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Temporal evolution of deforestation in the Xingu River Watershed between 2008 to 2020

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ABSTRACT: Anthropic activities that alter land cover patterns in Watersheds, such as deforestation, affect the food and sanitary security of the population. Thus, the objective of this study was to develop a quantitative analysis of the temporal evolution of deforestation in the Xingu River Watershed between the years 2008 and 2020. To achieve this, the methodology was organized into the following steps: Database construction (Xingu River Watershed boundaries, deforested areas, and Land Use and Land Cover); Data preprocessing; Analysis of the temporal evolution of deforestation; and Quantitative analysis of land cover change in the deforested areas. It became evident that deforestation did not exhibit a standardized behavior, due to the large proportion of deforested areas in 2008 and the abrupt reduction in 2012. Furthermore, the deforestation in 2012, 2016, and 2020 resulted in greater conversion of native forests into pasture than the regeneration of these areas. Therefore, it can be concluded that 2008 had the highest deforestation rate, due to the increase in soybean prices, and that 2012 had the lowest rates due to the implementation of environmental policies, highlighting the relationship between environmental policies and the seasonality of commodity prices with deforestation rates. It was also concluded that the main destination for the deforested areas has been pastureland for livestock, and a viable solution to identify and punish offenders, as well as support small-scale producers and recover areas devastated by deforestation, is land regularization.

Evolução temporal do desmatamento na Bacia Do Rio Xingu entre 2008 a 2020

RESUMO: As atividades antrópicas, como o desmatamento, alteram os padrões de cobertura do solo em bacias hidrográficas, afetando a segurança alimentar e sanitária da população. Diante disso, o objetivo do presente trabalho foi elaborar uma análise quantitativa da evolução temporal do desmatamento na Bacia do Rio Xingu, entre os anos de 2008 e 2020. Para isso, a metodologia foi disposta nas seguintes etapas: i) elaboração do banco de dados (limites da Bacia do Rio Xingu, áreas desmatadas e uso e cobertura da terra); ii) pré-processamento dos dados; iii) análise da evolução temporal do desmatamento; e iv) análise quantitativa da alteração da cobertura do solo nas áreas desmatadas. Os resultados evidenciaram que o desmatamento não apresentou um comportamento padronizado, em função da grande proporção de áreas desmatadas em 2008 e da redução abrupta em 2012. Os desmatamentos de 2012, 2016 e 2020 resultaram em conversão de floresta nativa em pastagem maior do que a regeneração dessas áreas. Assim, conclui-se que 2008 foi o ano com maior taxa de desmatamento, em função da alta no preço da soja e que 2012 foi o ano com menores índices em razão das políticas ambientais aplicadas, evidenciando a relação entre as políticas ambientais e a sazonalidade dos preços das *commodities* com as taxas de desmatamento. Concluiu-se, que o principal destino das áreas desmatadas tem sido a pastagem para a pecuária e que uma solução viável para identificar e punir os infratores, bem como apoiar os pequenos produtores e recuperar áreas pelos desmatamentos é a regularização fundiária

Introduction

Rapid population growth, coupled with changes in consumption patterns and the need for large volumes of water to meet the demands of the agricultural and industrial sectors, has exacerbated the imbalance in water availability and quality on the planet (Aparecido et al. 2016). Anthropogenic activities and conflicts of interest occurring in watersheds can directly affect the food and sanitary security of the population that depends on water resources from these areas.

For example, the Xingu River Watershed (XRW) is responsible for the water supply of 67 municipalities in the states of Pará and Mato Grosso (Lucas 2021). Due to its considerably large area (510,000 km^2) and its integration of two major global ecosystems, the Cerrado and the Amazon Rainforest, the XRW presents significant contrasts in its landscape. These range from extensive conservation corridors with some of the planet's highest biodiversity to vast agricultural areas, which have undergone significant land-use changes and investments, making it one of the country's largest soybean producers (Barona et al. 2010; Villas-Bôas 2012; Isa 2017).

Despite being an area with significant biodiversity, the intensification of agricultural activities in the region has driven deforestation, especially near the main sources of the XRW (Panday et al. 2015). Guerrero et al. (2020) explain that deforestation related to agricultural activities is the main driver of land cover change, affecting approximately 75% of the Earth's original surface and leading to biodiversity loss, reduced water availability, nutrient cycling, and climate regulation (Cruz et al. 2020).

In the Xingu River Watershed, the conversion of native forests into pastures and agricultural areas is the main objective of deforestation, as observed by Lense et al. (2020). Additionally, deforestation for road construction and the expansion of logging and mining areas is common in the Amazon region (Abe et al. 2018; Cruz et al. 2020).

In addition to biodiversity loss, the reduction of forested areas decreases evapotranspiration rates, which affects cloud formation and precipitation, thereby compromising the water supply of the region (Silvério et al. 2015; Wright et al. 2017). Studies linking deforestation in the XRW to extreme climate scenarios indicate increasing air temperatures throughout the watershed and irregular rainfall patterns between the northern and southern parts (Santos and Oliveira 2017; Da Silva 2019; Lucas et al. 2021).

In the current context, understanding the dynamics of land use in deforested areas is crucial, and techniques for analyzing these changes play a fundamental role. They help identify priority areas for monitoring, contributing to the formulation of environmental policies aimed at strategically controlling deforestation in the XRW region. A widely adopted methodology for this purpose involves the use of techniques from the field of geotechnologies. These tools enable spatial and temporal analyses that strengthen environmental assessments and watershed management, empowering decision-makers to act more effectively and precisely.

Therefore, the present study aimed to develop a quantitative analysis of the temporal evolution of deforestation in the Xingu River Watershed between the years 2008 and 2020.

Materials and Methods

The study area corresponds to the boundaries of the Xingu River Watershed (XRW) and has an approximate area of 510,000 km^2. The watershed is located in a transitional region between the Amazon Rainforest and the Cerrado biome, with approximately 60% of its territory covered by protected areas (Villas-Bôas et al. 2012). The drainage area of the XRW is divided between two Brazilian states, with a portion in Pará and another in Mato Grosso, between the meridians of 50°24'0"W and 55°48'0"W, and the parallels of 01°30'0"S and 15°00'0"S (Figure 1).

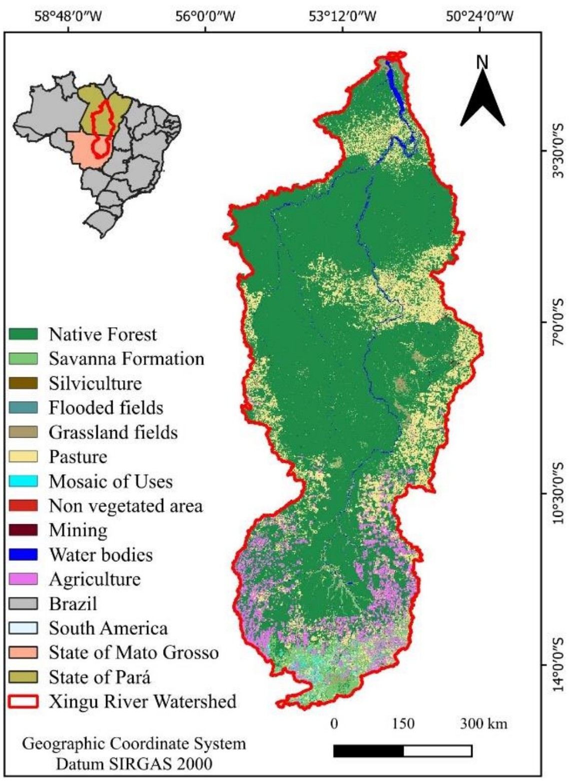


Figure 1. Location map of the study area - Xingu River Watershed.

The XRW is characterized by an equatorial climate (A), ranging from always humid (f), predominantly humid (m), or with summer rainfall (w), according to the Köppen-Geiger climate classification (Alvares et al. 2013). The average annual precipitation is around 2,090 mm, the air temperature ranges between 31.7 °C and 23.1 °C, and the relative humidity fluctuates between 77% (December to April) and 87% (June to September) (Medeiros Filho 2019).

Database Development

The database was composed of the following files:

- XRW boundaries: freely available in vector format (.shp) from the Agência Nacional de Águas (ANA 2023);
- Deforested areas for the years 2008, 2012, 2016, and 2020: freely available in vector format (.shp) from the TerraBrasilis platform (TERRABRASILIS 2023);
- Land Use and Land Cover for the years 2007, 2009, 2011, 2013, 2015, 2017, 2019, and 2021: separately and freely available in raster format (Geotiff) from the MapBiomas platform, collection 7.0 (MAPBIOMAS 2023).

Data Preprocessing

The file related to the annual deforestation increment, acquired from the Terra Brasilis platform, referred to the Legal Amazon as a whole. Therefore, the first step was to clip it to the area of interest (XRW). Subsequently, the generated file underwent a process of dissolving features based on the year of occurrence, so that all deforestation scars from each year were merged with their counterparts. Finally, each dissolved feature, corresponding to the study years (2008, 2012, 2016, and 2020), was individually exported for further qualitative and quantitative analysis.

The Land Use and Land Cover files, acquired from the MapBiomas platform (in raster format), for the study years (2007, 2009, 2011, 2013, 2015, 2017, 2019, and 2021), were initially subjected to vectorization (conversion from raster to vector format). Subsequently, in order to match each land cover feature with its respective counterparts, the vectorized file was dissolved. After dissolution, using the legend provided by MapBiomas, the attribute table of each file was updated to facilitate feature identification.

After this preprocessing, all files were reprojected to the Albers Equal Area Conic projection system. Finally, the attribute tables were updated with an area field, where the areas of each feature were calculated in hectares.

Analysis of Temporal Deforestation Evolution

To analyze the temporal deforestation evolution in the XRW, the files related to the deforested area in each of the studied years were compiled into an electronic spreadsheet using Microsoft Excel, version 1808. After compilation, the data were subjected to the creation of a graphical visualization to facilitate understanding and interpretation.

Quantitative Analysis of Land Cover Change in Deforested Areas

To analyze the influence of deforestation on land cover change, the files related to land use and land cover (LULC) were clipped under the mask of deforestation for the immediately preceding and subsequent years. Thus, eight land use and land cover files were generated, four for LULC before deforestation and four for LULC after deforestation.

Subsequently, the files resulting from the previous clipping step were subjected to a data intersection process to compare the converted area. In this case, the areas considered were those classified as native forests in the three years preceding deforestation.

The generated data were compiled into an electronic spreadsheet using Microsoft Excel, version 1808, to analyze the net gains and losses of Native Forests.

Results and Discussion

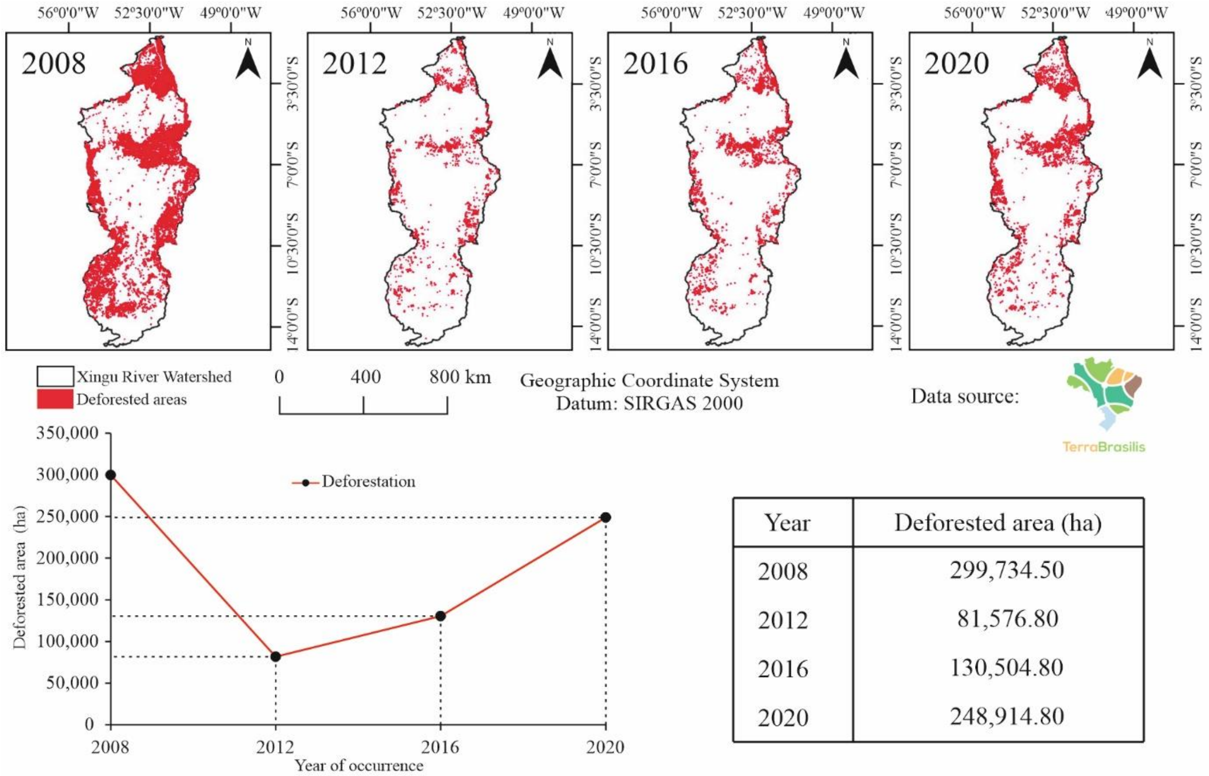
The results of the present research indicated that the XRW has experienced significant anthropogenic interference due to deforestation in all the analyzed years. However, it is evident from Figure 2 that deforestation did not exhibit a standardized behavior in terms of increasing or decreasing rates, mainly due to the large proportion of deforested areas in 2008 and the abrupt decrease in these records in 2012.

In 2008, according to the data obtained in Figure 2, an area of approximately 299,735 hectares was deforested, which represents about 60% of the total area of the Xingu River Watershed (XRW). The authors Ferreira and Coelho (2015), analyzing the average deforestation data in the Legal Amazon, provided by the National Institute for Space Research, confirmed the findings of this research, showing that deforestation in 2008 was almost three times greater than in 2012.

There are two points that can explain this abrupt reduction in deforestation between 2008 and 2012 in Amazonian regions, namely:

1) The rapid expansion of areas covered by soybean cultivation, due to market restructuring after a period of contraction from 2006 to 2007 with the drop-in market prices (Villas-Bôas 2012).

2) The implementation of more consistent and focused policies aimed at reducing deforestation starting in 2008 (Defries et al. 2013; Nepstad et al. 2014).



Year	Deforested area (ha)
2008	299,734.50
2012	81,576.80
2016	130,504.80
2020	248,914.80

Figure 2. Spatial and temporal evolution of deforestation in the Xingu River Watershed.

Regarding the price of soybeans, writer Formigoni (2017) analyzed the data on average annual prices in Brazilian reais per bag (R$.sc^{-1}) provided by the Center for Advanced Studies in Applied Economics (Cepea/Esalq) from 2007 to 2017. The analysis revealed a positive trend in soybean prices between 2007 (R$37.20.sc^{-1}) and 2008 (R$48.50.sc^{-1}). This fact supports the first hypothesis raised, related to the expansion of soybean cultivation areas due to price increases.

However, in 2012, according to Cepea data, the price of soybeans reached values close to R$69.00, representing a percentage increase of over 42% compared to the price in 2008. In this sense, the second hypothesis can be used to explain the reduction in deforestation rates, as from 2008, anti-deforestation policies were more comprehensive than those applied before, according to Barreto and Silva (2010).

The mentioned authors highlighted three specific policies that may have been responsible for this decreasing trend in deforestation rates in the years following 2008. According to them, one of these actions was the increase in field inspections focused on imposing fines, seizing assets, and imposing embargoes on the use of deforested areas in 36 municipalities with the highest deforestation rates in the Legal Amazon. As a result, deforestation decreased in various regions, including municipalities within the Xingu River Watershed.

Another action taken was the economic embargo on illegally deforested areas, which prohibited the commercialization of their products. This action was legalized by Normative Instruction N° 1 of the Ministry of the Environment, on February 29, 2008 (Brazil 2008).

Finally, the authors Barreto and Silva (2010) stated that credit restrictions were imposed on farmers who did not comply with environmental legislation. This action, established by Resolution N° 3545, of February 29, 2008, by the Central Bank of Brazil (BACEN 2008), required owners of areas larger than 400 hectares to demonstrate legitimate land ownership or be in the process of obtaining it, in addition to having environmental licensing to access agricultural credit. The goal was to restrict credit access for producers more prone to illegal deforestation.

Despite the positive performance of environmental policies related to deforestation in Brazil, there has been a new increase in rates in 2016 and 2020. Authors Alencar et al. (2022) support these data by presenting Technical Note No. 9 from the Instituto de Pesquisa Ambiental da Amazônia (IPAM). According to the authors, deforestation has reached an alarming level in recent years, comparable only to the levels seen in 2008.

According to the data presented in the IPAM Technical Note, presented by Alencar et al. (2022), the recent increases in deforestation rates are derived from both the disintegration of the agencies responsible for control and protection against deforestation and the setbacks in environmental policies in recent governments.

According to a note published in 2017 by the Xingu Program of the Socio-Environmental Institute

(ISA), most of this increase comes from municipalities in the state of Pará, related to the intensification of settlement occupation near highways, land-grabbing groups, road paving, and public policies. The paving of BR-163, which passes through the interior of the Xingu River Watershed, has contributed to forest degradation in its surroundings, according to PRODES/INPE data.

Although environmental issues can be positively influenced by political decisions, eliminating this practice, especially in less developed areas with fewer formal job opportunities and complementary education for the population, such as many of the municipalities within the Xingu River Watershed, is an extremely complex task. Therefore, it is important that before fully solving the deforestation problem, analyses are conducted to understand the influence of these practices on land cover change in order to develop specific management and protection strategies.

In this regard, the present research proposed the identification and quantification of forested areas that underwent changes in their land cover. After this analysis, it was observed that 1,633,008.11 hectares of native forest deforested in 2008 started a regenerative process in 2009, meaning that there was no change in land use in those areas. On the other hand, 241,192.03 hectares were converted from native forests to pasture during the same period (Table 1).

Table 1. Quantification of native forest areas that underwent changes in their coverage due to deforestation.

Land use classes		Evaluated periods			
		Deforestation 2008	Deforestation 2012	Deforestation 2016	Deforestation 2020
Before deforestation	After deforestation	2007 x 2009	2011 x 2013	2015 x 2017	2019 x 2021
		Converted area (hectares)			
Native Forest	Agriculture	3,147.81	1,382.99	2,827.37	2,089.63
Native Forest	Urbanized Area	-	22.19	8.24	11.46
Native Forest	Non-vegetated Area	0.06	14.09	84.04	17.36
Native Forest	Flooded Field	64.23	83.57	201.41	85.70
Native Forest	Water Bodies	35.20	44.30	456.39	8.34
Native Forest	Grassland Formation	156.22	16.27	7.61	17.10
Native Forest	Native Forest	1,633,008.11	24,075.76	37,340.44	61,226.95
Native Forest	Savanna Formation	1,813.84	80.27	25.19	35.22
Native Forest	Mining	23.16	52.67	354.18	507.61
Native Forest	Vegetation mosaic	10.18	66.20	39.40	0.03
Native Forest	Pasture	241,192.03	33,726.91	46,861.70	121,094.14
Native Forest	Silviculture	0.09	-	0.11	0.01

The results presented in Table 1 further demonstrate that the deforestation in 2012, 2016, and 2020 was responsible for the conversion of native forest into pastureland, which exceeded the regeneration of these areas (areas that were previously native forest and remained as native forest after deforestation). This can be understood through the changes in the public policies mentioned earlier in this discussion. A total of 33,726.91 hectares covered by native forests in 2011 were converted into pastureland in 2013 due to the deforestation recorded in 2012.

In 2017, there was an alteration of 46,861.70 (53.13%) hectares of native forest into pastureland compared to 2015. The deforestation that occurred in 2020, in turn, converted 121,094.14 (65.42%) hectares of native forests in 2019 into pastures in 2021.

This analysis highlights that the majority of deforestation occurrences in the study area are driven by the need to open new agricultural and livestock fronts. However, it is important to clarify that, according to Law nº. 12,651 of 2012, the permitted land use rate in the Legal Amazon is 20%, with 80% required to be allocated to Legal Reserves (Brasil 2012).

However, this region suffers from the lack of public policies focused on land regularization, which, according to Tupiassu, Fadel, and Gros-Désormeaux (2019), could be an efficient strategy in identifying and punishing offenders, as well as supporting small-scale farmers and recovering devastated areas. In this sense, it is important that deforestation control measures include the use of these tools to support rural producers located in the Xingu River Watershed (XRW) and prevent the illegal conversion of native areas into anthropized areas.

Based on the results obtained and other works that have analyzed the temporal evolution of deforestation in the XRW, it can be stated that understanding the spatial distribution and dynamics of deforestation occurrences provides relevant support for the planning of public policies that mitigate anthropic actions threatening the natural resources of this area (Simões et al. 2010).

Conclusions

After the completion of this research, it can be concluded that:

Environmental policies and the seasonality of agricultural commodity prices are directly related to deforestation rates in the Xingu River Watershed.

The year with the highest deforestation rate was 2008, due to the high price of soybeans, and the year with the lowest recorded rates was 2012 due to the implementation of environmental policies.

The main destination of deforested areas has been pastureland for livestock.

One viable solution for identifying and punishing offenders, as well as supporting small-scale producers and recovering areas devastated by deforestation, is land regularization.

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