Available on: https://jsshrs.ep-journals.org/ E-ISSN: 3051-3561, P-ISSN: 3051-3553

Journal of Social Science and Human Research Studies

Volume : 02 Issue : 11 November-2026

Deforestation in the Legal Amazon and the Tocantins-Araguaia River Basin and the Loss of Ecosystem Services: An Analysis of the 2020–2025 Period

Antonio Pereira de Lucena Neto
Ph.D. in Environmental Science and Technology from the University of Vale do Itajaí (UNIVALI). Faculty member at the Center for Humanities, Social Sciences, and Letters at the State University of the Tocantina Region of Maranhão (UEMASUL). https://orcid.org/0000-0003-1681-663X

Francircley Sampaio Nobre
Ph.D. in Environmental Science and Technology from the University of Vale do Itajaí (UNIVALI). Adjunct Professor at CCHSL—Center for Humanities, Social Sciences, and Letters at the State University of the Tocantina Region of Maranhão (UEMASUL).
https://orcid.org/0000-0002-3435-5155

Joaquim Paulo de Almeida Júnior
Ph.D. in Environmental Science and Technology from the University of Vale do Itajaí (UNIVALI). Adjunct Professor at CCENT—Center for Exact, Natural, and Technological Sciences at the State University of the Tocantina Region of Maranhão (UEMASUL).
https://orcid.org/0009-0007-1641-493

Nisângela Severino Lopes Costa
Ph.D. in Environmental Science and Technology from the University of Vale do Itajaí (UNIVALI). Adjunct Professor at CCA—Center for Agricultural Sciences at the State University of the Tocantina Region of Maranhão (UEMASUL). https://orcid.org/0000-0003-4797-4649

Zuilho Rodrigues Castro
Master's degree in Regional Management and Development from the University of Taubaté (UNITAU). Assistant Professor at the State University of Tocantins (UNITINS), Araguatins Campus, Tocantins. https://orcid.org/0000-0002-9282-8926

Published Date: November 21, 2026 **Article DOI: 10.65150/EP-jsshrs/V2E11/2026-24**

ABSTRACT: This study analyzed the relationship between deforestation in the Legal Amazon and the loss of ecosystem services in the Tocantins-Araguaia River Basin between 2020 and 2025. It was an applied research study that combined a quantitative analysis of official vegetation monitoring time series with a qualitative reading of scientific literature and institutional documents from the water and energy sectors. The data showed that the Legal Amazon lost 56,796 km² of primary forest during this period, peaking at 13,038 km² in 2021 and dropping to 5,731 km² in 2025. While deforestation rates in the Amazon declined, the clearing of native vegetation remained high in the Cerrado portion of the basin, particularly in the state of Tocantins, which lost 230,255 hectares in 2023 and 153,311 hectares the following year. The analysis identified losses in climate regulation, carbon storage, water regulation, water quality, and biodiversity services, and examined the nexus between land use, water availability, and energy. The literature on hydrological responses to deforestation presents mixed results; long-term studies within the Tocantins-Araguaia system itself point to increased river flows, indicating that seasonal distribution—rather than annual volume—should be the focus of the problem. Monetary valuation was used strictly as an exploratory exercise, without measuring actual economic damage. It is concluded that the reduction of deforestation in the Amazon cannot be analyzed in isolation; an integrated approach is required that considers the Amazon-Cerrado transition and the river basin as complementary planning units.

KEYWORDS: Ecosystem services, Amazon-Cerrado transition, Water security, Territorial governance, MATOPIBA.

1. INTRODUCTION

The climate regime and water availability of a large part of South America depend directly on the ecological dynamics of the Legal Amazon. The forest acts as a carbon sink, recycles moisture into the atmosphere, and generates aerial flows that reach regions far beyond the boundaries of the biome (Lovejoy; Nobre, 2018; Nobre et al., 2016). Amazonian conservation sustains local biodiversity, economic activities, and populations that rely on rainfall regularity and water security.

Official monitoring of Amazonian forest cover falls under the Satellite Monitoring Project of Deforestation in the Legal Amazon (PRODES), conducted by the National Institute for Space Research (INPE), which publishes the annual historical time series of clear-cut deforestation in primary forests. Between 2020 and 2025, the system recorded a cumulative loss of 56,796 km², peaking at 13,038 km² in 2021 and receding to 5,731 km² in 2025 (Inpe, 2026a, 2026b). Although this reversal is substantial, the reduction in Amazonian clear-cutting does not,

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

by itself, ensure the recovery of environmental integrity across territories interconnected with the forest. In the Tocantins-Araguaia River Basin, this dynamic takes on specific contours. Covering approximately 918,000 square kilometers across Goiás, Tocantins, Mato Grosso, Pará, Maranhão, and the Federal District—without crossing international borders—it is the largest river basin located entirely within Brazilian territory. Its spatial extent encompasses areas of both the Cerrado and Amazon biomes, agricultural properties, territories of traditional peoples and communities, as well as one of the country's largest hydroelectric complexes (Ana, 2009; Ons, 2025).

In the Cerrado portion, the Matopiba region has concentrated a significant share of recent deforestation, standing out in national statistics (MapBiomas, 2024–2026). In Tocantins, native vegetation clearing reached 230,255 hectares in 2023—the third highest mark in the country—and remained elevated in 2024, with 153,311 hectares (MapBiomas, 2025; Mpto, 2024). Thus, while clear-cutting in the Amazon showed a retraction, the Cerrado within the basin remained under intense land-use conversion pressure.

Together, these trends highlight a scale mismatch in environmental governance. The Amazon and the Cerrado are monitored by distinct systems with their own criteria and periodicities, structured according to biome boundaries or state divisions; however, hydrological flows and ecological processes are not restricted to these administrative borders. Within the basin, Cerrado areas located in headwaters and recharge zones integrate the same hydrological system that sustains public water supply, irrigation, the maintenance of aquatic ecosystems, and downstream energy generation. The relationship between vegetation cover and hydrological regime still sparks debate in the literature.

Long-term studies within the Tocantins-Araguaia system itself have pointed to an increase in average river flows after decades of conversion, a phenomenon attributed to reduced evapotranspiration (Coe et al., 2011; Costa; Botta; Cardille, 2003). Conversely, Almada and colleagues (Almada et al., 2026) identified greater seasonal variability and a reduction in baseflow during the dry season in micro-watersheds of the Cerrado-Amazon transition. This divergence redefines the central management question: the impact of land conversion may lie less in the total annual runoff volume and more in its seasonal distribution throughout the year. This perspective brings the debate closer to the nexus between land use, water, and energy, especially in a basin equipped with large reservoirs whose operation also depends on climatic variables, storage capacity, and operational decisions of the electrical grid (Ons, 2025).

2. THEORETICAL FRAMEWORKS

2.1 Ecosystem services: from the Millennium Assessment to nature’s contributions to people

The Millennium Ecosystem Assessment (MEA), conducted between 2001 and 2005, internationally consolidated the premise that human well-being depends directly on the functional integrity of ecosystems. The report conceptualized ecosystem services as the benefits societies obtain from nature for subsistence and production, classifying them into four primary categories (Mea, 2005).

The first category comprises provisioning services, referring to material goods extracted directly from the environment, such as water, food, fibers, and genetic resources. The second encompasses regulating services, associated with maintaining environmental balance, including climate regulation, the hydrological cycle, soil stability, pollination, and natural purification. The third brings together cultural services, which cover the symbolic, recreational, aesthetic, and educational values attributed to the landscape. Finally, the fourth category includes supporting services, corresponding to the fundamental ecological processes that sustain all others, such as soil formation, nutrient cycling, and primary production.

This typology established a direct link between ecological processes and socioeconomic outcomes. From this perspective, environmental degradation ceased to represent merely the loss of species, coming to signify reduced water availability, increased climate instability, and declining soil productivity as well.

Subsequently, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) broadened this approach by introducing the concept of "Nature’s Contributions to People" (NCP), integrating material and regulating benefits with cultural dimensions and the distinct ways in which social groups interact with the environment (Ipbes, 2019). The same assessment demonstrated that anthropogenic alterations to natural systems—most notably land-use conversion—rank among the primary drivers of pressure on contemporary biodiversity (Ipbes, 2019). In the present study, ecosystem services are adopted as an analytical category to evaluate the impacts of native vegetation clearing in the Legal Amazon and the Tocantins-Araguaia River Basin. The analytical scope prioritizes climate and water regulation, carbon storage, water quality protection, and biodiversity conservation, recognizing the latter as the indispensable ecological foundation for the continuity of all other functions.

This approach carries direct implications for public policy design. Law No. 14,119/2021 established the National Policy on Payment for Environmental Services, enabling the application of economic instruments aimed at compensating actors who conserve, restore, or enhance ecosystem functions of collective interest (Brasil, 2021). However, Payment for Environmental Services (PES) does not constitute a standalone solution to deforestation control; rather, it must operate as a complementary mechanism alongside policies for territorial planning, command and control, ecological restoration, and integrated natural resource management.

Another fundamental concept for analyzing Amazonian dynamics is the ecological tipping point. Lovejoy and Nobre (2018) emphasize that the forest generates a significant share of the precipitation that sustains it, recycling moisture into the atmosphere repeatedly along the continental trajectory of water vapor. Under the synergistic effects of deforestation, warming, and fires, the ecosystem would irreversibly lose this self-regulating capacity; the authors place the critical threshold at which such a collapse becomes probable between 20% and 25% of cumulative converted area. Nevertheless, the exact value of this threshold varies even within the core reference literature. Two years earlier, Nobre and colleagues (Nobre et al., 2016) had estimated the tipping point at 40% forest clearing or 4 °C of global warming—a figure nearly twice as high as that subsequently proposed by the same group. Furthermore, the empirical basis of this hypothesis has been subject to critical scrutiny. Tao and colleagues (Tao et al., 2023) demonstrated that vegetation optical depth, a metric widely used in Amazonian resilience assessments, suffers from soil moisture interference and cross-sensor discontinuities in the region, which compromises inferences regarding resilience loss derived exclusively from this variable.

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

More recent scientific formulations have moved beyond the notion of a single, uniform threshold. Flores and colleagues (Flores et al., 2024) propose regionalized thresholds according to disturbance typology, estimating that between 10% and 47% of Amazonian forests may be exposed to compound disturbances by 2050. According to this projection, 6% of the biome could transition into a bistable condition in the southern and central portions, while 3% could cross critical precipitation thresholds, shifting toward a stable savanna regime. The divergence among these approaches does not invalidate the existence of systemic risk; on the contrary, it demonstrates that the forest's ecosystemic response is conditioned by the spatial distribution of deforestation, thermal elevation, dry-season length, and regional ecological heterogeneities, refuting the application of a homogeneous percentage across the entire biome.

2.2 What the official data series measures regarding deforestation in the Legal Amazon

What PRODES measures defines what can be concluded from its data. The system records, year by year, the area of primary forest cleared in the Legal Amazon, organizing these records according to the "PRODES year"—which runs from August to July—thereby misaligning it with the calendar year (INPE, 2026a, 2026b). When interpreting this time series, it is necessary to distinguish between preliminary estimates and the consolidated rate. In October 2025, INPE released an estimate of 5,796 km² for that year (INPE, 2025), a figure that was later adjusted to 5,731 km² in the final, consolidated dataset (INPE, 2026b). While the difference is minor, it accounts for discrepancies between publications that may use one version of the data over the other.

Furthermore, it is essential to distinguish between deforestation and forest degradation. PRODES was designed primarily to monitor clear-cutting; therefore, a reduction in the deforestation rate does not necessarily imply that other processes of environmental deterioration have decreased to the same extent. Wildfires, selective logging, and forest fragmentation reduce biomass, biodiversity, and ecological regulatory capacity, even without the total conversion of forest cover (INPE, 2025; Lovejoy & Nobre, 2018). Consequently, the rate should be interpreted as a specific indicator of forest removal, rather than a comprehensive measure of the ecological integrity of the Amazon.

Changes in forest cover also trigger economic feedback loops. In their analysis of the southern Brazilian Amazon, Leite-Filho et al. (2021) identified links between the expansion of deforestation, a reduction in precipitation at certain spatial scales, and potential losses for agricultural and livestock activities. Productive expansion based on the continuous conversion of the forest may, therefore, compromise the climatic conditions upon which agriculture itself depends (Leite-Filho et al., 2021).

2.3 The Cerrado, energy, and the expansion of the land-use frontier in the Tocantins-Araguaia Basin

The Tocantins-Araguaia Hydrographic Region is of interest to this study because its waters support several activities. Water provides energy, irrigates crops, supplies cities, allows navigation and maintains aquatic ecosystems (Ana, 2009). The basin has an unusual territory, as it brings together areas of Cerrado and Amazon. The upper part and most of the headwater areas are in the Cerrado, while the north increasingly shows Amazonian influence.

Plants such as Serra da Mesa, Cana Brava, São Salvador, Peixe Angical, Luís Eduardo Magalhães, Estreito and Tucuruí operate on the Tocantins River and its main tributaries (Ons, 2025). These reservoirs increase the economic importance of water, because energy generation depends on other uses and storage and inflow conditions that are considered in energy planning (Ons, 2025).

At the same time, the basin is part of one of the largest agricultural expansion fronts in the country. Matopiba has much of the recent suppression of native vegetation in the Cerrado, combining increased production of agricultural commodities, logistical investments and rapid change in land cover (MapBiomas, 2024, 2025, 2026). Tocantins occupies a strategic place in this process, as it is almost entirely within the hydrographic region. The environmental importance of conversion is not just in the amount of vegetation that is removed. Nóbrega and collaborators (Nóbrega etal., 2017) compared microbasins with native Cerrado and pasture in the Amazonian agricultural frontier and observed higher soil density, lower total porosity and reduced saturated hydraulic conductivity in the converted area. The degradation of the physical properties of the soil, however, did not lead to loss of flow.

Evapotranspiration fell from 1004 to 639mm per year, the runoff coefficient rose from 0.27 to 0.40 and the base contribution remained above 95% in both conditions, with a smaller seasonal drop in the microbasin under pasture (Nóbrega etal., 2017).

This result aligns with findings from long-term studies conducted within the Tocantins-Araguaia system itself. Costa, Botta, and Cardille (2003) identified an approximately 25% increase in observed streamflow in the Tocantins River over a period of about fifty years, with no significant change in precipitation. During this time, the proportion of the basin covered by pasture and agriculture rose from 30% to 49%. Coe et al. (2011) reached a similar conclusion for the Araguaia River, where streamflow increased by 25% between the 1970s and the 1990s; they attributed roughly two-thirds of this rise to land-cover conversion. In both cases, the explanation lies in a reduction in evapotranspiration—a process that would otherwise return water to the atmosphere via vegetation, but which, when diminished, redirects that water into streamflow.

A controversy arises from findings that point in the opposite direction regarding the dry season. Almada et al. (2026), in a study of eight small watersheds in the Cerrado-Amazon transition zone, observed an increase in peak flows and seasonality, alongside a decrease in baseflow during the dry season in areas with higher levels of deforestation. This contrasts sharply with the work of Levy et al. (2018), who analyzed 324 watersheds along the "arc of deforestation" between 1950 and 2013 and found an increase in minimum dry-season flows—by four to ten percentage points compared to forested conditions. The scientific literature has yet to provide a definitive explanation for this discrepancy, and attributing it solely to the size of the watersheds studied would be an oversimplification. Nóbrega and colleagues (Nóbrega et al., 2017) studied micro-watersheds and found results opposite to those of Almada and colleagues (Almada et al., 2026). Three factors may explain this variation.

The first factor is the proportion of the basin that has been deforested. Coe, Costa, and Soares-Filho (2009) showed that a decrease in evapotranspiration leads to an increase in discharge—with simulated increases of 26% for the Tocantins River and 7% for the Madeira River. However, once deforestation exceeds approximately 30%, atmospheric feedbacks reduce precipitation, effectively reversing some of this gain.

The second factor is the intensity of land management, as soil compaction depends on livestock stocking density and the duration of land use.

The third factor is the influence of climatic signals. Rizzo et al. (2020) demonstrated that such signals can negate expected trends; for instance, in the Upper Xingu region, precipitation declined by approximately 245 mm over forty years, yet water yield showed no significant trend.

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

Therefore, correctly interpreting the hydrological role of native vegetation involves more than simply assuming that more forest equates to more water. Santos et al. (2018) modeled the Iriri River basin and found that a 57% increase in pasture area raised annual streamflow by 6.5%—with an increase of 99% in December and a decrease of 8% in April. While the annual balance remained positive, the seasonal contrast became more pronounced, indicating that the temporal distribution of water must be analyzed separately from the total volume.

2.4 Mechanisms for the loss of ecosystem services associated with land-use change

The conversion of forests and the Cerrado into pastures, agricultural crops, or infrastructure alters various components of ecosystem functioning. These effects vary from case to case, depending on the type of vegetation removed, soil characteristics, management intensity, the area's position within a watershed, the local climate, and the spatial scale under consideration. Nevertheless, the literature identifies several recurring mechanisms related to climate regulation, hydrology, water quality, and biodiversity.

The first mechanism concerns climate and carbon regulation. Amazonian vegetation stores large volumes of carbon in its biomass and soil, while also controlling the exchange of water and energy between the surface and the atmosphere (IPCC, 2023; Nobre et al., 2016). When this vegetation cover is removed, the carbon stock decreases, and processes such as evapotranspiration and moisture recycling are altered. However, carbon stock should not be equated with immediate emissions. The actual amount of carbon dioxide released depends on factors such as the existing biomass, combustion, decomposition, the fate of the timber, soil carbon content, and subsequent regeneration. For this reason, this study does not employ a single, uniform factor to convert deforested area into emissions.

Moisture recycling is another component of climate regulation in the Amazon. Lovejoy and Nobre (2018) demonstrate that the forest generates a significant portion of its own precipitation through evapotranspiration and the recycling of atmospheric moisture. Using empirical data, Leite Filho et al. (2021) showed that the relationship between forest cover and precipitation varies according to scale, and that high levels of deforestation reduce rainfall in the southern Amazon, thereby affecting agricultural and livestock productivity. The second mechanism relates to water regulation. The main consequence of this is that results obtained in areas spanning only a few square kilometers cannot be applied to continental river basins without simultaneously accounting for atmospheric feedbacks and the climatic signal (Coe; Costa; Soares Filho, 2009; Rizzo et al., 2020).

The third mechanism relates to erosion, sedimentation, and water quality. When vegetation is removed or land management is inadequate, the soil becomes more exposed to the impact of rainfall, and particles are transported into watercourses (Tucci, 2012). In riparian and headwater areas, the presence of vegetation protects the banks and traps sediments. An increase in sediment load affects aquatic habitats, water intake systems, and reservoirs, although the intensity of these impacts depends on local characteristics and the management practices employed.

The fourth mechanism involves the loss and fragmentation of habitats—a process identified by the IPBES (2019) as a primary driver of the decline in terrestrial biodiversity. In the Amazon-Cerrado transition zone, land conversion disrupts connectivity between various vegetation types, gallery forests, and forested areas, thereby reducing the space available to species and altering landscape-level ecological processes. Fragmentation intensifies edge effects, increases exposure to fire, and heightens the vulnerability of remaining habitat patches, meaning the scope of ecological alteration extends well beyond the area directly converted. The accounting of emissions from tropical reservoirs is a separate, highly debated topic. Tropical reservoirs release greenhouse gases due to biogeochemical processes occurring within the impounded water. Barros et al. (2011) demonstrated this across 85 systems worldwide, linking emissions to the age and latitude of these tropical reservoirs. Subsequently, Deemer et al. (2016) conducted a review and found that factors such as the trophic state and productivity of tropical reservoirs are better predictors of emissions than age or geographic location.

2.5 Ecosystem services, territory, and traditional communities

Ecosystem services gain social importance because they support the way people occupy the territory, produce food, guarantee water and live in a way linked to natural resources. The idea that nature contributes to people reinforces this view by showing that the benefits of ecosystems are perceived, used and valued in different ways by each social group and each territory (IPBES,2019).

In the Cerrado, this relationship is even more important because there is a lot of biodiversity, essential areas for water and great cultural diversity. Rigotto, Santos and Costa (2022) describe the biome as a living territory for indigenous peoples, quilombolas, geraizeiros, retreatiros, riverside dwellers, vacanteiros and babassu coconut breakers. These communities depend directly on native vegetation and rivers to reproduce their ways of life. The authors show that the advancement of agribusiness has different effects for each social group, concentrating environmental costs in populations that have less institutional support (Rigotto; Santos; Costa,2022). In the Tocantins Araguaia Basin, we see this situation in the field. Águas and Silva (2021) study the socio-hydrodiversity of the basin looking at the relationships between the Avá Canoeiro people, the quilombola communities of Cavalcante and Colinas do Sul, the sertanejos and riverside dwellers. They compare the ways of life linked to rivers with the construction of hydroelectric plants and the expansion of agriculture. Lucena Neto and collaborators (Lucena Neto et al., 2023a) find a similar pattern in the Cerrado Maranhense and point out that the people and communities that have lived there for a long time are well aware of the fauna, flora and the different uses they derive from them.

The removal of native vegetation, in this view, does not only change the soil cover; it also affects the ecological functions and resources that sustain the material and cultural life of these populations. Conservation and regional development, therefore, do not need to be opposites. How this relationship works depends on the way it is produced, the way the territory is governed and the ability to maintain the ecological functions on which the economy itself depends (Lucena Neto et al., 2023b; Lucena Neto; Nobre; Silva, 2025).

3. METHODOLOGICAL PROCEDURES

The research has a descriptive and explanatory objective and was carried out on two fronts at the same time. The first front, of a quantitative nature, organized and analyzed the series of deforestation and suppression of native vegetation. The second front, of a qualitative nature, investigated the mechanisms of loss of ecosystem services and how they are linked to water regulation, energy, biodiversity, territory and regional development.

Bibliographic review and document analysis support both fronts. The main time frame was the period from 2020 to 2025, chosen because deforestation in the Legal Amazon increased during this time and because the suppression of native vegetation in the Cerrado intensified. Scientific

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

publications and institutional documents before or after this interval were consulted whenever they were necessary for the conceptual basis, for the method or to consolidate the most recent data.

The quantitative analysis used two main sources of environmental monitoring. The first source was PRODES, which served to describe the annual trajectory of clearcutting of primary forest in the Legal Amazon, using rates from the years 2020 to 2025 (Inpe, 2026a, 2026b). The second source was MapBiomas Alerta, which served to describe the dynamics of native vegetation suppression in the Cerrado, Matopiba and, especially, in the state of Tocantins (MapBiomas, 2024, 2025, 2026). As PRODES and MapBiomas Alerta have differences in reference period, minimum detection unit, territorial coverage and types of vegetation monitored, the PRODES results and the MapBiomas Alerta results were not combined into a single series, but were treated in a complementary way.

The state series for Tocantins was taken in full from the Annual Report on Deforestation in Brazil 2024 (MapBiomas, 2025). This choice avoided combining values from different editions of the report, because successive revisions create small differences between publications. Therefore, state data that combines MapBiomas Alerta with other detection systems were not included.

To characterize the area and hydrology of the Tocantins Araguaia Basin, documents from the National Water and Basic Sanitation Agency were used (Ana, 2009). Information about the hydroelectric system and energy planning was obtained from documents from the National Electric System Operator (Ons, 2025). Federal environmental legislation was directly consulted to analyze the Legal Reserve percentages and conservation and Payment for Environmental Services instruments (Brazil, 2012, 2021). The literature review focused on deforestation in the Legal Amazon and Cerrado, ecosystem services and their valuation, Cerrado Amazon transition, climate and water regulation, hydroelectricity and reservoir emissions, territorial governance, Matopiba and traditional communities. Recent scientific articles and institutional documents were prioritized, maintaining previous works when they were references for the substantiation of the theme. As an explicit criterion, divergent evidence was sought whenever the analyzed mechanism presented active controversy in the literature, a procedure applied to the hydrological response to deforestation, the ecological inflection threshold of the Amazon, valuation by value transfer and reservoir emissions. In the four themes, convergent and divergent results are presented together, with a discussion of plausible reasons for the discrepancy.

The analysis of ecosystem services used the typology from the Millennium Ecosystem Assessment (MA, 2005) and subsequent contributions from the IPBES (2019) as a conceptual framework. Priority was given to services directly linked to the issue under investigation: climate regulation and carbon storage; water regulation; water protection and quality; the maintenance of biodiversity; and ecological functions associated with the social and productive uses of the territory.

The analytical procedure was carried out in five stages. First, the annual trajectory of deforestation in the Legal Amazon was systematized using data from the PRODES series. Next, the dynamics of native vegetation loss in the Cerrado and the state of Tocantins were analyzed based on MapBiomas reports. In the third stage, the identified patterns were linked to the mechanisms of ecosystem service loss described in the scientific literature. The fourth stage examined the nexus between land use, water availability, and energy. Finally, the territorial and socio-environmental implications of the loss of these services were discussed. The relationship between deforestation, hydrology, and energy was presented in an interpretive and mechanistic manner, rather than as a direct causal link. The hydrological studies employed explain how changes in vegetation alter the water balance and the seasonality of streamflow; however, these results were not extrapolated to the entire Tocantins-Araguaia Basin, nor were they used to calculate losses in hydroelectric power generation. Where studies disagree regarding the direction of an effect, this divergence is noted, with differences in spatial scale suggested as a plausible explanation (Coe, Costa, & Soares-Filho, 2009).

The socio-environmental dimension was analyzed solely through scientific literature and secondary documents, without the use of interviews, field observations, questionnaires, or direct measurement of impacts on traditional peoples and communities. The social relations discussed are treated as territorial implications supported by the literature, rather than as impacts measured empirically during the period under study.

The economic valuation of ecosystem services was used solely as a preliminary exploration. We applied an average value of US$ 5,382 per hectare per year—estimated by Costanza et al. (2014) for tropical forests, in 2007 international dollars—to the cumulative area of the Amazon rainforest deforested during the period. The result was compared with a spatially explicit estimate produced specifically for the Brazilian Amazon (Strand et al., 2018) and interpreted as a potential order of magnitude for the service flows associated with the lost forest cover; it does not represent observed economic damage, environmental compensation, or market value. We did not produce our own estimate of total greenhouse gas emissions, as this would have required detailed data on biomass, soil carbon, combustion, decomposition, and the fate of organic matter. Instead, we organized the data into tables and charts—created by the author—calculating annual percentage changes and relative shares based on official datasets, while maintaining the units and reference periods specific to each system. The results were interpreted by cross-referencing official data, scientific literature, and institutional documents. As the study relied exclusively on publicly available secondary data, it did not generate any primary, personal, or sensitive information.

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

4. RESULTS AND DISCUSSION

4.1 Reduction of deforestation in the Legal Amazon and the persistence of environmental pressures

The initial result of the analysis shows that deforestation in the Legal Amazon has stopped increasing. Table 1 presents the consolidated rates for the period, including year-on-year variations and the share of each year in the total.

Table 1: Annual rate of clear-cut deforestation in the Legal Amazon, 2020–2025

Year PRODES	Deforested area (km²)	Variation (%)	% of the total 2020-2025
2020	10.851	–	19,1
2021	13.038	+20,2	23,0
2022	11.594	−11,1	20,4
2023	9.064	−21,8	16,0
2024	6.518	−28,1	11,5
2025	5.731	−12,1	10,1
Total	**56.796**	**−56,0 (2025 vs. 2021)**	**100,0**

Source: Prepared by the author based on consolidated rates from PRODES/INPE (INPE, 2026a, 2026b). PRODES: covers the period from August 1st of the previous year to July 31st of the reference year. The variation shown in the total row refers to the comparison between 2025 and 2021, not an annual variation.

The variation shown in the total line compares 2025 with 2021; it is not an annual variation. The data reveal two very different periods. The rate rose from 10,851 km² in 2020 to 13,038 km² in 2021—a 20.2% increase, which was the largest in the series. From 2022 onward, the rate began to decline: 11,594 km², followed by 9,064 km², 6,518 km², and finally 5,731 km² in the subsequent years. Consequently, the 2025 rate was approximately 56% below the peak (INPE, 2026a, 2026b). The first two years accounted for 42.1% of the total area deforested during this period, indicating that the subsequent decline did not offset the intensity of the initial land conversion.

Figure 1 compares this trajectory with the series on the clearing of native vegetation in the state of Tocantins, highlighting the disparity between the two territories.

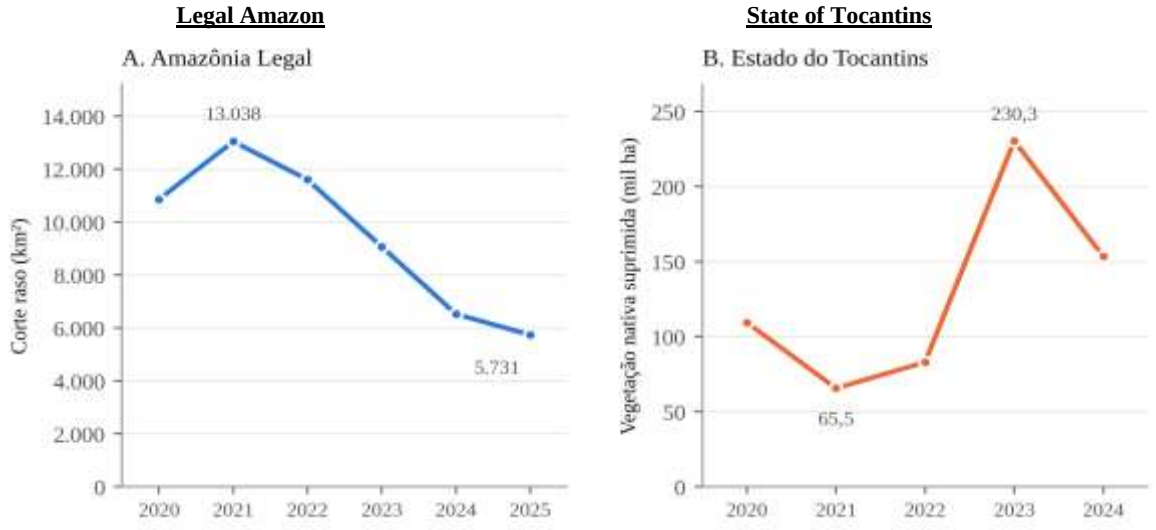


Figure 1: Deforestation in the Legal Amazon (2020–2025) and the clearing of native vegetation in the state of Tocantins (2020–2024)
Source: Prepared by the author based on PRODES/INPE (INPE, 2026a, 2026b) and MapBiomas Alerta (MapBiomas, 2025). The datasets have different units, reference periods, and vegetation typologies, which is why they are presented in separate panels.

The comparison makes it clear that the two trajectories follow opposite paths midway through the data series. Between 2022 and 2024, as the rate for the Amazon fell from 11,594 km² to 6,518 km², the area cleared in Tocantins rose from 82,871 to 153,311 hectares, reaching 230,255 hectares in 2023 (INPE, 2026b; MapBiomas, 2025). Despite the use of different units of measurement, examining both series together reveals that progress in one system coincided with deterioration in the other. The reduction in Amazonian deforestation occurred during a period when the government resumed the use of federal instruments for deforestation prevention and control—including the fifth phase of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon, which spans from 2023 to 2027 (MMA, 2023). This plan integrates satellite monitoring, the allocation of public lands, enforcement actions, economic incentives, and support for lower-impact production chains. The alignment between the implementation of these measures and the observed decline underscores the significance of "command-and-control" policies, although this study cannot isolate the specific effect of each individual policy.

A decrease in the deforestation rate does not imply that lost ecological functions have already recovered. The 56,796 km² cleared between 2020 and 2025 remain as an accumulated total of forest cover transformation, except in areas where subsequent regeneration or restoration processes may have taken place (INPE, 2026a). Converted areas cease to perform functions such as carbon storage, moisture recycling, soil

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

protection, habitat maintenance, and landscape connectivity; the recovery of these services depends on the land use established following deforestation and the potential for natural regeneration.

The spatial distribution of deforestation remains concentrated. In 2025, the states of Pará, Mato Grosso, and Amazonas accounted for the majority of the clear-cutting recorded in the Legal Amazon (INPE, 2025, 2026b). Aggregate reductions may coexist with stable or even increasing pressure in specific states, municipalities, or expansion frontiers; therefore, the regional downward trend must be analyzed alongside the persistence of critical areas. This caution is particularly significant given that the forest is vulnerable to fire, drought, and the combined effects of climate change and fragmentation. Lovejoy and Nobre (2018) demonstrate that the stability of the Amazonian system depends on the interplay between forest cover, moisture recycling, and regional climate. Flores et al. (2024) add that exposure to compound disturbances could affect between 10% and 47% of Amazonian forests by 2050, with varying impacts across different regions. Continued vegetation loss, compounded by global warming and an increased frequency of extreme events, could compromise the feedback mechanisms that sustain the forest's own environmental conditions.

From the perspective of ecosystem services, the trajectory from 2020 to 2025 involves two simultaneous elements. The first is a sharp reduction in clear-cutting following the peak in 2021. The second is the presence of factors that warrant caution when interpreting this trend. Continued conservation depends on maintaining low deforestation rates, addressing degradation, restoring areas that have already been converted, and integrating environmental policies across the Amazon, the Cerrado, and the river systems that connect these territories.

4.2 The shift of the frontier toward the basin's Cerrado and territorial governance

The second finding shows that the reduction in clear-cutting within the Legal Amazon does not correspond to an equivalent decrease in pressure on native vegetation in territories connected to the Tocantins-Araguaia Basin. While PRODES recorded a continuous decline starting in 2022, the Cerrado experienced a sharp increase in vegetation clearing in 2023, with a significant concentration in the Matopiba region (MapBiomas, 2024, 2026). Table 2 details the recent trends in the annual area cleared in the state of Tocantins.

Table 2: Clearing of native vegetation in the state of Tocantins, 2019–2024

Year PRODES	Deforested area (ha)	Variation (%)
2019	99.160	–
2020	109.308	+10,2
2021	65.538	−40,0
2022	82.871	+26,4
2023	230.255	+177,8
2024	153.311	−33,4

Source: Prepared by the author based on the 2024 Annual Report on Deforestation in Brazil, from MapBiomas Alerta (MapBiomas, 2025).

The data series shows significant fluctuations. In 2021, the area decreased by 40.0%. In 2022, it increased by 26.4%. In 2023, the area rose by 177.8%, reaching 230,255 hectares—the third-highest figure nationwide for cleared land (MapBiomas, 2025; Mpto, 2024). In 2024, the area fell by 33.4% to 153,311 hectares; however, the state's ranking remained unchanged, as the decline started from a very high level. By 2025, the state had dropped out of the top three, a list now occupied by Maranhão, Piauí, and Bahia (MapBiomas, 2026).

This pattern indicates that recent dynamics cannot be explained solely by the boundaries of the Legal Amazon or the traditional division between biomes. The basin spans both Amazonian and Cerrado regions, encompassing territories with varying intensities of agricultural expansion, distinct vegetation protection regimes, and differing state-level environmental licensing frameworks. A reduction in one part of the system may occur simultaneously with an increase in land conversion elsewhere, sustaining pressure on ecological functions that are interconnected through atmospheric circulation, the hydrological system, and regional economic flows.

The metrics used to monitor the two biomes are not equivalent. PRODES primarily measures the clear-cutting of primary forest formations, whereas MapBiomas Alerta includes various types of native vegetation, such as savanna and grassland formations (INPE, 2026a; MapBiomas, 2026). A downward trend in the official Amazon deforestation rate cannot, on its own, serve as an indicator for the conservation of the entire basin, given that its headwaters and recharge areas are located within Cerrado landscapes. The hypothesis that pressure is being displaced is supported by studies on "leakage." Villoria et al. (2022) estimated that domestic leakage offsets between 43% and 50% of the deforestation avoided through commitments within Brazil's soy supply chain; meanwhile, cross-border leakage remains minimal, as the displaced production shifts to areas in the United States that are already under agricultural use. These findings suggest that some of the expansion into the Cerrado represents a reallocation of the restrictions imposed on the Amazon, rather than an independent phenomenon. However, since the offset is less than 100%, there remains a net environmental gain from these sectoral commitments, even when accounting for such displacement.

The institutional dimension adds another layer. In their analysis of deforestation in the Cerrado between 2018 and 2023, Morales, Laurini, and Dou (2026) identified significant heterogeneity across states, with persistent upward trends concentrated along the Matopiba frontier; they observed consistently higher levels of deforestation in states that had adopted simplified licensing procedures. While this association is robust, it exists alongside competing explanations that the study itself does not account for.

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

Polizel et al. (2021) offer one such explanation by examining the Matopiba region between 1990 and 2017—a period during which approximately 8.4 million hectares of native vegetation were lost, while the area dedicated to soy cultivation grew by 326%. The authors link this pattern to land tenure structures and a failure to comply with the Forest Code on large landholdings, shifting the focus from licensing procedures to land governance. These two interpretations are not mutually exclusive; permissive state-level regulations and the concentration of land ownership may act cumulatively. Disentangling them would require an analytical framework capable of separating regulatory effects from the influence of property structures. Federal law treats the two biomes differently: Article 12 of Law No. 12.651/2012 mandates that rural properties located within the Legal Amazon's forest areas must maintain 80% of their land as a "Legal Reserve." This requirement drops to 35% for properties located within the Cerrado (within the same region) and to 20% for *campos gerais* (grasslands/open fields) in that area—a threshold that also applies to the rest of the country (Brazil, 2012). Consequently, large swaths of Cerrado vegetation can be legally converted, provided that other environmental requirements are met. To interpret the data, it is essential to distinguish between environmental illegality and authorized land conversion; both result in the loss of native vegetation cover and ecosystem functions, yet they necessitate different public policy responses.

This distinction helps explain why territorial pressure cannot be addressed solely through "command-and-control" strategies focused on illegal deforestation in the Amazon. When land conversion occurs within the bounds of the law, complementary instruments are required—such as territorial planning, incentives to maintain vegetation beyond the mandatory "Legal Reserve," payments for environmental services, the protection of water recharge areas, and coordination among agricultural, environmental, and water resource policies. The challenge shifts from merely preventing illegal clearing to determining the extent, location, and conditions under which vegetation conversion can remain compatible with maintaining the ecosystem functions of the watershed.

4.3 Water-energy-land use nexus in the Tocantins-Araguaia Basin

The preceding results allow for an interpretation of the relationship between deforestation and ecosystem services through a nexus of land use, water availability, and energy generation. In the Tocantins-Araguaia Basin, this is particularly relevant because a large portion of the headwaters and hydrological catchment areas consists of Cerrado formations currently undergoing agricultural expansion, while downstream, the Tocantins River hosts a series of major hydroelectric power plants (ANA, 2009; ONS, 2025). The direction of the hydrological impact of deforestation remains unsettled in the literature—an ambiguity that must be incorporated into the analysis rather than ignored. Most regional evidence—including two long-term datasets from the Tocantins-Araguaia system itself and a sample of 324 basins within the "arc of deforestation"—indicates an increase in streamflow following land-cover conversion, even during the dry season (Coe et al., 2011; Costa, Botta, & Cardille, 2003; Levy et al., 2018). Conversely, findings by Almada et al. (2026) suggest a reduction in baseflow; however, none of the hypotheses proposed to explain this discrepancy have been tested within this basin.

This uncertainty has direct implications for management. If the total annual runoff can actually increase following land-cover conversion, then the hydrological argument for conservation cannot be predicated on the notion of aggregate water scarcity. The most promising hypothesis shifts the focus toward the temporal distribution of water and the landscape's capacity to buffer intra-annual variability in streamflow—a mechanism consistent with changes in the physical properties of soil in converted areas (Nóbrega et al., 2017) and with the increased seasonal contrast observed in modeling of the Amazon basin (Santos et al., 2018). However, this hypothesis has not yet been verified for the Tocantins-Araguaia Basin; in fact, evidence from a larger sample points in the opposite direction, specifically regarding the dry season (Levy et al., 2018). For a system that relies on reservoirs, this distinction is of critical practical importance. The National Electric System Operator's (ONS) Energy Operation Plan assesses how the National Interconnected System can meet demand under various streamflow scenarios, analyzing the impact of each scenario on reservoir storage levels and power generation (ONS, 2025). When streamflow becomes more irregular over time, the role of reservoirs and coordinated management becomes even more vital for balancing energy production, water supply, irrigation, navigation, and the maintenance of environmental flows. Because operations depend on a complex interplay of climate, stored water volume, diverse demands, exchanges between subsystems, and operational decision-making, it is not possible to directly attribute a specific, localized drop in streamflow to deforestation.

In this scenario, the conservation of vegetation cover at headwaters and in recharge areas functions as a complement to physical infrastructure, forming an ecological infrastructure that helps ensure water security within the basin. The argument is not based on the premise that deforestation reduces the annual volume of water—a claim not supported by regional literature—but rather on the idea that vegetation cover can buffer intra-annual variability, a hypothesis that has yet to be verified for this basin. Environmental assessments of hydroelectric power must account for the biogeochemical processes occurring within reservoirs, though there remains significant debate regarding how these should be quantified. Fearnside and Pueyo (2012) argue that global compilations often underestimate emissions by failing to include downstream processes—which, in the case of the Tucuruí plant (located within this same basin), account for 88% to 93% of total methane emissions. Conversely, Prairie et al. (2018) contend that gross surface flux overstates the net impact, as it fails to subtract emissions that were already present in the landscape. Almeida et al. (2019) shift the focus toward dam design, demonstrating that dams located in Amazonian floodplains can emit 133 kg of CO_2 equivalent per megawatt-hour, compared to 39 kg for dams situated in upland areas. None of these studies link such emissions to surrounding deforestation, and the present study likewise does not do so.

4.4 Exploratory valuation and the scale of ecosystem service losses

The scale of losses associated with deforestation between 2020 and 2025 can be examined in both biophysical and economic terms, provided that the limitations of such estimates are clearly stated. During the period under analysis, PRODES recorded a cumulative loss of 56,796 km² of primary forest in the Legal Amazon, equivalent to approximately 5.68 million hectares (INPE, 2026a, 2026b). This represents an extensive area that no longer stores carbon, recycles moisture, regulates water flows, or maintains habitats.

Regarding carbon, Nobre et al. (2016) estimate that Amazonian ecosystems store between 150 and 200 billion tons of carbon, highlighting the forest's significance to the global climate system. Converting the annual deforested area directly into emissions would require spatially specific data on biomass, below-ground carbon, vegetation type, the fate of removed biomass, combustion, decomposition, and subsequent

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

regeneration. While carbon stocks and carbon dioxide emissions are related, they are not equivalent; therefore, this study treats the deforested area as evidence of a loss in potential storage capacity, rather than as an immediate emission.

Monetary valuation requires a different kind of caution. Costanza et al. (2014) estimated a unit value for tropical forests of approximately US$ 5,382 per hectare per year—expressed in 2007 international dollars—based on the aggregation of various categories of ecosystem services. Applied to the approximately 5.68 million hectares cleared between 2020 and 2025, this coefficient yields an order of magnitude of around US$ 30.6 billion per year in potential service flows associated with that land cover.

The contrast with territorially specific estimates, however, is significant. In a spatially explicit valuation of ecosystem services in the Brazilian Amazon, Strand et al. (2018) arrived at maximum values ranging from US$ 56.72 to US$ 737 per hectare per year—with the upper end of this range applying to only 12% of the remaining forest. This difference—roughly an order of magnitude compared to the global coefficient—stems from distinct methodological choices regarding which services are included, how "willingness to pay" is defined, and how spatial heterogeneity is addressed. Consequently, this aggregate exercise should be interpreted as a rough upper bound rather than an approximation of the likely magnitude.

This discrepancy is to be expected, given established methodological critiques. Toman (1998) argued that economic values are defined at the margin, and that aggregating all of an ecosystem's services produces a figure that does not correspond to any concrete decision-making process. Rosenberger and Stanley (2006) identified three simultaneous sources of error in the transfer of values between sites; the approach adopted here incurs all three by applying an international average coefficient to a specific territory. In their own work, Costanza et al. (2014) acknowledge that transferring average values between ecosystems serves only as an initial approximation, lacking a specific decision-making context.

Another limitation is that the coefficient used pertains specifically to tropical forests; for this reason, it was not applied to deforested areas of the Cerrado in Tocantins or the Matopiba region. A mechanical extension of this value to savanna-like formations would yield a conceptually inadequate estimate, especially because the importance of the Cerrado for this research is linked to water regulation, groundwater recharge, and the maintenance of flow seasonality—functions that cannot be represented by the amount of biomass in the landscape.

The economic dimension of losses within the basin also encompasses components that an aggregate analysis fails to capture—such as changes in water treatment costs resulting from increased sediment transport, greater variability in water availability during the dry season, impacts on water-dependent productive activities, loss of habitats, and effects on downstream users. Quantifying these components would require specific studies on environmental valuation and basin-scale hydrological modeling.

Taken together, the results identify four primary dimensions of loss during the period in question. The first is a reduction in climate regulation capacity and carbon storage. The second is an alteration in hydrological regulation, with a pronounced effect on the seasonal distribution of streamflow. The third is the potential impairment of water quality in landscapes prone to erosion. The fourth is the loss and fragmentation of habitats, with consequences for biodiversity as well as for the social and productive uses of natural resources.

4.5 Socio-environmental and territorial implications of the loss of ecosystem services

The losses identified extend beyond the simple biophysical issue of deforestation. Changes in water regulation, water quality, biodiversity, and the availability of natural resources affect territories where social groups and economic activities depend—to varying degrees—on the functioning of ecosystems. In the Tocantins-Araguaia Basin, this situation is intensified by the presence of agricultural expansion, hydroelectric power generation, protected areas, cities, rural communities, and territories occupied by traditional peoples and communities.

The distribution of these effects is not uniform. Rigotto, Santos, and Costa (2022) show that the encroachment of agribusiness into the Cerrado concentrates environmental costs upon populations with less institutional capacity, creating what they term "sacrifice zones." Groups whose livelihoods, production systems, or territorial identities are more heavily dependent on local ecosystems end up feeling the impacts—such as changes in water availability and quality, biodiversity, and plant resources—most directly. Águas and Silva (2021) observe a similar situation within this same basin, where *quilombola* (maroon) and riverine communities face the dual pressures of hydroelectric infrastructure development and the expansion of the agricultural frontier.

The issue of water resources makes this asymmetry even more apparent. During periods of greater flow variability—especially in the dry season—various users find themselves in intensified competition for this resource. Irrigated agriculture, urban water supply, energy generation, ecosystem maintenance, and the needs of local populations all rely on the same water base, even though they possess vastly different economic, technological, and institutional capacities to respond to times of reduced availability. Academic research on the "Pre-Amazon" region of the eastern Amazon sheds light on the relationship between economic activity and conservation. Lucena Neto, Nobre, and Marenzi (Lucena Neto; Nobre; Silva, 2025) examined açaí production by traditional communities, finding that economic opportunities often emerge alongside socio-environmental challenges, such as deforestation, biodiversity loss, land-use conflicts, and inequalities within the supply chain. The authors highlight that ecological management, traditional knowledge, and community organization are essential for developing sustainable production strategies. Lucena Neto, Silva, and Marenzi (Lucena Neto et al., 2023b) further argue that regional development can be analyzed through the lens of supply chains linked to natural resources, rather than viewing the expansion of converted land as the sole means of generating income.

The problem within the basin does not lie in the existence of economic activities themselves, but rather in the manner, intensity, and location of the conversion of vegetation cover. Barros and Stege (2021) studied the spatial relationships between socioeconomic development and deforestation in the Cerrado, demonstrating that economic growth, agricultural production, and the conversion of vegetation do not manifest uniformly across the entire territory. Development strategies for the basin must account for both the economic benefits derived from the productive use of land and the environmental costs associated with the loss of functions that ensure water availability, soil stability, and biodiversity.

The data from this study do not allow for the conclusion that specific communities lost income, were displaced, or experienced reduced access to natural resources between 2020 and 2025. The research did not involve fieldwork, nor did it directly measure such consequences. This analysis serves to demonstrate that the environmental services affected by deforestation are integral to the social and economic conditions of the territory, and it paves the way for future research that incorporates population, territorial, and qualitative data. Recognizing that environmental services are part of the population's living conditions shapes the development of environmental policies. The National Policy for Payment for

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

Environmental Services (Brazil, 2021) provides a mechanism that can offer economic compensation for conservation, restoration, and sustainable management efforts that sustain services of collective interest. In the Tocantins-Araguaia Basin, such mechanisms are particularly relevant for recharge areas, headwaters, ecological corridors, and properties that preserve native vegetation beyond legal requirements—provided that their implementation adheres to well-defined environmental, territorial, and social criteria.

Ecological restoration must also be approached in an integrated manner. Restoring riparian forests and degraded areas helps protect the soil, connect habitats, and improve water quality; however, its effectiveness depends on the location of the interventions, the scale of the restoration, and how these efforts are coordinated with other land uses within the basin. Prioritizing areas solely based on the number of hectares restored may be less efficient than selecting zones where restoration yields simultaneous benefits for biodiversity, water regulation, and the populations that rely on these services.

4.6 Study limitations

The limitations of this study stem from its documentary nature, which constrains the scope of its conclusions. PRODES and MapBiomas Alerta employ different objectives, reference periods, and detection criteria; consequently, the datasets were analyzed separately, with the specific versions used duly noted (INPE, 2026a; MapBiomas, 2026). The territory of Tocantins—almost entirely contained within the basin—provides a sound approximation for this analysis, even though the Tocantins-Araguaia Hydrographic Region also encompasses parts of Goiás, Mato Grosso, Maranhão, Pará, and the Federal District (ANA, 2009). The scope adopted here focuses primarily on clear-cutting and the removal of native vegetation; therefore, processes such as recurring fires and progressive degradation—which also impact ecosystem services—remain to be addressed in future research.

Two methodological choices warrant mention, as they necessitate a cautious interpretation of the findings. In the hydrological dimension, the literature offers conflicting views regarding the direction of the impact of deforestation on streamflow (Coe, Costa, & Soares Filho, 2009; Rizzo et al., 2020); the analysis presented here is conceptual, underscoring the need for basin-specific modeling. In the economic dimension, the international average coefficient applied differs from the spatially explicit valuations available for the Brazilian Amazon (Strand et al., 2018). Finally, the socio-environmental dimension—documented in literature concerning the peoples and communities of the Cerrado and the eastern fringes of the Amazon (Lucena Neto et al., 2023a; Rigotto, Santos, & Costa, 2022; Águas & Silva, 2021)—paves the way for future field research to complement the documentary foundation of this study.

5. FINAL CONSIDERATIONS

This study analyzed the relationship between deforestation in the Legal Amazon—focusing on the Tocantins-Araguaia River Basin—and the loss of ecosystem services between 2020 and 2025. The objective was met. Data from the PRODES monitoring system showed a decline of approximately 56% between the 2021 peak and 2025; however, an integrated assessment revealed that areas of the Cerrado biome linked to the basin continued to undergo intensive land-cover conversion during the same period. The state of Tocantins ranked third nationally in deforestation in 2023 and 2024, before dropping out of the top three in 2025. This discrepancy between the two datasets highlights the need to move beyond analyses that consider only individual biomes or states, as the Amazon and Cerrado within this basin form an interdependent territorial and hydrological system.

The primary contribution of this work lies in acknowledging that the hydrological impact of land-cover conversion remains uncertain. Most regional evidence—including two long-term datasets from the Tocantins-Araguaia system itself and a sample of 324 watersheds within the "arc of deforestation"—indicates an increase in streamflow following conversion, even during the dry season, which is attributed to a reduction in evapotranspiration. Conversely, a recent study of small watersheds in the Cerrado-Amazon transition zone identifies greater seasonality and a loss of baseflow during the dry season. Given this divergence, the findings suggest that the distribution of water throughout the year warrants as much attention as the total volume of runoff. This remains an open question for the Tocantins-Araguaia Basin, underscoring the importance of conducting region-specific hydrological studies. The identified losses include a reduction in carbon storage and climate regulation, changes in hydrological regulation, increased vulnerability to erosion, the loss and fragmentation of habitats, and risks to the use of resources by Indigenous peoples, traditional communities, and other users—even though the study did not directly measure the impacts on these groups. A preliminary monetary valuation—approximately US$ 30.6 billion per year, based on an international average coefficient—was ten times higher than the spatial estimates currently available for the Brazilian Amazon. This calculation serves to demonstrate that the lost functions possess an economic value not captured by production statistics, rather than to quantify the exact extent of the damage.

In light of these results, it is recommended that monitoring be strengthened by using the river basin as a complementary unit of analysis, integrating data on clear-cutting, the clearing of Cerrado vegetation, degradation, and fire. Conservation and restoration efforts must prioritize recharge areas, springs, riparian forests, and ecological corridors—not merely based on the number of hectares, but because of the vital role these areas play within the hydrological system. The conservation of vegetation beyond legal requirements can be encouraged through economic instruments, such as Payments for Environmental Services (PES), particularly in regions where authorized land conversion remains a significant pressure. Agricultural, environmental, water, and energy planning must be progressively integrated, ensuring that decisions regarding the expansion of productive activities account for the ecological functions upon which those very activities depend.

Regarding a research agenda, there is a need for studies at the sub-basin scale that integrate data on vegetation cover, water flow, reservoirs, irrigation, and socioeconomic indicators. Spatial hydrological modeling would be crucial for determining which hypothesis explains the divergences found in the existing literature; furthermore, localized economic assessments—complemented by field research involving local communities and water users—would complete the picture presented in this study, which was developed using secondary data. The recent trajectory of deforestation cannot be evaluated solely by the decline in rates within the Legal Amazon. The Tocantins-Araguaia Basin demonstrates that the impacts of landscape transformation transcend the boundaries between biomes, states, and economic sectors. While reducing deforestation remains a necessary condition, the preservation of ecosystem services also requires territorial governance, the conservation of hydrologically strategic areas, and development models that reconcile production with environmental integrity.

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

DECLARATIONS / CONFIRMATIONS

* **Financiamiento / Funding:** Se financió con recursos propios. / It was financed with its own resources.
* **Conflictos de interés / Conflicts of interest:** Se declara no presentar conflicto de interés. / No conflict of interest is declared.

REFERENCES

1) AGÊNCIA NACIONAL DE ÁGUAS (ANA). Plano estratégico de recursos hídricos da bacia hidrográfica dos rios Tocantins e Araguaia: relatório síntese. Brasília: ANA, 2009. 256 p.
2) ALMADA, H. K. S. et al. Hydrological impacts of deforestation on flow dynamics of small watersheds in the Brazilian Cerrado–Amazon transition region. Journal of Hydrology X, v. 30, 100214, 2026. DOI: https://doi.org/10.1016/j.hydroa.2026.100214.
3) ALMEIDA, R. M. et al. Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning. Nature Communications, v. 10, 4281, 2019. DOI: https://doi.org/10.1038/s41467-019-12179-5.
4) BARROS, N. et al. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nature Geoscience, v. 4, n. 9, p. 593-596, 2011. DOI: https://doi.org/10.1038/ngeo1211.
5) BARROS, P. H. B.; STEGE, A. L. Socioeconomic development and deforestation in the Cerrado biome, Brazil: spatial interactions and heterogeneity. Revista Brasileira de Estudos Regionais e Urbanos, v. 15, n. 3, p. 393-415, 2021. DOI: https://doi.org/10.54766/rberu.v15i3.792.
6) BRASIL. Lei nº 12.651, de 25 de maio de 2012. Dispõe sobre a proteção da vegetação nativa e dá outras providências. Diário Oficial da União: seção 1, Brasília, DF, 28 maio 2012.
7) BRASIL. Lei nº 14.119, de 13 de janeiro de 2021. Institui a Política Nacional de Pagamento por Serviços Ambientais. Diário Oficial da União: seção 1, Brasília, DF, 14 jan. 2021.
8) COE, M. T. et al. The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. Biogeochemistry, v. 105, n. 1, p. 119-131, 2011. DOI: https://doi.org/10.1007/s10533-011-9582-2.
9) COE, M. T.; COSTA, M. H.; SOARES-FILHO, B. S. The influence of historical and potential future deforestation on the stream flow of the Amazon River: land surface processes and atmospheric feedbacks. Journal of Hydrology, v. 369, n. 1-2, p. 165-174, 2009. DOI: https://doi.org/10.1016/j.jhydrol.2009.02.043.
10) COSTA, M. H.; BOTTA, A.; CARDILLE, J. A. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. Journal of Hydrology, v. 283, n. 1-4, p. 206-217, 2003. DOI: https://doi.org/10.1016/S0022-1694(03)00267-1.
11) COSTANZA, R. et al. Changes in the global value of ecosystem services. Global Environmental Change, v. 26, p. 152-158, 2014. DOI: https://doi.org/10.1016/j.gloenvcha.2014.04.002.
12) DEEMER, B. R. et al. Greenhouse gas emissions from reservoir water surfaces: a new global synthesis. BioScience, v. 66, n. 11, p. 949-964, 2016. DOI: https://doi.org/10.1093/biosci/biw117.
13) FEARNSIDE, P. M.; PUEYO, S. Greenhouse-gas emissions from tropical dams. Nature Climate Change, v. 2, n. 6, p. 382-384, 2012. DOI: https://doi.org/10.1038/nclimate1540.
14) FLORES, B. M. et al. Critical transitions in the Amazon forest system. Nature, v. 626, n. 7999, p. 555-564, 2024. DOI: https://doi.org/10.1038/s41586-023-06970-0.
15) INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS (INPE). Monitoramento do Desmatamento da Floresta Amazônica Brasileira por Satélite (PRODES). Plataforma TerraBrasilis. São José dos Campos: INPE, 2026a. Disponível em: https://terrabrasilis.dpi.inpe.br. Acesso em: 20 ago. 2026.
16) INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). Climate change 2023: synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report. Geneva: IPCC, 2023. Disponível em: https://www.ipcc.ch/report/ar6/syr/. Acesso em: 25 ago. 2026.
17) INTERGOVERNMENTAL SCIENCE-POLICY PLATFORM ON BIODIVERSITY AND ECOSYSTEM SERVICES (IPBES). Global assessment report on biodiversity and ecosystem services. Bonn: IPBES Secretariat, 2019. DOI: https://doi.org/10.5281/zenodo.3831673.
18) LEITE-FILHO, A. T. et al. Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. Nature Communications, v. 12, 2591, 2021. DOI: https://doi.org/10.1038/s41467-021-22840-7.
19) LEVY, M. C. et al. Land use change increases streamflow across the arc of deforestation in Brazil. Geophysical Research Letters, v. 45, n. 8, p. 3520-3530, 2018. DOI: https://doi.org/10.1002/2017GL076526.
20) LOVEJOY, T. E.; NOBRE, C. Amazon tipping point. Science Advances, v. 4, n. 2, eaat2340, 2018. DOI: https://doi.org/10.1126/sciadv.aat2340.
21) LUCENA NETO, A. P.; NOBRE, F. S.; MARTINS, F. R. S.; SILVA, I. R. Impactos ambientais no Cerrado Maranhense. In: BRANCO, J. O.; CIONEK, V. M. (org.). Conservação da biodiversidade na Região Tocantina do Maranhão. 1. ed. Itajaí: Univali, 2023a. p. 50-67. E-book. Disponível em: https://authentic-cuddle-867e555521.media.strapiapp.com/Anexo_e_book_Conservacao_da_Biodiversidade_na_Regiao_Tocantina_do_Maranhao_78e098a12f.pdf. Acesso em: 24 ago. 2026.
22) LUCENA NETO, A. P.; NOBRE, F. S.; SILVA, I. R. da. Desafios à estratégia da sustentabilidade na produção de açaí por comunidades tradicionais na Pré-Amazônia Oriental. Revista Políticas Públicas & Cidades, v. 14, n. 8, e2348, 2025. DOI: https://doi.org/10.23900/2359-1552v14n8-18-2025.

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

23) LUCENA NETO, A. P.; SILVA, I. R.; MARENZI, R. C. Local production arrangement in the Eastern Pre-Amazon: case study of açaí production in association in Povoado 1700, in the municipality of Imperatriz – MA. Observatorio de la Economía Latinoamericana, v. 21, n. 12, p. 24892-24909, 2023b. DOI: https://doi.org/10.55905/oelv21n12-079.
24) MAPBIOMAS ALERTA. Relatório anual do desmatamento no Brasil 2023. São Paulo: MapBiomas, 2024. Disponível em: https://alerta.mapbiomas.org/wp-content/uploads/sites/17/2024/10/RAD2023_COMPLETO_15-10-24_PORTUGUES.pdf. Acesso em: 20 ago. 2026.
25) MAPBIOMAS ALERTA. Relatório anual do desmatamento no Brasil 2024. São Paulo: MapBiomas, 2025. Disponível em: https://alerta.mapbiomas.org/wp-content/uploads/sites/17/2025/11/RAD2024_28_10.pdf. Acesso em: 20 ago. 2026.
26) MAPBIOMAS ALERTA. Relatório anual do desmatamento no Brasil 2025. São Paulo: MapBiomas, 2026. Disponível em: http://alerta.mapbiomas.org/wp-content/uploads/sites/17/2026/06/RAD2025_12.06.26.pdf. Acesso em: 20 ago. 2026.
27) MILLENNIUM ECOSYSTEM ASSESSMENT (MEA). Ecosystems and human well-being: synthesis. Washington, DC: Island Press, 2005. Disponível em: https://www.millenniumassessment.org/documents/document.356.aspx.pdf. Acesso em: 20 ago. 2026.
28) MINISTÉRIO DO MEIO AMBIENTE E MUDANÇA DO CLIMA (MMA). Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm): 5ª fase (2023-2027). Brasília: MMA, 2023. Disponível em: https://dados.mma.gov.br/ja/dataset/plano-de-acao-para-a-prevencao-e-controle-do-desmatamento-na-amazonia-legal-ppcdam-5a-fase. Acesso em: 20 ago. 2026.
29) MORALES, A. B.; LAURINI, M. P.; DOU, Y. Unveiling Cerrado deforestation: a comparative analysis among Brazilian states. Land Use Policy, v. 167, 108062, 2026. DOI: https://doi.org/10.1016/j.landusepol.2026.108062.
30) NOBRE, C. A. et al. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. Proceedings of the National Academy of Sciences of the United States of America, v. 113, n. 39, p. 10759-10768, 2016. DOI: https://doi.org/10.1073/pnas.1605516113.
31) NÓBREGA, R. L. B. et al. Effects of conversion of native cerrado vegetation to pasture on soil hydro-physical properties, evapotranspiration and streamflow on the Amazonian agricultural frontier. PLoS ONE, v. 12, n. 6, e0179414, 2017. DOI: https://doi.org/10.1371/journal.pone.0179414.
32) OPERADOR NACIONAL DO SISTEMA ELÉTRICO (ONS). Plano da operação energética 2025/2029 (PEN 2025). Rio de Janeiro: ONS, 2025. Disponível em: https://www.ons.org.br/paginas/noticias/details.aspx?i=11629. Acesso em: 20 ago. 2026.
33) POLIZEL, S. P. et al. Analysing the dynamics of land use in the context of current conservation policies and land tenure in the Cerrado – MATOPIBA region (Brazil). Land Use Policy, v. 109, 105713, 2021. DOI: https://doi.org/10.1016/j.landusepol.2021.105713.
34) PRAIRIE, Y. T. et al. Greenhouse gas emissions from freshwater reservoirs: what does the atmosphere see? Ecosystems, v. 21, n. 5, p. 1058-1071, 2018. DOI: https://doi.org/10.1007/s10021-017-0198-9.
35) RIGOTTO, R. M.; SANTOS, V. P.; COSTA, A. M. Territórios tradicionais de vida e as zonas de sacrifício do agronegócio no Cerrado. Saúde em Debate, v. 46, n. esp. 2, p. 13-27, 2022. DOI: https://doi.org/10.1590/0103-11042022E201.
36) RIZZO, R. et al. Land use changes in Southeastern Amazon and trends in rainfall and water yield of the Xingu River during 1976-2015. Climatic Change, v. 162, n. 3, p. 1419-1436, 2020. DOI: https://doi.org/10.1007/s10584-020-02736-z.
37) ROSENBERGER, R. S.; STANLEY, T. D. Measurement, generalization, and publication: sources of error in benefit transfers and their management. Ecological Economics, v. 60, n. 2, p. 372-378, 2006. DOI: https://doi.org/10.1016/j.ecolecon.2006.03.018.
38) SANTOS, V. dos et al. Hydrologic response to land use change in a large basin in eastern Amazon. Water, v. 10, n. 4, 429, 2018. DOI: https://doi.org/10.3390/w10040429.
39) STRAND, J. et al. Spatially explicit valuation of the Brazilian Amazon forest's ecosystem services. Nature Sustainability, v. 1, n. 11, p. 657-664, 2018. DOI: https://doi.org/10.1038/s41893-018-0175-0.
40) TAO, S. et al. Little evidence that Amazonian rainforests are approaching a tipping point. Nature Climate Change, v. 13, n. 12, p. 1317-1320, 2023. DOI: https://doi.org/10.1038/s41558-023-01853-8.
41) TOMAN, M. Why not to calculate the value of the world's ecosystem services and natural capital. Ecological Economics, v. 25, n. 1, p. 57-60, 1998. DOI: https://doi.org/10.1016/S0921-8009(98)00017-2.
42) TUCCI, C. E. M. (org.). Hidrologia: ciência e aplicação. 4. ed. Porto Alegre: ABRHidro; Oficina de Textos, 2012.
43) VILLORIA, N.; GARRETT, R.; GOLLNOW, F.; CARLSON, K. Leakage does not fully offset soy supply-chain efforts to reduce deforestation in Brazil. Nature Communications, v. 13, 5476, 2022. DOI: https://doi.org/10.1038/s41467-022-33213-z.
44) ÁGUAS, C. L. P.; SILVA, C. T. Os saberes das águas: interculturalidade e sócio-hidrodiversidade no Cerrado brasileiro. Sociedade e Cultura, Goiânia, v. 24, e67334, 2021. DOI: https://doi.org/10.5216/sec.v24.e67334.

License: This is an open access article under the CC BY 4.0 license: https://creativecommons.org/licenses/by/4.0/

Corresponding Author: Antonio Pereira de Lucena Neto