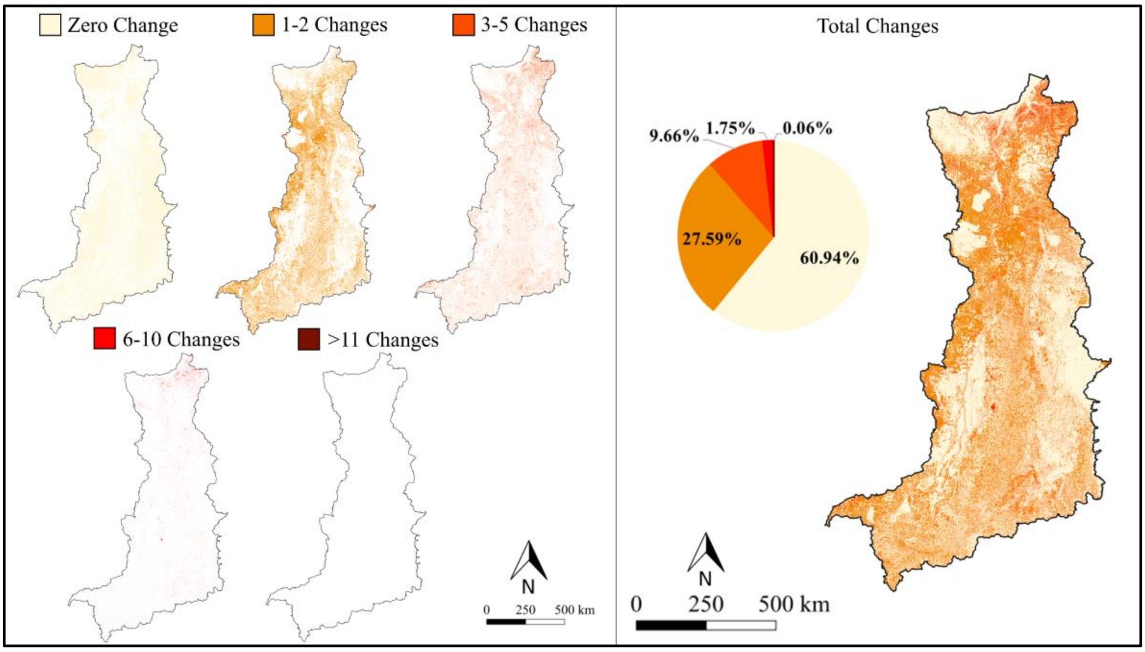
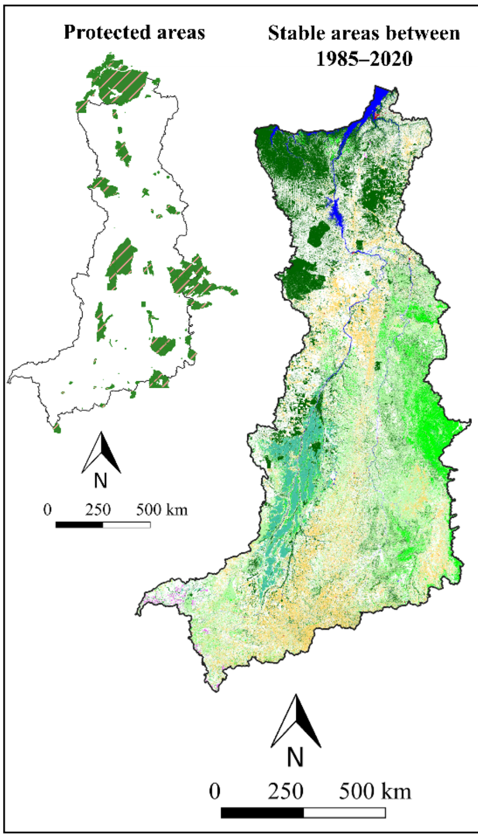


Fig. 3 Separate change intensity maps (left) and a combined map (right) representing the 1985 to 2020 period for the Tocantins-Araguaia hydrographic basin. Colors indicate the frequency of changes for each pixel during the analyzed period

Regarding the composition of stable areas (Fig. 4), savanna formations, natural forests, and pastures exhibited the highest stable area values. However, within the stable areas of natural categories, only 17.08% of wetlands, 11.89% of natural forests, and 9.37% of savanna formations were protected. Conversely, grasslands had 33.13% of their stable areas within protected areas. Nonetheless, the natural categories’ stable areas seemed to spatially match the protected areas layout in many parts of the map.



Composition of the stable areas

Color	Category	Total	Protected	Unprotected
	Natural Forest	169.734,75 km^2	20.175,00 km^2 (11,89 %)	149.559,75 km^2 (88,11 %)
	Savanna Formation	184.294,58 km^2	17.265,14 (9,37 %)	167.029,44 km^2 (90,63 %)
	Grassland	46.982,06 km^2	15.565,30 km^2 (33,13 %)	31.416,76 km^2 (66,87 %)
	Wetland	34.746,83 km^2	5.934,02 km^2 (17,08 %)	28.812,81 km^2 (82,92 %)
	Pastures	106.346,13 km^2	2.636,81 km^2 (2,48 %)	103.709,32 km^2 (97,52 %)
	Agriculture	2.201,94 km^2	3,19 km^2 (0,14 %)	2.198,75 km^2 (99,86 %)
	Urban Infrastructure	928,52 km^2	33,86 km^2 (3,65 %)	894,66 km^2 (96,35 %)
	Other Human Activity	213,90 km^2	25,52 km^2 (11,93 %)	188,38 km^2 (88,07 %)
	Other Natural Formation	3,08 km^2	0,03 km^2 (1,12 %)	3,05 km^2 (98,88 %)
	Water	14.163,12 km^2	3.067,83 km^2 (21,66 %)	11.095,29 km^2 (78,34 %)

Fig. 4 Mapping of stable areas between 1985 and 2020 (left) and breakdown of stable area compositions in terms of area and percentage (right)

Over the 35-year study period, the uniform intensity resulted in a 2.41% annual change in the TOAR's land area (Fig. 5). A timeline analysis revealed periods of both rapid and slow landscape changes. Between 1985/1986 and 2004/2005, the landscape experienced more frequent rapid changes. Starting from 2005/2006 and extending until the end of the study period, there was a shift in the pattern, resulting in a slower pace of landscape change over these periods, with only a few exceptions.

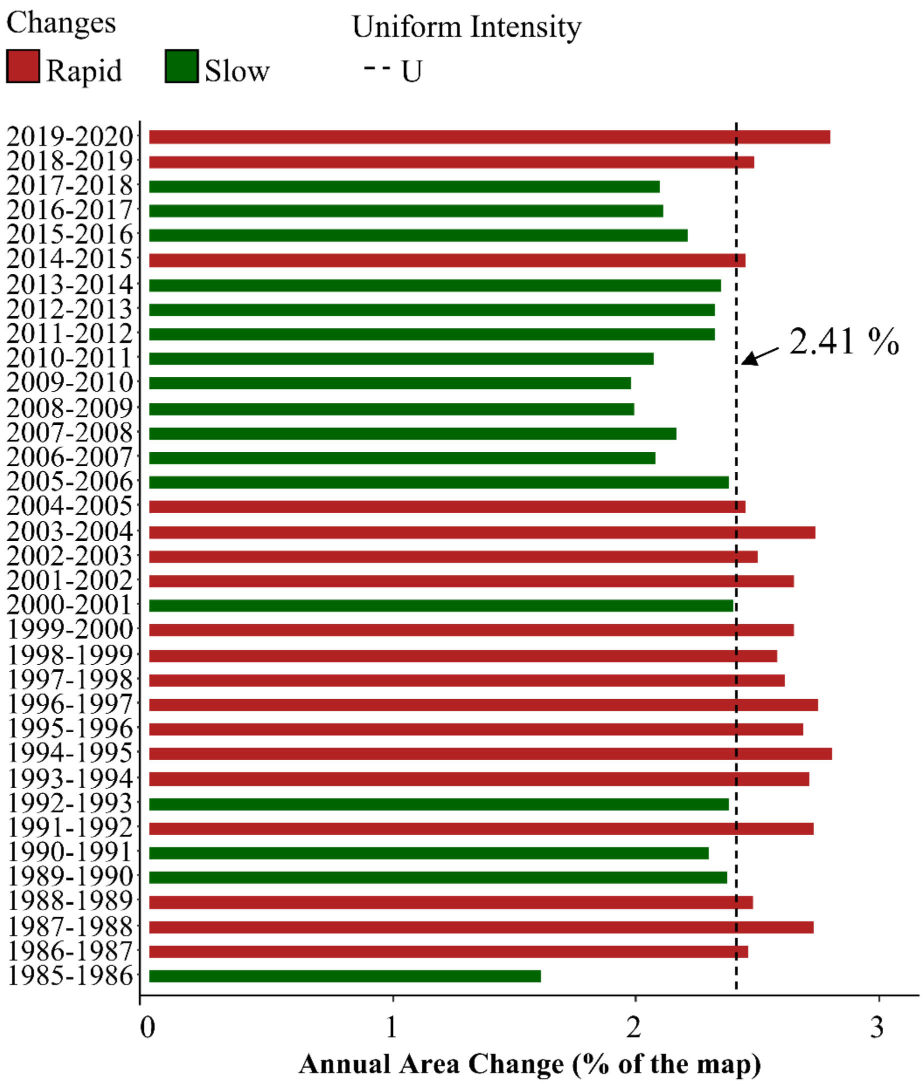


Fig. 5 Interval-level results of the land use intensity analysis for the 1985 to 2020 period. Rapid landscape changes are indicated by red lines, while slow landscape changes are represented by green lines. The dotted line corresponds to the uniform change intensity (U)

In most of the analyzed intervals, natural forests exhibited a gain intensity below and loss intensity above the uniform change intensity of the landscape (Fig. 6). Savannas consistently showed both gain and loss intensities below the uniform change intensity throughout the entire period, with only a few exceptions. In the case of pastures, the gain intensity consistently exceeded the uniform threshold, particularly at the beginning of the series. Conversely, pasture loss intensity closely followed the uniform threshold in most intervals. Regarding agricultural areas, they displayed the highest gain intensities among all categories, transitioning from a peak of approximately 20% in 1986/1987 to 10% in 2019/2020. The agriculture loss intensity closely followed the uniform threshold in most intervals.

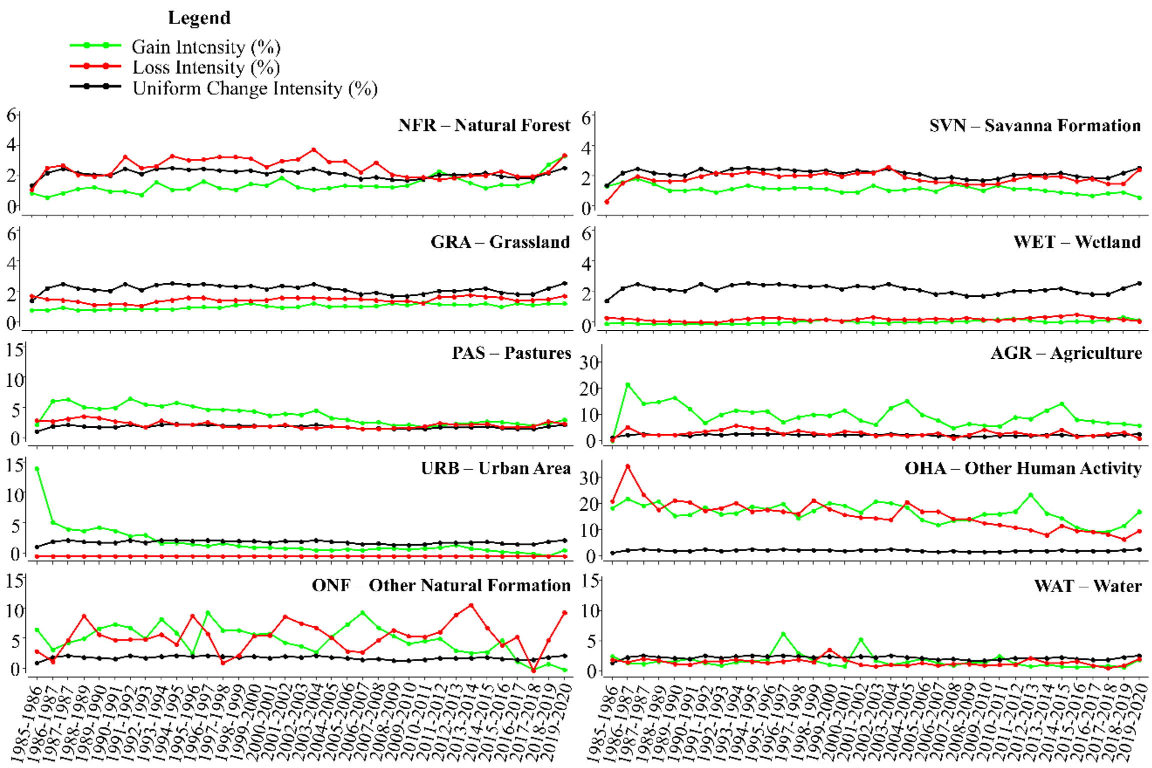


Fig. 6 Results of the category-level land use intensity analysis comparing the intensities of loss (represented by the red line) and gain (indicated by the green line) for various categories with the uniform landscape change intensity (depicted by the black line) across all yearly intervals spanning from 1985 to 2020

2.3.3 Intensity analysis: systematic transitions

Fig. 7 presents the systematic transitions derived from the transition level of the intensity analysis for all six *m* categories. When examining the results with natural forest as the m category, it becomes evident that only pastures and water prioritized gaining area from natural forests throughout the entire 35-year study period. Pastures emerged as the primary targeting category in terms of occurrence, area, and intensity. Savanna was systematically targeted by other human activity, pastures, and water categories. Concerning occurrence and intensity, the other human activity category stood out as the most prominent *n* category. However, in terms of area, the pastures category accounted for 88% of all systematically lost savanna areas.

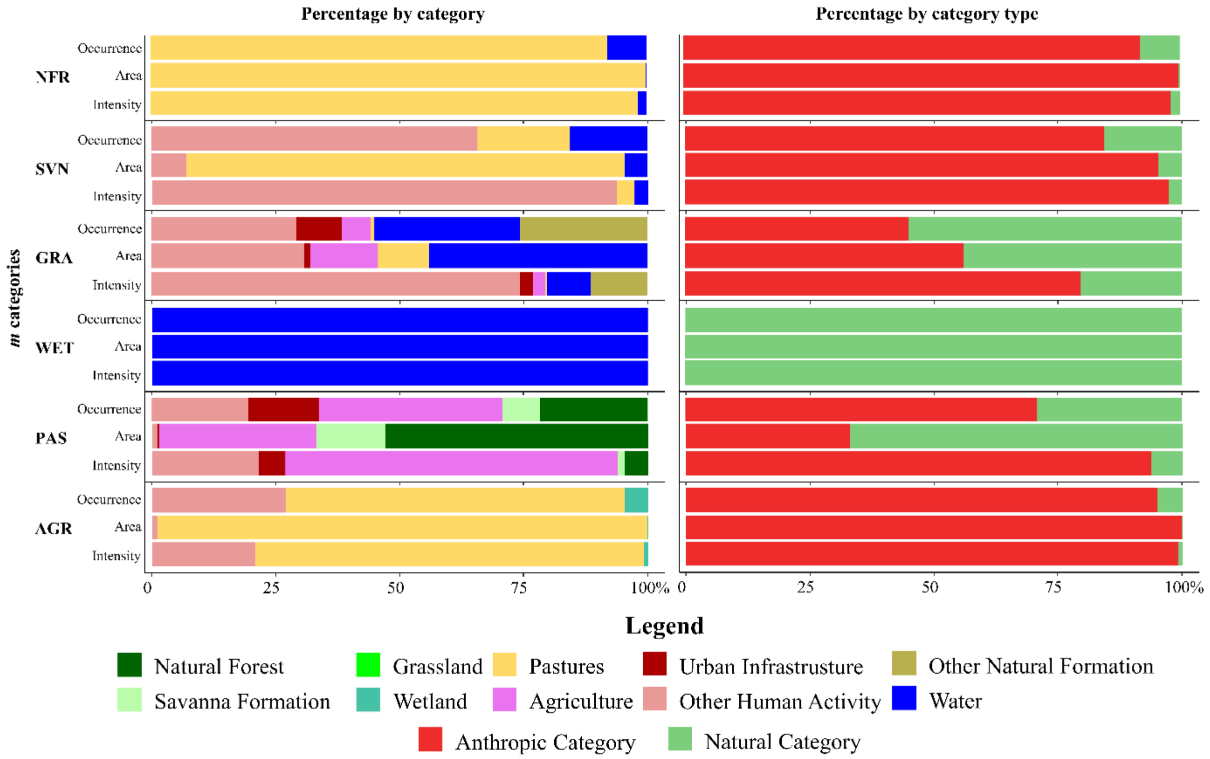


Fig. 7 Composition of the target systematic transitions of each *m* category sorted by *n* category (left) and by *n* category type (right). For each *m* category, the figure displays the output in terms of occurrence, area, and intensity. The analyzed *m* categories were as follows: NFR – Natural forest; SVN – Savanna formation; GRA – Grassland; WET – Wetland; PAS – Pastures; AGR – Agriculture

The grassland category was systematically targeted by six other categories. In terms of occurrence, the majority was represented by other human activity, water, and other natural formations. The area output was also evenly distributed among the *n* categories, with water (43.99%) and other human activity (30.83%) being the main contributors. The intensity output for grassland was largely influenced by the other human activity category (74.19%).

When using the pastures category as *m*, there were transitions with five targeting categories. The occurrence output was evenly distributed, with agriculture being the most prominent *n* (36.96%). The area output consisted of natural forest (52.98%), agriculture (31.59%), and savanna (13.97%). Despite representing about 14% of the occurrences, the urban infrastructure category accounted for only 0.3% of pastures lost area. In terms of intensity, agriculture represented 66.98%, followed by the other human activity category at 21.55%.

Despite accounting for the majority of the area output, the natural forest category only contributed 4.8% to the intensity.

Lastly, when agriculture was used as the *m* category, the results demonstrated a predominance of transitions involving the other human activity and pastures targeting categories. Pastures accounted for 68.29% of the occurrences, 98.66% of the area, and 78.22% of the intensity. Consequently, transitions involving agriculture were significantly dominated by anthropic targeting categories.

2.2 Discussion

Our key findings reveal that the TOAR landscape experienced remarkable anthropogenic changes during the past 35 years, which have primarily been driven by the expansion of agricultural activities. Upon examining the entire hydrographic basin, we determined that less than half of the area changed over the past 35 years, with fewer than 13% of the analyzed pixels experiencing three or more alterations. Stable areas were predominantly of natural forest, savanna, and pastures, aligning spatially with legally protected areas in various regions of the TOAR. The natural forests, savannas, and grassland categories—representing the vegetation types of the Amazon and Cerrado biomes—exhibited remarkable area losses over time. Natural forests experienced substantial area loss at high intensities due to pasture expansion, whereas the savanna and grassland categories exhibited area reductions at lower intensities. In contrast, pastures and agricultural areas expanded significantly at high intensities. Furthermore, the systematic target transitions between categories revealed that the natural forest, savanna, and grassland categories were primarily targeted by pastures and other human activities, while pastures and agriculture systematically lost area to each other.

Historical inland colonization in Brazil has been closely linked to disordered land occupation and deforestation (Barros and Baggio, 2021; Fearnside and Graça, 2006; Reydon et al., 2020). To assert control over sparsely populated and remote regions, numerous Brazilian governments have implemented strategies—especially in the northern and central-western states—to encourage the establishment of new settlements and expansion of agricultural frontiers (Barros and Baggio, 2021). One of these mechanisms involves investments in transport infrastructure—notably the construction of highways—which play a pivotal role in the process of forest losses by encouraging population migration and fostering the expansion of human infrastructure (Barros and Baggio, 2021; Fearnside, 2001; Fearnside and Graça, 2006). Highway construction, and even the mere prospect of it, frequently leads to land grabbing, which is an activity where individuals explore the forest for unclaimed land and create the facade of ownership by clearing the land, all with the expectation of future profits from selling the land at higher prices due to its proximity to the highway (Fearnside, 2023; Fearnside and Graça, 2006; Ferrante et al., 2021). In addition to contributing to deforestation, this practice frequently spawns a pattern of violence, with competing land grabbers frequently engaging in armed conflicts over land disputes (Fearnside and Graça, 2006; Ferrante et al., 2021).

Beyond deforestation driven by settlements and highways, the landscape of the Amazon/Cerrado ecotone faces threats from various soybean cultivation hubs and expansive areas designated for cattle ranching, which have historically been the primary causes of forest loss in Brazil (Escobar et al., 2020; Nepstad et al., 2014). Historical deforestation rates in Brazil have long been linked to agricultural expansion (Gibbs et al., 2010), while targeted interventions involving producers, processors, and buyers within the soy and beef supply chains have contributed to a 70% reduction in deforestation between 2005 and 2013 in the Amazon region (Nepstad et al., 2014; Reydon et al., 2020). However, our findings revealed a substantial loss of approximately 111,000 km² of natural forest, which occurred at high intensities, along with 62,000 km² of savanna loss within the TOAR between 1985 and 2020. Additionally, these results confirm that these categories were systematically affected by the expansion of pastures areas. These findings raise concerns regarding the unchecked expansion of livestock operations in the basin. This is a worrisome trend since this activity has already been linked to elevated rates of deforestation and habitat fragmentation worldwide (Lapola et al., 2014; Nepstad et al., 2014; zu Ermgassen et al., 2020), as well as the introduction of invasive species, resulting in biodiversity loss (DiTomaso, 2000). This scenario indicates that instead of recklessly expanding pastures areas, producers should consider investing in intensification systems, such as implementing rotational grazing and incorporating crop rotations into an integrated crop and cattle system. These practices have already demonstrated their ability to significantly enhance profitability and facilitate land conservation, thereby slowing down further expansion (Gama-Rodrigues et al., 2022; Garrett et al., 2018; Gil et al., 2018).

For decades, Brazil has implemented policies prioritizing development at the expense of the environment (Azevedo-Santos et al., 2017; Ferrante and Fearnside, 2019; Pelicice et al., 2021; Reydon et al., 2020). It is well-documented that habitat loss and fragmentation caused by human activities are the primary drivers of the ongoing biodiversity crisis and the decline in ecosystem services (Jacobson et al., 2019; Newbold et al., 2015; Vitousek et al., 1997). In fact, human activities have significantly altered the terrestrial biosphere to the extent that 95% of lands show some evidence of human activity (Kennedy, 2019). Tropical humid forests, such as the Amazon rainforest, are the only high-biodiversity biomes that still have more than half of their area experiencing relatively low levels of human influence (Jacobson et al., 2019). In contrast, tropical dry forests, which include the Brazilian Cerrado, are notable for having some of the world’s highest levels of human influence and an increasing fragmentation rate (Jacobson et al., 2019). Presently, the TOAR, essentially the ecotone between the Amazon and Cerrado biomes, is the primary region targeted for agricultural expansion in Brazil, as indicated in Presidential Decree 8447 of 2015 (Pelicice et al., 2021; Polizel et al., 2021). Furthermore, Brazil is the world's second-largest agricultural producer and is projected to experience the most substantial output increases among all countries worldwide over the next four decades (Escobar et al., 2020; FAO, 2006; Strassburg et al., 2014). This, combined with the historical and recurring governmental incentives for occupation and agricultural expansion in the basin (Barros and Baggio, 2021; Polizel et al., 2021), along with the resulting population influx (Fearnside, 2001), is likely to further expand the regions where future human-induced modifications will occur in the TOAR landscape, ultimately impacting the biodiversity of the Cerrado and Amazon biomes.

In addition to deforestation, the TOAR confronts ongoing threats from other human activities, such as mining. While mining is often overshadowed by other forms of land use, its impacts are profoundly damaging (Azevedo-Santos et al., 2021; Pelicice et al., 2021). In our analysis, mining was categorized under the broader category of “other human activity,” which encompassed activities such as silviculture, aquaculture, and mining (MapBiomas, 2021; Souza et al., 2020). This categorization decision was made due to the other human activity category's relatively small spatial extent, amounting to a maximum of 0.28% of the landscape in 2020. However, despite its limited spatial extent, this category presented a substantial impact in terms of both intensity and occurrence in the systematic transitions analysis, especially with savanna and grassland. Furthermore, the high gain and loss intensity values of the other human activity category confirm the widespread and highly impactful nature of these activities on ecosystems. Specifically regarding mining, in addition to the significant changes in landscape composition and aesthetics, this activity also has impacts related to water quality, disruptions in river continuity, and reductions in habitat availability resulting from the establishment of mines (Azevedo-Santos et al., 2021; Queiroz et al., 2022).

Furthermore, the mine tailings generated during the extraction and refinement of various minerals pose risks to the atmosphere, aquatic ecosystems, and biota (Moreno-Brush et al., 2019; Vasconcellos et al., 2022). This raises additional concerns when considering that certain compounds are bioaccumulative, entering the food chain and ultimately affecting humans, particularly through the consumption of fish (Vasconcellos et al., 2022). Fish is an economically vital food resource for traditional communities and a key attraction for sport fishing tourism in the region (Santana et al., 2021; Vasconcellos et al., 2022). Additionally, mining activity often leads to indirect environmental harm, including the migration of people to the region, resulting in precarious settlements with common social issues such as inadequate sanitation, the spread of epidemic diseases, labor exploitation, deforestation, prostitution, and violence (Fearnside, 2001; Moreno-Brush et al., 2019; Queiroz et al., 2022).

Another significant concern in the TOAR is river damming, a well-documented cause of extreme alterations in ecosystem biodiversity and functioning (Agostinho et al., 2016; Latrubesse et al., 2017; Pelicice et al., 2017; Winemiller et al., 2016). Our findings indicate relative stability in the wetland and water categories within the TOAR. However, it is crucial to assess the Tocantins River and the Araguaia River separately. Whereas the Tocantins River presently features seven major hydroelectric dams and numerous smaller dams in its tributaries (Pelicice et al., 2021; Swanson and Bohlman, 2021), the Araguaia River essentially maintains its natural free-flowing regime. It hosts the most geodiverse floodplain in the Cerrado, having more fish species than any other basin in the region (Latrubesse et al., 2019; Martins et al., 2021; Pelicice et al., 2021). Despite the critical importance of preserving biodiversity through the maintenance of a natural free-flowing regime (Agostinho et al., 2016; Swanson and Bohlman, 2021), the Araguaia River basin has multiple dams planned along its main channel and tributaries (Latrubesse et al., 2017; Santana et al., 2021). Therefore, a detailed analysis of changes in the water and wetland categories for each river could highlight notable differences between these two ecoregions (Swanson and Bohlman, 2021). Concerning wetlands, which are more abundant in the Araguaia River Basin (Martins et al., 2021), their stability may be attributed to the presence of significant legally protected areas, including the Araguaia Island National Park, Bananal Island Protected Area, and Araguaia State Forest (INDE, 2023). Although these protected areas encompassed approximately 17% of the total stable wetland areas between 1985 and 2020, the presence of protected areas and their land use characteristics may have contributed to a positive spillover effect, resulting in fewer land use changes than would have occurred otherwise, thus contrasting what occurred in the unprotected surroundings (Fuller et al., 2019; Schmitz et al., 2023).

Indeed, protected areas currently represent the primary response to the challenge of enhancing conservation efforts and safeguarding biodiversity (Azevedo-Santos et al., 2017; Fuller et al., 2019; Jacobson, 2019). Brazil's allocation of legal protection for the Amazon and Cerrado biomes is relatively limited, with only 28.7 and 7.5% of their respective areas under the current protection (Polizel et al., 2021). Moreover, there exists a substantial knowledge gap within the Cerrado and Amazon biomes (Borges and Loyola, 2020; Castro et al., 1999; Hopkins, 2007), where a significant portion of biodiversity remains undescribed and thus faces even greater threats. In light of this, the creation of various types of protected areas can substantially mitigate the progression of forest and biodiversity loss. Sometimes, even the mere prospect of establishing a protected area can deter encroachment (Azevedo-Santos et al., 2017; Fearnside and Graça, 2006; Fuller et al., 2019). Our findings illustrate the spatial alignment between stable areas of natural categories and legally protected regions across the TOAR, particularly in the case of natural forests, wetlands, savannas, and grasslands. It is important to note that our study did not consider the year of creation of the protected area neither their land use regulations. However, whether the protected area was established to preserve already conserved ecosystems or to restore degraded ones, the spatial alignment we observed underscores the vital importance of protected areas in conservation practices.

This information gains significance in light of recent events in Brazil, including science denial and environmental setbacks (Pelicice and Castello, 2021; Thomaz et al., 2020). On recent years, Brazil has witnessed frequent actions such as the downgrading, downsizing, and reclassification of protected areas (Azevedo-Santos et al., 2017; Conceição et al., 2022; Metzger et al., 2019) as well as ongoing budget reductions—particularly affecting scientific agencies (Reydon et al., 2020). Misplaced governmental actions have had a detrimental effect on the Brazilian licensing system for works/activities with potential impact and have eroded the operational capacity and autonomy of key institutions tasked with assessing, monitoring, and enforcing environmental legislation (Azevedo-Santos et al., 2017; Ferrante and Fearnside, 2019; Reydon et al., 2020; Siqueira-Gay et al., 2020; Trindade et al., 2022). Additionally, our findings illustrate a significant decline in natural forests and savannas and an escalation in change intensity during the later years of the study period. These trends align with the data reported in the MapBiomas Brazilian Annual Deforestation Report for 2022 (Alerta

MapBiomas, 2023). The MapBiomas report highlighted a 22.3% increase in forest loss in Brazil from 2021 to 2022, with the Amazon and Cerrado biomes accounting for 58 and 32.1% of the deforestation, respectively (Alerta MapBiomas, 2023).

Whether through the disruption of freshwater ecosystems (Santana et al., 2021), the transformation of the Amazon-Cerrado ecotone into vast farmlands (Pelicice et al., 2021; Polizel et al., 2021), or due to ill-conceived political decisions, the degradation of the TOAR is emerging as a matter of global concern, highlighting the urgent need for Brazil to intensify its focus on conservation activities within this basin. Our results have revealed that a substantial portion of the TOAR has remained unchanged over the past 35 years despite various impacts linked to human expansion. Therefore, it is crucial to acknowledge that the primary driver of deforestation and biodiversity loss worldwide is not solely population growth but rather consumption patterns, particularly in developed nations (Hughes et al., 2023). As previously mentioned, Brazil—and particularly the present Amazon/Cerrado agricultural frontier—plays a significant role in this regard, serving as a hub for the production of export-oriented commodities such as beef and soybeans (Escobar et al., 2020; Nepstad et al., 2014; Strassburg et al., 2014; zu Ermgassen et al., 2020). A fundamental reevaluation of agricultural practices and expansion is imperative to reduce Brazil's environmental footprint. Achieving this necessitates improved land planning and participatory governance (Nepstad et al. 2014; Strassburg et al., 2014), increased investments in environmental oversight and law enforcement, and the preservation and establishment of protected areas (Azevedo-Santos et al., 2017; Pelicice and Castello, 2021). Additional appropriate measures would involve initiatives that encourage sustainable farming intensification, offering the potential to generate employment opportunities while minimizing land use (Garret et al., 2018; Gil et al., 2018; Hughes et al., 2023). Furthermore, the decarbonization of production chains stands as a means to offset environmental impacts while augmenting the value associated with products (Escobar et al., 2020; Gama-Rodrigues et al., 2022).

Given the nation's abundant natural resources and its significance in both present and projected agricultural production, Brazil should actively engage as a primary participant in global dialogues concerning biodiversity conservation (FAO, 2006; Strassburg et al., 2014). Notable examples of Brazilian public policies include the revival of the Amazon Fund, which had faced a prolonged suspension due to disagreements among participating countries (Government of Brazil, 2023), and the recent establishment of the trilateral alliance between Brazil, Democratic Republic of Congo, and Indonesia. This alliance is designed to foster cooperation in the bioeconomy field and advance the sustainable stewardship, preservation, and rejuvenation of tropical forests and critical ecosystems (Government of Brazil, 2022). Currently, this alliance is negotiating funding mechanisms linked to the REDD+ program, which promotes policies aimed at reducing greenhouse gas emissions, curbing deforestation, and preserving and safeguarding forest carbon stocks (UNFCCC, 2023). The conclusion of Brazil's previous presidential administration (2019–2022), which oversaw a series of environmental setbacks (Capobianco, 2019; Pelicice and Castello, 2021; Thomas et al., 2020), undoubtedly represents a significant moment for conservation efforts in the nation. Nevertheless, it is important to note that a change in government alone does not guarantee improvements in Brazil's environmental sector (Fearnside, 2023). While the new government has made a promising beginning, it is imperative that its forthcoming actions are subject to vigilant scrutiny by the scientific community, stakeholders, and the global community. This oversight would ensure that Brazil's extraordinary environmental significance is duly recognized and addressed.

2.3 Conclusion

The analysis of land use and environmental conservation in the context of the TOAR has highlighted the complexity of landscape changes over the last three decades. The results of this study underscore the importance of coordinated actions to curb the loss of natural resources and biodiversity, especially in transition regions between biomes such as the Cerrado and the Amazon. Furthermore, the need for effective governance, the promotion of sustainable agricultural intensification, and the crucial role of protected areas emerges as essential elements in preserving these ecosystems. It is essential for Brazil to recognize its significant global role and intensify its efforts to balance economic development with environmental conservation. These efforts include national actions and broad international cooperation to address increasingly urgent challenges such as climate change and biodiversity loss. Continuous monitoring and the active participation of various stakeholders are essential to ensure that the country fulfills its responsibilities in protecting the unique ecosystems of the TOAR.

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3 UNSUSTAINABLE LAND USE TRAJECTORIES IN THE TOCANTINS/ARAGUAIA BASIN: INSIGHTS FROM FUTURE SCENARIO MODELING

ABSTRACT

The Tocantins/Araguaia Basin (TOAR) is a major watershed encompassing the Brazilian Cerrado and Amazon biomes. Recent land use and land cover changes have led to numerous environmental challenges. To plan for a more sustainable future with fewer environmental impacts, we modeled future land use in TOAR (2015–2045) under three area demand scenarios: Business-as-usual (BAUS), Conservation-based (CONS), and Production-based (PROD). We used a spatially explicit land use and land cover model CLUE. Our findings show that the land use changes in TOAR are primarily driven by key agricultural factors, including predominant soil type, average solar radiation, average yearly precipitation, and wind speed. Projections for the year 2045 indicate the persistence of ongoing deforestation and fragmentation patterns in the basin, particularly under the PROD scenario. Natural forests, savannas, and grassland are projected to experience significant losses, comprising only 13%, 19.2%, and 3.8% of the 2045 landscape, respectively, in the most optimistic conservation-based scenario. These results highlight the urgent need for proactive conservation efforts, stricter regulations, and enhanced environmental considerations in developmental plans to alleviate the adverse impacts on TOAR and the Cerrado biome.

***Keywords*:** Sustainability; Conservation; Amazon; Brazilian Cerrado; Water Resources; Public Policy.

3.1 Introduction

Freshwater ecosystems, including rivers, lakes, and wetlands, play pivotal roles in ecology, economy, and human well-being (Chamon et al., 2022; Lovejoy and Nobre, 2018; Salmona et al., 2023; Vitousek et al., 1997). They provide essential habitats for numerous species, preserving biodiversity (Chamon et al., 2022) and in addition, contribute to water purification and flood control (Latrubesse et al., 2019; Nóbrega et al., 2020; Salmona et al., 2023). Furthermore, they sustain vital industries such as fishing, tourism, and energy production while providing water for agriculture and human needs (Latrubesse et al., 2019; Salmona et al., 2023). However, these ecosystems face various challenges, including pollution from agricultural and urban sources, anthropogenic expansion, habitat fragmentation, and climate change (Latrubesse et al., 2019; Nóbrega et al., 2020; Pelicice et al., 2021; Vitousek et al., 1997). Additionally, unregulated land use practices leading to deforestation, degradation of wetlands, and habitat loss, ultimately undermine ecosystem resilience and biodiversity (Polizel et al., 2021; Salmona et al., 2023; Vitousek et al., 1997).

Brazil has been exhibiting alarming rates of ecosystem degradation over the last decades, where deforestation poses a particularly significant challenge in environmental planning and management, especially within the Brazilian Savanna (Cerrado) (Bispo et al., 2023; Latrubesse et al., 2019; Pelicice et al., 2021; Polizel et al., 2021). Widespread deforestation in this biome not only jeopardizes its exceptional biodiversity but also has far-reaching consequences for the hydrological cycles of the entire region (Cardoso da Silva and Bates, 2002; de Oliveira et al., 2019; Latrubesse et al., 2019; Salmona et al., 2023). The reduction of vegetation cover in the Cerrado results in soil erosion, diminished water quality, and disrupted rainfall patterns, a matter of particular relevance when considering that the Cerrado biome encompasses the headwaters and the largest portion of crucial South American watersheds, including the Paraná/Paraguay, Tocantins/Araguaia, and São Francisco along with the upper catchments of major Amazon tributaries (Latrubesse et al., 2019; Salmona et al., 2023).

Despite the significance of the Cerrado biome, it is frequently omitted from Brazilian sustainability plans, with most focus on the Amazon biome (Bispo et al., 2023; Latrubesse et al., 2019;). Some of the past efforts to counteract increasing deforestation in the Amazon did not extend to, were delayed for, or were not replicated in the Cerrado biome. Examples include the exclusion of the Cerrado from the Soy Moratorium, the less stringent Brazilian forest code (20-35% obligatory protection in Cerrado versus 80% in the Amazon), and the delayed inclusion of the Cerrado in the National Plan for Prevention and Control of Deforestation (established in 2004 for the Amazon and only in 2010 for the Cerrado) (Bispo et al., 2023; Nepstad et al., 2014;).

Positioned centrally in the Brazilian Cerrado, the Tocantins/Araguaia Basin (TOAR) is one of Brazil's most threatened large watersheds (Pelicice et al., 2021). Situated between the Pantanal in the south and the Amazon Forest in the north, it is predominantly characterized by the Cerrado biome. The basin is home to diverse flora and fauna, including endangered species such as jaguars, giant otters, and the Araguaia River dolphin. Furthermore, the basin encompasses one of the world's largest and most biodiverse floodplains (Latrubesse et al., 2019), sheltering approximately 700 fish species, with many of them being endemic and endangered (Pelicice et al., 2021). Nevertheless, the TOAR is within the current agricultural frontier of Brazil (Bispo et al., 2023; Latrubesse et al., 2019; Pelicice et al., 2021), and the anthropogenic pressure has direct consequences for water quality, aquatic habitats, and the livelihoods of local communities depending on the basin's natural resources (Latrubesse et al., 2019; Nóbrega et al., 2020; Polizel et al., 2021). Furthermore, despite its critical ecological and socioeconomic importance, the basin lacks comprehensive studies and data compared to other regions of Brazil.

All these challenges underscore the critical importance of conducting basin-level analyses, as they aid in comprehending the intricate interplay of natural and human factors affecting the ecosystems, offering valuable information for informed decision-making (Couto et al., 2020; Mello et al., 2021). Land use analysis, closely intertwined with hydrographic basin management, is a crucial tool in environmental planning and the management of natural resources (Couto et al., 2020; Schmitz et al., 2023). In turn, land use modeling facilitates the digital representation and analysis of land use changes over time, providing particularly valuable insights for future scenarios, enabling the anticipation of challenges posed by urbanization, agricultural expansion, and deforestation (Malek et al., 2015; Verburg and Overmars, 2009; Zhou et al., 2022).

Given the necessity of environmental sustainability amid the expansion of anthropogenic activities, our primary goal was to assess future land use and land cover for the TOAR. Our study focused on three distinct land use demand scenarios spanning from 2015 to 2045, specifically addressing the basin’s primary vegetation and farming categories. These scenarios were modeled to offer valuable insights into the potential future land use trajectories and patterns in the basin. The first scenario, referred to as the "business-as-usual," maintained historical land use change rates while assuming no change in the local integrally protected areas. This scenario allows exploration of current trends and the potential consequences of inaction concerning land use policies and conservation efforts. In contrast, the "conservation-based" scenario simulated stricter land regulations by minimizing overall landscape changes while considering all protected areas as exclusion zones. This scenario aims to embody a proactive approach toward environmental preservation. Conversely, the "production-based" scenario, which serves as a cautionary exploration, incorporated higher overall change rates and considered the entire TOAR extent, including protected areas, as changeable.

We hypothesized that under the "business-as-usual" scenario, the primary vegetation cover in the TOAR basin will experience continued losses, with an increase in areas like pastures and agriculture. Implementing the "conservation-based" scenario with stricter land use regulations will lead to reduction in the rate of conversion of natural forests, savannas and grassland to other land use types. Finally, the "production-based" will lead to the most significant alterations in the basin's land use composition, with high area losses from vegetation categories and substantial increase in pastureland and agricultural areas. By assessing these scenarios, our study aimed to provide policymakers, researchers, and stakeholders with valuable information for informed decision-making concerning land use and conservation strategies within the TOAR.

3.2 Methods

3.2.1 Study area

This study encompasses the Tocantins/Araguaia hydrographic Basin (TOAR), a region of significant ecological and geographical importance located in central Brazil (Fig. 1). This basin harbors the Tocantins and Araguaia rivers and extends over approximately 967,059 km², making it one of the largest in Brazil. It spans five Brazilian states, namely Pará, Maranhão, Goiás, Tocantins, and Mato Grosso, holding crucial positions in the heart of the country (Coelho et al., 2012). The primary geographic features of the TOAR are shaped by its two main rivers. The Tocantins River, with a length of nearly 2,600 kilometers, flows from the southwestern region of the Goiás state to the north of the Pará state, having several hydropower dams and reservoirs along its extension. In contrast, the Araguaia River essentially maintains its free-flowing nature, preserving extensive floodplain systems (Latrubesse et al., 2019).

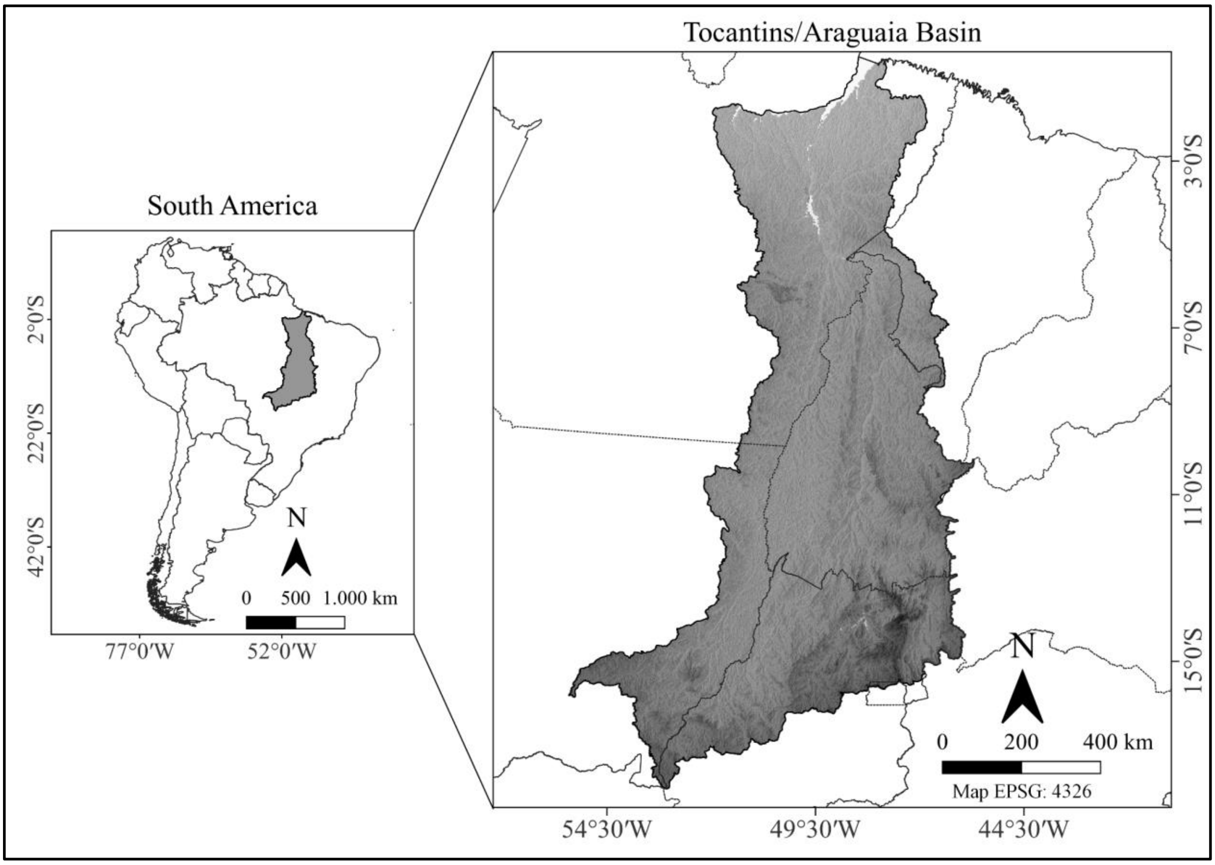

Fig. 1 Geographical localization of the Tocantins/Araguaia Basin. The dotted lines depict the boundaries of Brazilian states

Despite having about 9 million inhabitants, the TOAR displays a relatively low population density, with an average of approximately 9.3 inhabitants per square kilometer (a). Most of the population resides in major urban centers and state capitals, leaving substantial portions of the basin sparsely populated (Latrubesse et al., 2019; Ministry of Environment, 2005). Furthermore, the TOAR serves as a critical ecological corridor, facilitating the movement of numerous species between the Pantanal in the south and the Amazon Forest in the north (Latrubesse et al., 2019). This role underscores its importance for biodiversity conservation in Brazil. Nevertheless, the TOAR is located in the Brazilian current agricultural frontier, a region called MATOPIBA, in which activities such as deforestation, hydropower generation, mining, and extensive agriculture and cattle ranching exert significant pressure on the region's natural ecosystems (Alerta Mapbiomas, 2023; Pelicice et al., 2021; Polizel et al., 2021).

3.2.2 Model inputs

Land use maps were acquired from collection 6 of the Mapbiomas platform (Mapbiomas, 2021; Souza et al., 2020), covering the years 1985 and 2015 for the TOAR. The Mapbiomas project is a collaborative, multi-institutional initiative aimed at producing land use and land cover maps, in which automated classification processes are applied to satellite imagery to generate annual and national land use maps for Brazil (Mapbiomas, 2021). The original 21 Mapbiomas categories present in the TOAR maps were reclassified to 9 new categories: natural forest, savanna, grassland, wetland, pasture, agriculture, urban infrastructure, other human activity and water (Table 1). For each category, the area change rate between 1985 and 2015 was calculated for subsequent analyzes.

Table 1. Reclassification rules applied on the original MapBiomas land use and land cover

MapBiomas Categories	New Category	Type
3, 5, 49	Natural forest	Natural
4	Savanna formation	Natural
12	Grassland	Natural
11	Wetland	Natural
15, 21	Pastures	Anthropic
20, 39, 40, 41, 46, 47, 48	Agriculture	Anthropic
24	Urban infrastructure	Anthropic
9, 25, 30, 31	Other human activity	Anthropic
33	Water	Natural

To model land use changes in the TOAR we gathered 12 spatial characteristics (Table 2), also known as driving factors, commonly described in land-use prediction literature (Banerjee et al., 2022; Das et al., 2019; Malek et al., 2015; Trisurat et al., 2010; Wang et al., 2021; Zhou et al., 2022). The selection of the driving factor considered spatially distributed data that could affect the distribution of land use in the future. To prevent multicollinearity, we performed Spearman correlation tests between the 12 driving factors, maintaining those that did not show Spearman's $| r | \geq 0.6$ (Dormann et al., 2013). Therefore, the variables Digital elevation model and Average solar radiation were omitted from the analysis as they showed high multicollinearity with Average temperature and Average precipitation (Supplementary Material S1). To meet the model requirements for input data, both land use maps and driving factors were standardized to a 1000x1000 meters spatial resolution and subjected to alignment and null filling processes, ensuring all input data presented the same extension, spatial alignment, and cell count. The shapefile for protected areas was obtained from the Brazilian Ministry of the Environment website (Ministry of the Environment, 2023a). We performed all data processing using QGIS environment, version 3.22.

3.2.3 Land use modeling

We used the Dyna-CLUE software (Verburg and Overmars, 2009), a spatially explicit land use and land cover change model. CLUE is one of the most used land use models worldwide, and it was allready applied across different scales in many world regions in over 180 studies (IVM, 2023). In the wider South America region, the model has been applied to model deforestation reduction policies in the Amazon and Cerrado biomes (Banerjee et al., 2022), land use in Colombia (Banerjee et al., 2023; Clerici et al., 2019), sustainable development in Ecuador (Salazar et al., 2020), and agricultural and water management in Argentina (Lima et al., 2015). CLUE includes a nonspatial and a spatial module (Verburg et al. 2002), in which the nonspatial module calculates demand for all land use categories usually defined by a scenario or obtained from economic models or other projections. The spatial module translates these demands through a spatial allocation process based on probabilities and rules for different land use categories and a preset of land change restrictions (Verburg and Overmars, 2009). An advanced description of the CLUE-S model implementation and operation can be found in Verburg et al. (2002) and Verburg and Overmars (2009).

We modeled future land use and cover based on three distinct area demand scenarios:

i) Business-as-usual scenario (BAUS), reproducing the historical change rates (1985–2015). In this scenario, we considered the whole TOAR area as changeable, except the areas corresponding to integrally protected areas. Concerning this choice, studies have shown that the stricter land use regulations in this type of Brazilian protected areas can halt some anthropogenic landscape changes (Schmitz et al., 2023). Thereby, the TOAR protected areas were classified according to the Brazilian protected areas classification (Government of Brazil, 2000), and the integrally protected areas were considered as unchangeable in the BAUS scenario. Conversely, sustainable use areas were allowed to hold changes. This scenario allowed the exploration of current trends and the potential consequences of inaction regarding land use policies and conservation efforts.

ii) Conservation-based scenario (CONS), which was modeled with a 10% reduction in the change rates applied over the BAUS scenario. In the CONS scenario all the TOAR protected areas were considered as not changeable, regardless of their type or land use regulations. This scenario aims to reflect a proactive approach toward environmental preservation.

iii) Production-based scenario (PROD), which serves as a cautionary exploration, consisted of a 10% increase over the BAUS change rates. In this scenario, the whole TOAR was considered as changeable, regardless of protected areas.

To align with previous studies on future land use scenarios that employed various change rates (Trisurat et al., 2010; Wang et al., 2021), we selected a ±10% change rate (CONS and PROD scenarios) to represent a conservative and plausible range for future projections. Thereby, for each scenario, we simulated changes for the TOAR five main categories: natural forest, savanna, grassland, pasture, and agriculture. The remaining categories maintained fixed area values equal to those of the year 2015. The spatial representation of the scenario areas is presented in Fig. 2.

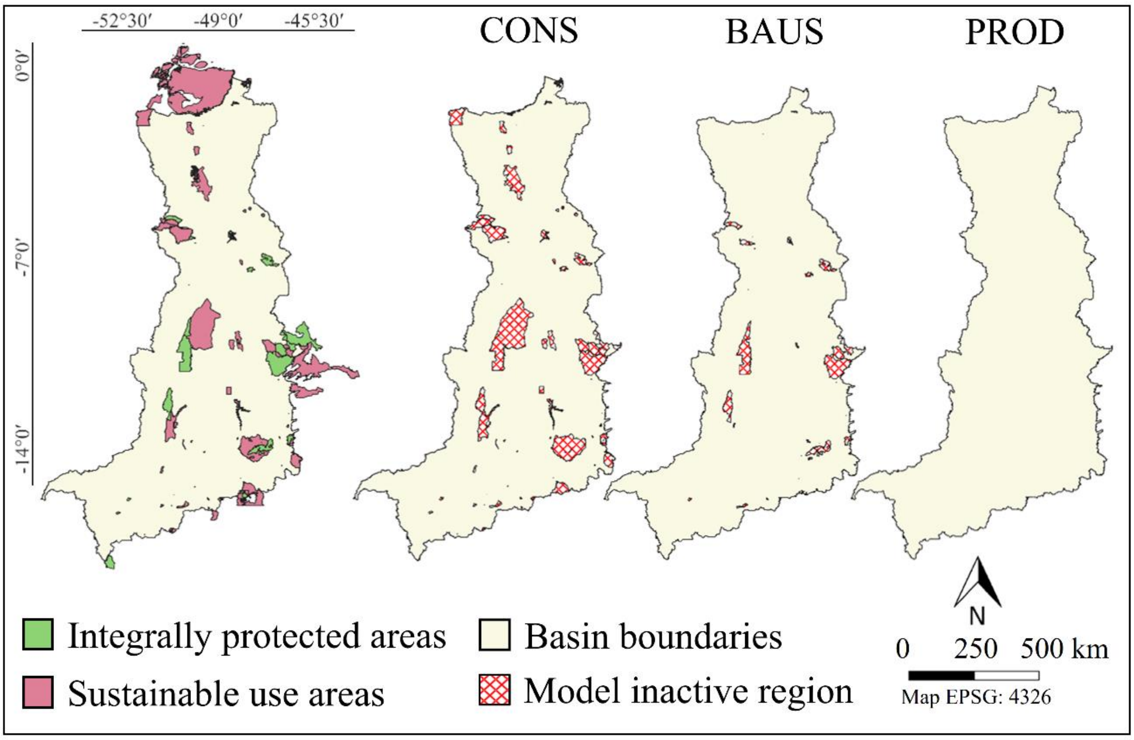

Fig. 2 Tocantins/Araguaia Basin map highlighting the protected areas and the inactive modeling region for each of the area demand scenarios: CONS: Conservation-based scenario; BAUS: Business-as-usual scenario; PROD: Production-based scenario

The relationship between driving factors and land use categories for each scenario was calculated through a logistic regression analysis using the stepwise method (Verburg et al., 2002), through the IBM SPSS Statistics software, version 29.01. The regression coefficients for each driving factor are shown in Table 2. All the scenarios encompassed yearly changes from 2015 to 2045.

Table 2. Description of the driving factors with their respective results of the stepwise logistic regression. All variables were significant at the $p < 0.01$ entry and $p > 0.02$ removal levels, except for those marked *. The variables Digital elevation model and Average solar radiation presented high correlation and were removed from the models.

Variable description	Original Variable Reference	Land use category									
		Natural Forest		Savanna		Grassland		Pasture		Agriculture	
		β	Exp β	β	Exp β	β	Exp β	β	Exp β	β	Exp β
Digital elevation model (DEM)	United States Geological Survey (2023)	*	*	*	*	*	*	*	*	*	*
Slope	Derived from DEM	0.00712	1.00714	*	*	*	*	*	*	-0.02209	0.97815
Predominant soil type	IBGE (2001)	0.01300	1.01314	-0.01876	0.98137	-0.00395	0.99606	0.02185	1.02199	-0.02420	0.97615
Average solar radiation	Fick & Hijmans (2017)	*	*	*	*	*	*	*	*	*	*
Average yearly precipitation	Fick & Hijmans (2017)	0.02532	1.02576	-0.03246	0.96827	-0.01547	0.98465	-0.00393	0.99608	-0.00304	0.99697
Average temperature	Fick & Hijmans (2017)	0.05617	1.05772	0.03698	1.03789	*	*	-0.03848	0.96243	-0.38576	0.68069
Proximity of main state and national roads	Ministry of Transportation (2023)	0.00001	1.00001	0.00001	1.00001	*	*	*	*	0.00001	1.00001
Proximity of rivers (Strahler's order ≥ 4)	Lehner & Grill (2013)	*		*	*	0.00001	1.00001	0.00001	1.00001	0.00002	1.00002
Proximity of municipalities	IBGE (2023b)	0.00001	1.00001	*	*	0.00001	1.00001	*	*	*	*
Proximity of municipalities with more than 100,000 inhabitants	IBGE (2023b)	0.00001	1.00001	*	*	*	*	*	*	*	*
Population density (2015)	IBGE (2023a)	-0.00045	0.99955	-0.00328	0.99672	-0.00252	0.99748	*	*	-0.00271	0.99729
Per capita Internal Gross Product (2015)	IBGE (2023a)	0.00001	1.00001	0.00001	1.00001	*	*	*	*	0.00001	1.00001
Constant	-	-5.17470		3.17041		1.04187		1.61651		10.76219	

We calculated the Kappa Simulation coefficient and its components KTransition and KTransloc to assess the model accuracy. Kappa Simulation is an accuracy measure that is identical in form to the Kappa statistic, but instead applies a more appropriate stochastic model of random allocation of class transitions relative to the initial map (Van Vliet et al., 2011). While KTransition addresses the amount of land use changes, KTransloc evaluates the spatial allocation of these changes (Van Vliet et al., 2011). Thereby, we used the Mapbiomas land use maps of 2015 and 2020 and our simulated 2020 map in the BAUS scenario. The three maps were subjected to a reclassification procedure to isolate the five modeled categories. Subsequently, we performed a moving window resampling procedure over the three maps using “modal” function in a 3x3 pixel matrix. These resampled maps were used to calculate the Kappa Simulation coefficients. The moving window procedure was performed using the “focal” function of the “terra” package in R version 4.3. The Kappa Simulation analysis was conducted using the Map Comparison Kit software (Visser & de Nijs, 2006).

3.3 Results

Despite considering different sized areas for each modeled scenario, in all of them five land use categories comprised about 94% of the basin area. These categories were natural forest, savanna, grassland, pasture and agriculture. Considering the BAUS scenario, the main area changes between 1985 and 2015 occurred in pasture and natural forest areas. While natural forest losses represented 12% of the TOAR landscape, pasture increased about 15.2% (Table 3). In terms of amplitude, the main growth occurred in the agriculture category, which increased its original size by about 1200%.

Table 3. Area change observed (1985–2015) and modeled (2015–2045) for the five categories of interest in the three area demand scenarios: CONS: Conservation-based scenario; BAUS: Business-as-usual scenario; PROD: Production-based scenario. The (-) sign represent area losses.

		Area change (%)				
Scenario	**Period**	**Natural Forest**	**Savanna**	**Grassland**	**Pasture**	**Agriculture**
CONS	1985–2015	-12.45	-5.73	-0.80	15.65	3.25
	2015–2045	-11.2	-5.16	-0.72	14.10	2.92
BAUS	1985–2015	-11.97	-5.69	-0.90	15.28	3.15
	2015–2045	-11.97	-5.69	-0.90	15.28	3.15
PROD	1985–2015	-11.66	-5.48	-0.88	14.85	3.06
	2015–2045	-12.83	-6.03	-0.97	16.33	3.36

In the CONS scenario the main vegetation categories still present high area losses over time. As a result, in 2045, natural forest, savanna, and grassland will compose 13%, 19.2% and 3.8% of the landscape. Conversely, in the PROD scenario the vegetation categories present less area coverage in 2045, while the farming categories seem similar to the other scenarios. This apparent similarity in farming area percentages does not represent lesser area gain, once that the PROD scenario accounts the entire landscape for change, including protected areas.

The changes to 2030 (Supplementary Material S2) and then to 2045 represent a continuum of farming expansion over vegetation in the TOAR (Fig. 3). At first, the model output mainly allocates farming expansion over isolated vegetation pixels in the entire basin. While pasture expanded all over the area, agriculture grew from current occupied regions, mainly in the southern portion of the basin. In these simulations, the vegetation categories presented both dispersed area reductions and a smooth reduction in their larger patches. In the maps of the simulated year 2045 it is possible to notice that natural forest is left restricted to the northern parts of the TOAR, except in the excluded protected areas of the BAUS and CONS scenarios. Moreover, there is massive expansion in pasture and agriculture categories over the basin, especially in the PROD scenario.

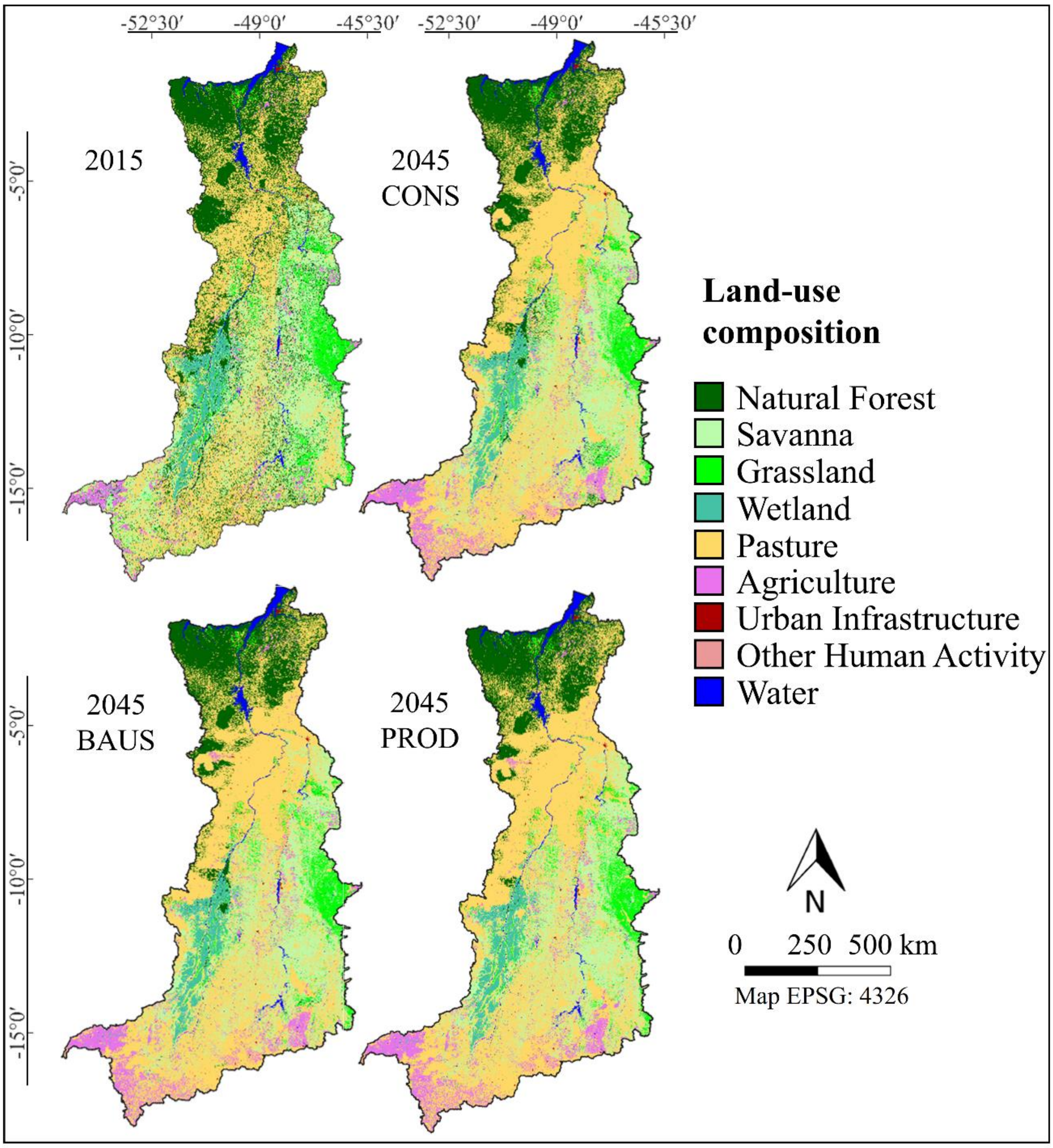

Fig. 3 Modeled future land use maps of the Tocantins/Araguaia Basin for the year 2045. Modeled area demand scenarios: CONS: Conservation-based scenario; BAUS: Business-as-usual scenario; PROD: Production-based scenario

The simulated vegetation losses highlight a dispersed pattern of natural forest loss over the TOAR (Fig. 4). Furthermore, deforestation occurred in all bigger patches of natural forest, except those in the far northern portion of the basin. Excluding protected areas in the CONS and BAUS scenarios granted them stability in these models. The main savanna losses occurred in the southern portion of the basin, where the agriculture and pasture categories actively increased in the area. In turn, grassland losses were restricted to smaller areas in the east and far northern regions, where this category occurs.

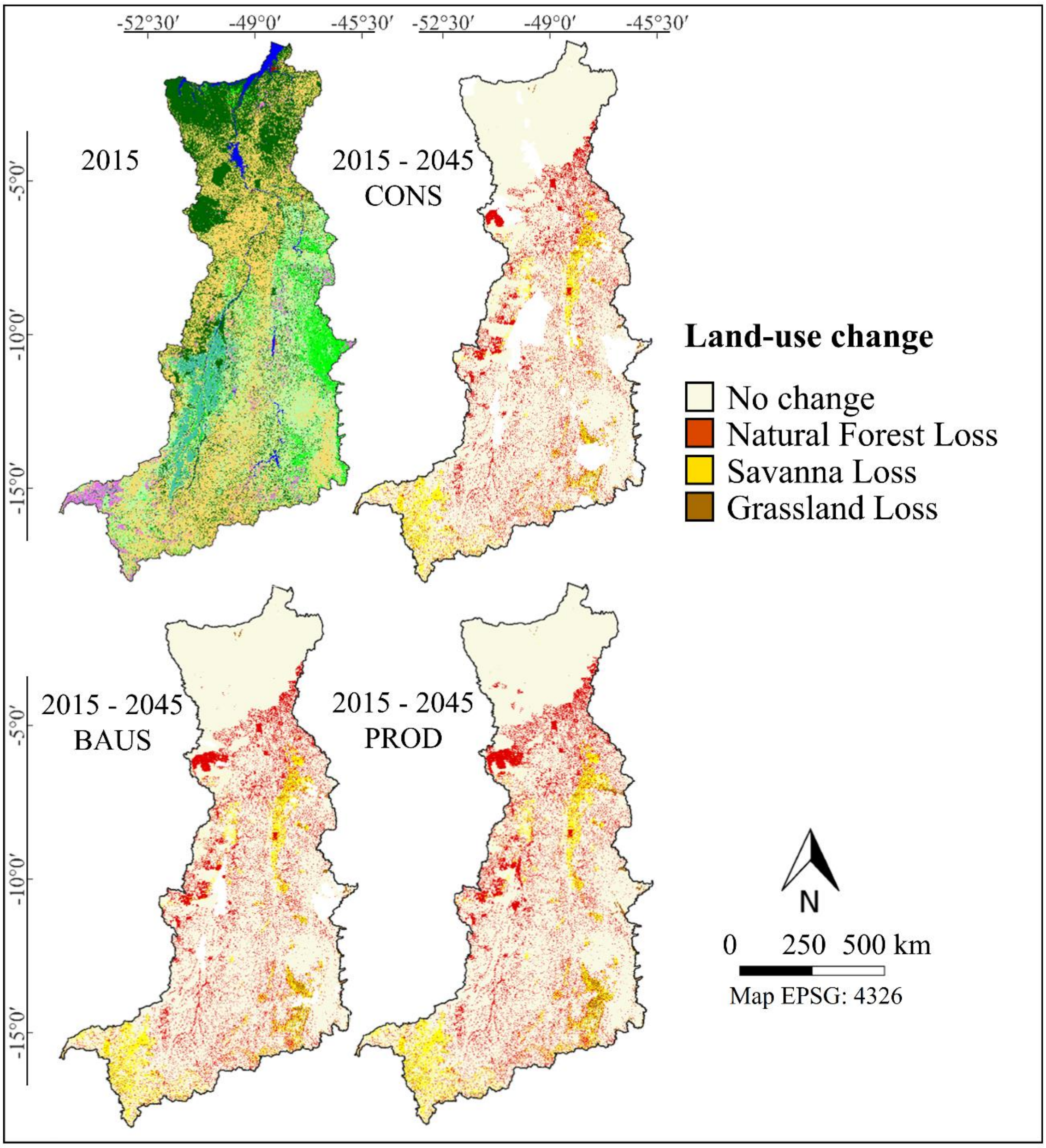

Fig. 5 Vegetation change maps between the base year of 2015 and the modeled year of 2045 of the Tocantins/Araguaia Basin. Modeled area demand scenarios: CONS: Conservation-based scenario; BAUS: Business-as-usual scenario; PROD: Production-based scenario

Regarding the performance of the model, the Kappa Simulation measure of accuracy ranged from 0.137 to 0.289, being comparable to several studies in the literature (Hewitt et al., 2014; Malek et al., 2015; Zhou et al., 2022). The KTransition coefficient was high for all categories and for the overall analysis (0.574 – 0.788), showing that the model accurately simulated the amount of land use changes in the TOAR. The KTransloc, on the other hand, was not so high (0.234 – 0.367), but also presented good values considering the size and diversity of the TOAR landscape and the nature of this measure (Van Vliet et al., 2011). The complete accuracy results and change maps can be found in the Supplementary Material S4.

3.4 Discussion

Our primary findings identify five key land use categories covering approximately 94% of the TOAR total area. These categories were found to be associated with agricultural key driving factors, including predominant soil type, average temperature, and average yearly precipitation. Furthermore, significant changes in land use occurred over the analyzed 30-year period (1985–2015), with natural forest losses accounting for 12% of the total landscape. Conversely, pastureland observed a 15.2% increase, while agriculture expanded by 1200% from its initial extent. In all simulated scenarios, the vegetation categories experienced significant losses. Projections for 2045 indicate the continuation of the ongoing deforestation and fragmentation patterns in the basin. Furthermore, natural forests, savannas, and grasslands will make up only 13%, 19.2%, and 3.8% of the landscape, respectively, in the most optimistic conservation-based scenario. In contrast, pastureland expands significantly across the entire basin, while agriculture experiences exponential growth, mainly in the southern regions.

Historically, one of the most persistent threats to Brazil's biodiversity is deforestation, which is mainly driven by anthropogenic expansion (Gibbs et al., 2010; Reydon et al., 2019). Deforestation rates for 2022 underscore the ongoing challenge, with 58% of the total deforested area in Brazil occurring within the Amazon and 32.1% in the Cerrado (Alerta Mapbiomas, 2023). To illustrate the magnitude of the environmental impact in this data, on average, the Cerrado lost about 75.3 ha per hour (Alerta Mapbiomas, 2023). It is important to emphasize that 99.3% of the deforested area in Brazil in 2022 showed indicators of irregularity, and legal authorities took action in only 8.8% of the cases up to the date of the report (Alerta Mapbiomas, 2023). This persistent issue is also observed in the TOAR through our general land change analysis, revealing significant and continuing reductions in the basin’s main vegetation categories over the past three decades, encompassing the primary vegetation types of the Amazon and predominantly the Cerrado biomes (Pelicice et al., 2021).

The significance of the Amazon and Cerrado biomes in providing essential ecosystem services cannot be overstated, as these biomes are crucial to various ecological processes. The Amazon significantly contributes to global climate regulation by absorbing and storing vast amounts of carbon dioxide (Bullock and Woodcock, 2020), a function shared by the Cerrado biome (Dionizio et al., 2020). Furthermore, Cerrado's high endemism rates have earned it a place on the world's biodiversity hotspots list (Mittermeier et al., 2004). The integrity of these ecosystems enhances human well-being through water regulation (Latrubesse et al., 2019; Lovejoy and Nobre, 2018; Nóbrega et al., 2020; Salmona et al., 2023), supports food production through agricultural activities (Latrubesse et al., 2019; Lovejoy and Nobre, 2018), enhances biodiversity conservation (Chamon et al., 2022; Polizel et al., 2021), and provides resources for traditional and indigenous communities (Bowman et al., 2021). Concerning our results, the rates of vegetation loss were high even in the conservation-based scenario, which simulated the complete preservation of protected areas coupled with a 10% reduction in change rates. Thus, continuous deforestation threatens the region's numerous ecosystem services and raises significant concerns about its long-term sustainability (Agostinho et al., 2023).

Our predicted maps indicate a gradual elimination of small and isolated natural forest and savanna patches in both past and upcoming years, accompanied by a reduction in the size of larger patches. Human alterations to the landscape are among the primary drivers of worldwide biodiversity loss (Newbold et al., 2015; Vitousek et al., 1997). Furthermore, habitat fragmentation can result in a reduction in biodiversity, disruption of key ecosystem functions, and severe alterations in nutrient cycles (Fletcher et al., 2018; Latrubesse et al., 2019; Salmona et al., 2023). The observed trend of habitat fragmentation in the TOAR raises concerns about habitat connectivity in the basin, especially considering that a significant portion of Cerrado species are associated with gallery and dry forest habitats, which represent only 20% of the total area of the biome (Cardoso da Silva and Bates, 2002; de Oliveira et al., 2019).

In recent decades, the TOAR has emerged as an appealing region for agricultural development, a trend strongly corroborated by a remarkable 1200% increase in agricultural land since 1985. Consequently, the primary factors influencing land change in the TOAR are closely associated with soil type, average temperature, and average precipitation — factors that directly impact agricultural productivity. Furthermore, in 2015, the Brazilian government launched the MATOPIBA program to promote agricultural techniques related to monocultures and cattle rearing in the region that encompasses the ecotone between the Amazon, Cerrado, and Caatinga biomes (Agostinho et al., 2023; Pelicice et al., 2021; Polizel et al., 2021; Vieira et al., 2021;). This has resulted in the conversion of natural landscapes into farmland, leading to deforestation and habitat fragmentation, ultimately affecting the basin's ecosystem structure and functioning (de Oliveira et al., 2019; Polizel et al., 2021; Salmona et al., 2023; Vieira et al., 2021). Moreover, while Brazil is the world's second-largest agricultural producer and is projected to experience the most substantial output increases among all countries over the next four decades (FAO, 2006), it also holds the distinction of being the largest per capita and per area user of chemical fertilizers and pesticides in agriculture (Wittmann et al., 2015), and is one of the countries with the highest rates of agricultural-related deforestation worldwide (Alerta Mapbiomas, 2023; Strassburg et al., 2014). This fact is frequently overlooked by regional and national governments, and the effects of deforestation and pollution on water quality, ecosystem functioning, and human wellbeing are poorly investigated (Nicolella et al., 2005; Wittmann et al., 2015).

Despite Brazil's focus on combating Amazon deforestation, as illustrated by initiatives like the revival of the Amazon Fund, there is a troubling surge in deforestation rates in other biomes and ecosystems, notably the MATOPIBA region, that is being overlooked (Bispo et al., 2023; Oliveira et al., 2017; Pelicice et al., 2021). Notwithstanding several studies highlighting the past and current unsustainable trajectory of the MATOPIBA (Agostinho et al., 2023; Pelicice et al., 2021; Polizel et al., 2021; Vieira et al., 2021), the Brazilian government appears to be overlooking this concern. Consequently, a recent Brazilian decree (Government of Brazil, 2023b) launching the MATOPIBA development plan and outlining the formation of a management group, has been facing criticism for what seems to be a lack of inclusion of environmental concerns. The decree establishes a committee comprising representatives from executive government agencies, civil society organizations, and the productive sector. Still, it excludes any representatives from environmental agencies or organizations (Government of Brazil, 2023b).

Considering that the MATOPIBA region largely encompasses the Cerrado biodiversity hotspot, confronting severe pressure from deforestation and land degradation (Agostinho et al., 2023; Polizel et al., 2021; Salmona et al., 2023; Strassburg et al., 2014; Vieira et al., 2021), the absence of environmental voices on the committee could imply that crucial environmental concerns are being disregarded in the development planning process. The decree also specifies that the committee may invite experts and representatives from other public or private entities to participate in its meetings and discuss specific issues, but these guests will not possess voting rights (Government of Brazil, 2023b). Consequently, the absence of environmental representation on the committee and the restricted role of environmental experts in the decision-making process represent a missed opportunity to guarantee that the development of the MATOPIBA region will be balanced and will not compromise the environment.

On the other hand, the Brazilian government has implemented different measures to address environmental concerns and advance sustainable development. In light of the growing deforestation rates in the Cerrado, the government has recently proposed the fourth version of a sustainable development plan specifically tailored for the Cerrado biome (PPCerrado) (Government of Brazil, 2023a; Ministry of the Environment, 2023b). Notably, this new plan, which had its first version in 2010, stands out for its integrative approach, involving a consortium of agencies, encompassing environmental and agricultural entities, to ensure a holistic and well-balanced strategy. Concurrently, an ongoing legislative initiative (law project 5462/2019) seeks to establish a comprehensive policy for sustainable development in the Cerrado (Federal Senate of Brazil, 2019). Moreover, certain states, exemplified by Bahia and Tocantins, have proactively implemented state-level plans dedicated to Cerrado conservation, contributing to a more nuanced and region-specific approach to sustainable development (SEMA, 2023; SEMARH, 2023).

Attempts involving the establishment of protected areas with diverse land use restrictions have also been made in the Cerrado (de Marco Jr. et al., 2023; Latrubesse et al., 2019; Pelicice et al., 2021). Nonetheless, a study by Oliveira et al. (2017) uncovered that the ratio of protected areas to Cerrado land is notably lower than the national average (0.8–4% in the Cerrado watersheds versus 28.44% in Brazil). Furthermore, 62% of the Cerrado vegetation remnants exist within private landholdings, which have the authority to convert 65% to 80% of all native vegetation by the Brazilian Forest Code (Bispo et al., 2023; de Marco Jr. et al., 2023). In the context of our study, the TOAR currently includes 127 protected areas within or adjacent to its boundaries, constituting 8.9% of general protected areas and 2.9% of integrally protected areas. Moreover, several protected areas in the TOAR are too fragmented to guarantee the persistence or representativeness of plant and animal species (Oliveira et al., 2017). Additionally, the effectiveness of non-integrally protected areas in Brazil in reducing deforestation and promoting sustainable agriculture is still a matter of debate (Oliveira et al., 2017; Schmitz et al., 2023).

Increased investments are crucial for establishing protected areas in the Cerrado, aiming to match at least the average national protection rate (de Marco Jr. et al., 2023; Oliveira et al., 2017; Pelicice and Castello, 2021). Moreover, focused attention must be dedicated to environmental oversight and law enforcement, given the alarmingly high number of irregular deforestation events in the country (Alerta Mapbiomas, 2023; Bispo et al., 2023). The Brazilian Cerrado is experiencing a shift towards intensified agriculture, and while agriculture offers economic benefits (Agostinho et al., 2023; Latrubesse et al., 2019; Lovejoy and Nobre, 2018), it presents environmental challenges, particularly related to deforestation and habitat loss (Latrubesse et al., 2019; Oliveira et al., 2017; Polizel et al., 2021; Salmona et al., 2023; Vieira et al., 2021). The production-based scenario in our study aimed to portray a pessimistic land use evolution, considering both intensified agricultural expansion and inadequate environmental responsibility. Unfortunately, it mirrored ongoing trends in the TOAR and, ultimately, in the Cerrado biome, encompassing deforestation in protected areas (Alerta Mapbiomas, 2023) and government-backed agricultural expansion seemingly lacking environmental consideration (Government of Brazil, 2023b). Unfortunately, this unsustainable trajectory is unfolding in a megadiverse, understudied, and highly significant Brazilian region.

It is essential to emphasize that agriculture should not be perceived as the irremediable villain, as conscientious and legal agricultural improvement is crucial for sustainable development and food security (Latrubesse et al., 2019; Reydon et al., 2019; Strassburg et al., 2014). As previously mentioned, almost all Brazilian deforestation in 2022 exhibited some irregularity (Alerta Mapbiomas, 2023). In the Cerrado biome, only 1.17% of the deforestation was officially reported and approved by the environmental agency (Alerta Mapbiomas, 2023). Therefore, public policies must tackle and curb the benefits of illegal deforestation. This necessitates stricter law enforcement and direct regulation of commodity production chains, including, for example, the incorporation of the Cerrado in the European Regulation on Deforestation-Free Products and the Soy Moratorium (Bispo et al., 2023). Moreover, legislative initiatives such as the law project 5462/2019 should be approved and encouraged (Federal Senate of Brazil, 2019). Furthermore, development plans such as the MATOPIBA should incorporate robust scientific and environmental guidance, as enhanced planning for economic development and biodiversity preservation can prevent the destruction of crucial ecosystem services, some of which are vital for agricultural production (Agostinho et al., 2023; Pelicice et al., 2021; Salmona et al., 2023).

3.5 Conclusions

The findings of our study underscore the critical challenges faced by the vast Brazilian Cerrado biome, particularly within the Tocantins/Araguaia Basin. The escalating rates of deforestation, anthropogenic activities, and inadequate conservation measures pose severe threats to the basin's ecological integrity, biodiversity, and the well-being of local communities. The modeled future scenarios reveal alarming projections, indicating continuing deforestation trends and habitat fragmentation. Notably, the persistence of deforestation even in a conservation-based scenario raises concerns about the efficacy of existing protection measures and the urgent need for strengthened conservation efforts. Moreover, our study highlights the inadequacies in some current governance and policy frameworks in which environmental voices are overlooked in the decision-making process. We believe that to safeguard the TOAR and the Cerrado biome, a holistic approach is imperative, encompassing stricter law enforcement, focused attention on environmental oversight, increased investments in protected areas, and integrating of robust scientific guidance into development plans. In essence, the TOAR stands at a crossroads, requiring concerted efforts from policymakers, researchers, and stakeholders to ensure the sustainable management of this vital Brazilian ecosystem for the benefit of both current and future generations.

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4 CONCLUDING REMARKS

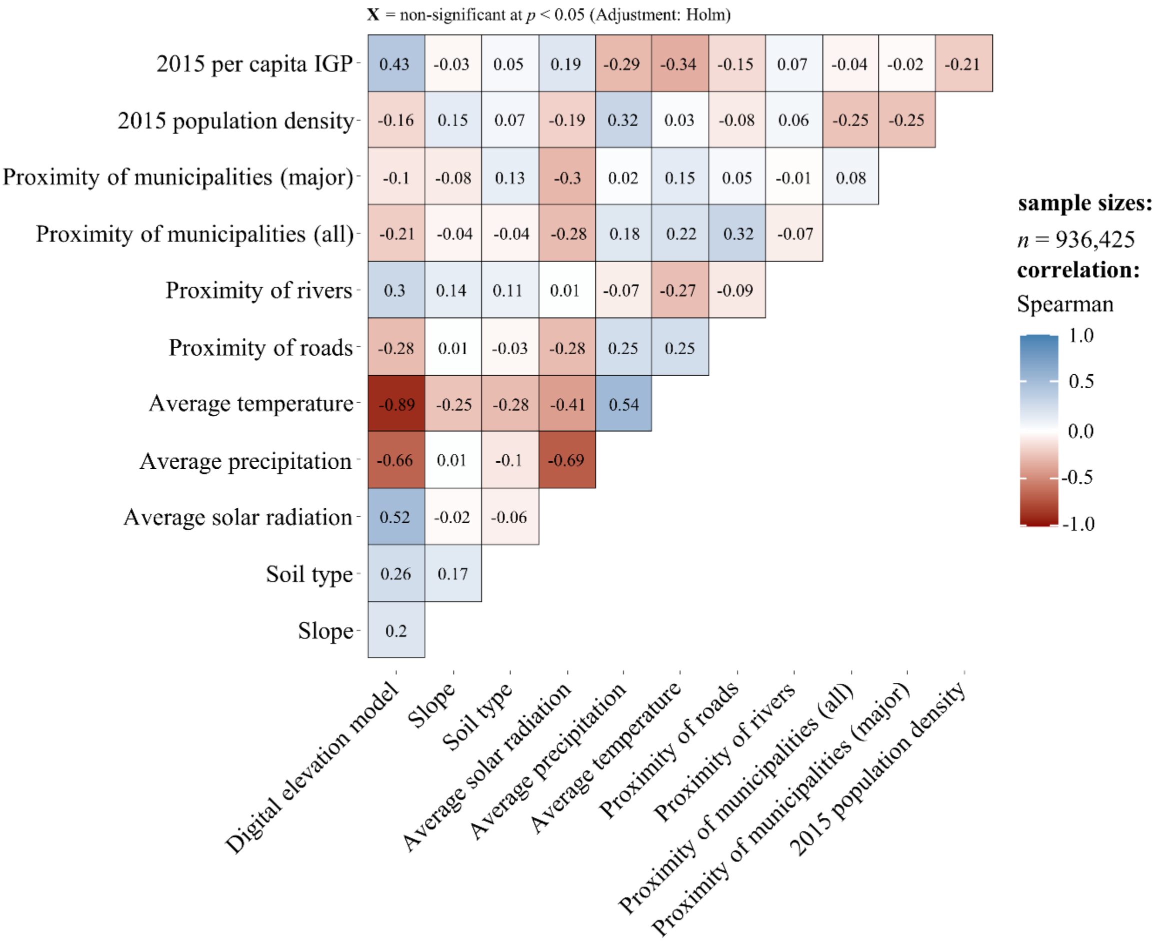
This comprehensive Tocantins/Araguaia Basin (TOAR) assessment reveals pressing challenges and a compelling call to action. The escalating rates of deforestation, coupled with anthropogenic activities, pose formidable threats to the ecological integrity, biodiversity, and well-being of the TOAR region. The future scenarios projected in the study depict a concerning continuation of deforestation trends and habitat fragmentation, even under conservation-based efforts. These findings underscore the urgency of addressing existing inadequacies in governance and policy frameworks. The persistence of deforestation in scenarios aimed at conservation raises questions about the efficacy of current protection measures, emphasizing the need for a reevaluation and strengthening of conservation strategies.

Additionally, the study highlights the critical importance of incorporating environmental voices into decision-making processes, ensuring a holistic approach that includes stricter law enforcement, focused environmental oversight, increased investments in protected areas, and integrating robust scientific guidance into development plans. The TOAR, standing at an ecological crossroads, necessitates concerted efforts to secure its sustainable management. Learning from past successes and challenges is imperative, advocating for a balanced approach that safeguards the TOAR for both current and future generations.

Finally, these results serve as a clarion call for coordinated actions, emphasizing the need for effective governance, sustainable agricultural practices, and international cooperation. Brazil's significant global role demands intensified efforts to harmonize economic development with environmental conservation. Continuous monitoring, active stakeholder participation, and a commitment to fulfill responsibilities in protecting the country’s unique ecosystems are paramount. The TOAR's fate is intertwined with the collective commitment to fostering a harmonious coexistence between human activities and preserving nature.

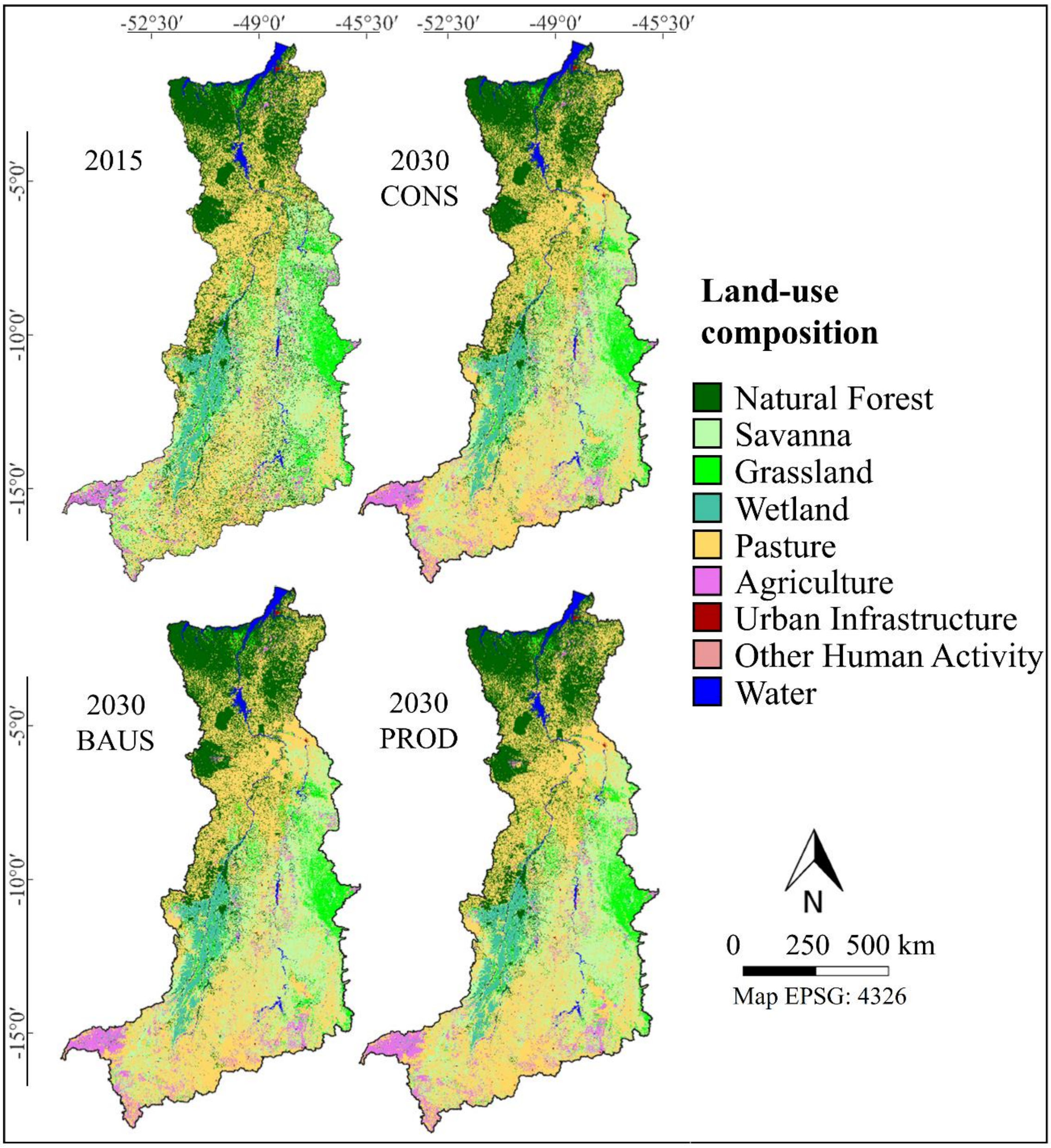
APPENDIX A - Supplementary material S1

Results of the Spearman correlation tests between the land use driving factors. All the tests were significant at $p < 0.05$.



APPENDIX B - Supplementary material S2

Modeled future land use maps of the Tocantins/Araguaia Basin for the year 2030. Modeled area demand scenarios: CONS: Conservation-based scenario; BAUS: Business-as-usual scenario; PROD: Production-based scenario.



APPENDIX C - Supplementary material S3

Kappa Simulation coefficients considering the changes from 2015 to 2020 in the BAUS scenario.

	Kappa Simulation	KTransloc	KTransition
Natural Forest	0.17526	0.28577	0.61331
Savanna	0.22662	0.31630	0.71648
Grassland	0.28888	0.36657	0.78805
Pasture	0.14651	0.23439	0.62510
Agriculture	0.13681	0.23823	0.57429
Overall	0.182	0.279	0.653

Maps showing: i) the change between the reference years of 2015 and 2020; ii) the change between the reference year 2015 and the simulated year 2020; iii) The model hits and misses.