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(In)Effectiveness of Permanent Preservation Areas in Controlling Deforestation in the Amazon: A Case Study of the Mapinguari National Park, Brazil

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A B S T R A C T

Deforestation in the Amazon Biome, particularly in the "arc of deforestation," threatens essential ecosystem services such as carbon storage, climate regulation, and habitat conservation. Protected Areas (PAs) are critical for mitigating these impacts, but their effectiveness is under constant challenge. This study analyzed deforestation dynamics within the boundaries and Buffer Zone (BZ) of Mapinguari National Park (MNP) and assessed the impact of national policies between 2009 and 2021. Using the 2018 Management Plan and cartographic data from MapBiomas, ICMBio, and SICAR, changes in land use and land cover (LULC) were quantified. Geospatial analyses were conducted using QGIS and R software. Results reveal limited deforestation within the park boundaries but significant expansion in the BZ, particularly in the south and southeast, driven by pre-existing farms and urban proximity. This expansion compromises the BZ's buffer function and highlights gaps in enforcement and land management policies. The findings emphasize the urgent need for improved financial mechanisms and strengthened conservation policies to ensure the sustainability of protected areas and their ecosystem services.

Keywords: Arc of Deforest; Conservation Units; Anthropogenic Pressure; Environmental Policies.

(In)Efetividade das Áreas de Preservação Permanente no Controle do Desmatamento na Amazônia: Um Estudo de Caso do Parque Nacional Mapinguari, Brasil

R E S U M O

O desmatamento no Bioma Amazônico, especialmente no "arco do desmatamento," ameaça serviços ecossistêmicos essenciais, como o armazenamento de carbono, a regulação climática e a conservação de habitats. As Áreas Protegidas (APs) são fundamentais para mitigar esses impactos, mas sua eficácia está constantemente em desafio. Este estudo analisou a dinâmica do desmatamento nos limites e na Zona de Amortecimento (ZA) do Parque Nacional Mapinguari (PNM) e avaliou o impacto de políticas nacionais entre 2009 e 2021. Utilizando o Plano de Manejo de 2018 e dados cartográficos do MapBiomas, ICMBio e SICAR, foram quantificadas mudanças no uso e cobertura da terra (LULC). As análises geoespaciais foram realizadas nos softwares QGIS e R. Os resultados indicam desmatamento limitado dentro dos limites do parque, mas uma expansão significativa na ZA, especialmente nas porções sul e sudeste, impulsionada por fazendas preexistentes e pela proximidade de áreas urbanas. Essa expansão compromete a função de amortecimento da ZA e evidencia lacunas na fiscalização e no manejo territorial. Os achados reforçam a necessidade urgente de mecanismos financeiros aprimorados e políticas de conservação mais robustas para garantir a sustentabilidade das áreas protegidas e de seus serviços ecossistêmicos.

Palavras-chave: Arco do Desmatamento; Unidades de Conservação; Pressão Antrópica; Políticas Ambientais.

Introduction

Historically, indiscriminate deforestation driven by human activity has led to the loss of more than one-third of global forest cover, with agricultural expansion being one of the primary contributors to this degradation (Bologna & Aquino, 2020; Hu et al., 2021; Jayathilake et al., 2021). In the Amazon, the world's largest tropical rainforest, this issue is further exacerbated due to the region's critical role in global environmental processes, such as the carbon cycle, climate regulation, and the preservation of water resources (Borma et al., 2022; Gómez-Betancur et al., 2022). Moreover, the Amazon is one of the principal providers of ecosystem services, hosting the planet's greatest biodiversity and supporting traditional communities that rely on its resources (Neves et al., 2020; Seymour & Harris, 2019; Siqueira-Gay et al., 2022; Stabile et al., 2020).

Despite its global significance, the Amazon is under intense pressure from deforestation, particularly concentrated in the "deforestation arc," which encompasses areas in southern Amazonas state (Silva et al., 2021; Li et al., 2021). This region, characterized by ecological transitions between dense forests and natural grasslands, has experienced escalating deforestation driven by agricultural expansion and population growth (Lopes & Steinke, 2024). Municipalities such as Lábrea, Boca do Acre, and Apuí stand out due to their high rates of environmental degradation, which not only compromise ecological integrity but also challenge the effectiveness of Conservation Units (CUs) established to mitigate such impacts (Carvalho & Domingues, 2016; Jayathilake et al., 2021).

Conservation Units (CUs), categorized into Sustainable Use and Full Protection, should act as barriers to deforestation (Silva & Silva, 2022). However, failures in public policies, gaps in monitoring, and the advancement of anthropogenic activities within Buffer Zones (BZs) compromise their functions (Duarte et al., 2019). Although established to mitigate the impacts of deforestation, there are still significant gaps in the documentation and evidence of the effectiveness of these strategies in critical regions, such as southern Amazon (Börner et al., 2020).

Understanding land use dynamics in these areas is essential for directing more effective public policies and strengthening the territorial management of Conservation Units (Rudke et al., 2020), ensuring the conservation of ecosystem services and the sustainable development of the region (Kalogiannidis et al., 2023; Soares-Filho et al., 2023; Stabile et al., 2020).

Recent studies highlight the essential role of management plans in improving the effectiveness of Protected Areas (PAs) as tools for forest conservation (Powlen et al., 2021). In Brazil, although their implementation is formally required shortly after the creation of a PA, many management plans face significant delays, leaving several areas without approval for extended periods. Evidence from quasi-experimental studies indicates that PAs with approved management plans tend to be more effective in reducing deforestation over time, even if the observed impacts are modest (West et al., 2022). Therefore, investing in the development and effective implementation of these plans is crucial to strengthening PA governance and achieving tangible conservation outcomes, particularly in regions under intense anthropogenic pressure.

Given this issue, the present study aims to analyze the deforestation dynamics within the boundaries and Buffer Zone (BZ) of Mapinguari National Park (MNP), assessing the evolution of land use and land cover between 2009 and 2021. Additionally, it sought to evaluate the effectiveness of recently adopted national policies for the protection of Conservation Units and their associated ecosystems.

Materials and methods

Study area

The MNP was created by Decree No. s/nº on June 5th, 2008, with the purpose of preserving natural ecosystems of great ecological relevance and scenic beauty. It prioritizes the conservation of important savanna enclaves in the Purus-Madeira interfluve, integrating the southern mesoregion of Amazonas. The MNP is also intended for scientific research and the development of activities related to environmental education, recreation in contact with nature, and ecological tourism. The park covers an area of 1.8 million hectares, while its surrounding BZ spans 1.16 million hectares, consisting of a 10 km buffer from the park's boundaries (Figure 1).

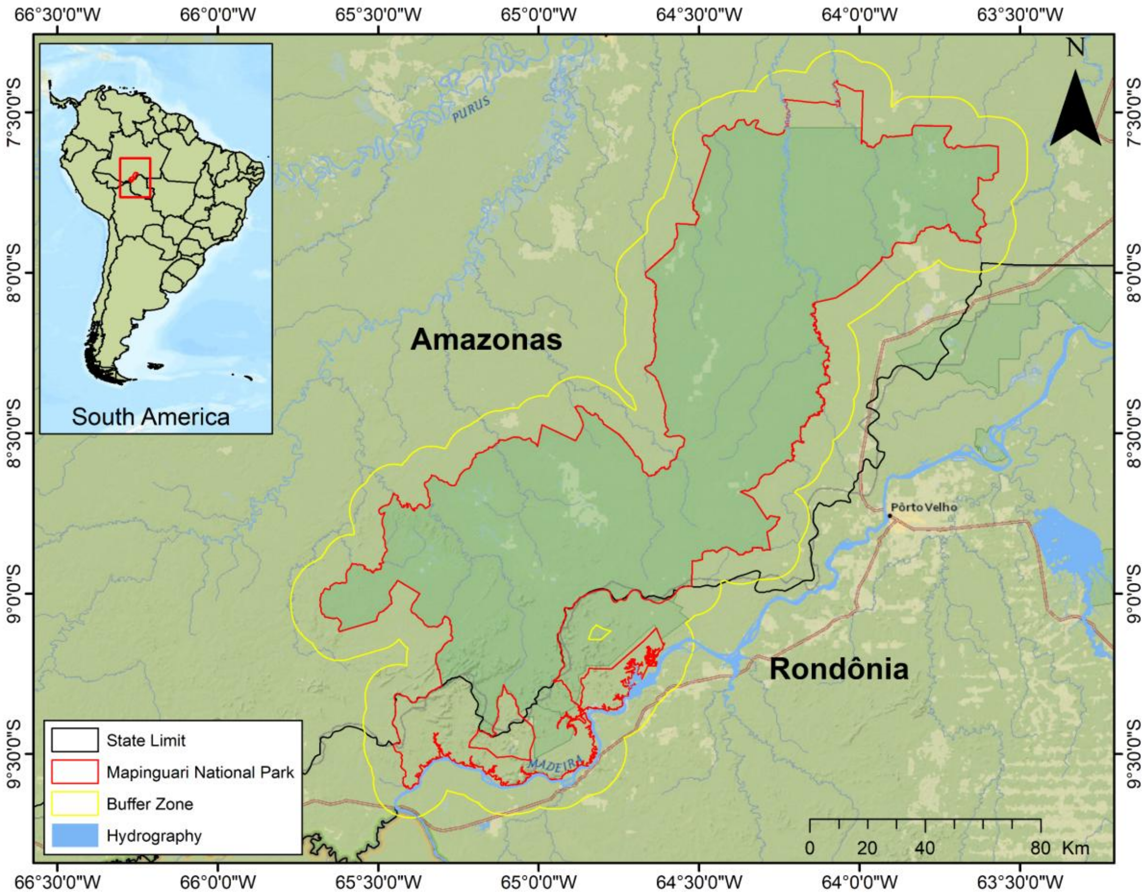

Figure 1. Location of the Mapinguari National Park and its buffer zone, as well as the delimitation of the Park between the state areas of Rondônia and Amazonas.

According to Köppen's climate classification, climate of the southern mesoregion of Amazonas is rainy tropical. The average annual temperatures range between 25 and 27°C, with minimum and maximum temperatures of 17 and 36°C, respectively. The average relative humidity varies between 85 and 90%, with the possibility of reaching minimum levels below 50% during the dry season (Alvares et al., 2013; Martins et al., 2023). The study area has Red-Yellow Argisol (Acrisols) located in the Amazon Plain between the Purus and Madeira rivers, linked to recent and ancient alluvial sediments from the Quaternary period. This region is characterized by the presence of large tabular reliefs with very gentle slopes, and deficiency of natural drainage. The altitude within the park ranges from 51 to 256 m (Bello et al., 2022).

Cartographic Bases and Spatial Analyses

The necessary maps to calculate changes in Land Use and Land Cover (LULC), both within and in the BZ of the MNP, were obtained from the cartographic databases of MapBiomas (MAPBIOMAS, 2019a) and ICMBio (ICMBIO, 2021), respectively. Further information regarding the extent of the park's Buffer Zone was obtained from its management plan (MMA, 2018a; MMA, 2018b). Cartographic data outlining the boundaries of rural properties in the municipalities sharing territory with the park were acquired in vector format through the SICAR electronic portal (SICAR, 2021). All the used materials, and their characteristics are available in Chart 1.

Chart 1. Used materials and their specifications.

	Materials	Source	Characteristics
Data	Land use/cover	MAPBIOMAS – Collection 5	From 2009, 2011, 2013, 2015 and 2017 with resolution of 30 m – raster
		MAPBIOMAS – Collection 7	From 2019 and 2021 with resolution of 30 m – raster
	Environmental rural registry	SICAR (Environmental Rural Registry National System)	Lábrea, Canutama and Porto Velho municipalities Vector - *shapefile*
	CU boundaries, states, municipalities and drainage	IBGE (Brazilian Institute of Geography and Statistics)/ICMBio (Brazilian Chico Mendes Institute for Biodiversity Conservation)/ MNP's Management Plan	Vector – *shapefile*
Others	*Software* QGIS	Qgis.org	GIS - Version 3.16 (QGIS Development Team, 2021)
	Software RStudio and R	Rstudio.com and R Cran Project	RStudio (version 1.3.1093) (RStudio Team, 2020); R (version 4.0.3) (R Core Team, 2020)

In order to classify and tally the data, all maps were reprojected in the SIRGAS 2000 reference system, with the UTM coordinate system, zone 20S. Thus, the process applied for the analysis and tallying of changes in LULC is depicted in **Erro! Fonte de referência não encontrada.**, with a description of each step presented thereafter.

Step 1: LULC classification. Initially, changes in land use history within the MNP and its BZ were assessed by creating a base map, cropped out of the boundaries of the park and the BZ. The classes defined by the original MapBiomas map (MAPBIOMAS, 2019b) were evaluated and subsequently reclassified according to their origin, either Natural Formation (C1) or Anthropogenic Area (C2), which were used in the interpretations of changes in the LULC of the study area.

Step 2: LULC calculation. From the result of Step 1, the quantity of pixels belonging to each new class (C1 or C2) was separated and tallied. The total number of pixels was then converted to hectares by multiplying the value by $30^2/10{,}000$, resulting in the total area occupied by each class in each of the years (in hectares). The annual values were compared within the intervals between the years, as shown in Figure 2, to account for the variation in the area occupied by anthropogenic activity over the study period.

Step 3: Environmental Rural Registry evaluation. Both resulting vectors were overlaid assess areas within the MNP registered as properties and declared in the SICAR, and the presence of intersections was then verified. These intersections were subsequently clipped and merged for the calculation of the total overlapped area.

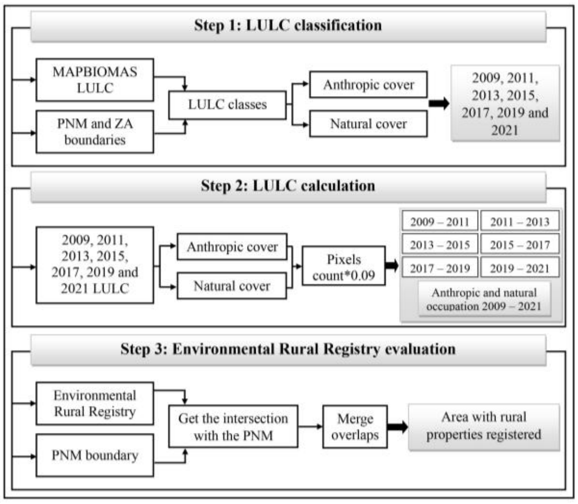

Figure 2. Flowchart of the method for assessing the dynamics and land use policy in the Mapinguari National Park and its BZ.

In summary, the temporal evolution of landscapes was analyzed using a set of six MapBiomas images representing different time periods. The original classes were rearranged into two main categories: areas of natural formation (C1) and areas of anthropogenic formation (C2). Then, changes between dates were identified by comparing the pixels of each category over time. The total time of each pixel remained unchanged since the last change was accumulated to provide a measure of the stability or dynamics of these areas. The output was a progression map using a graduated color palette, highlighting areas with more recent transitions in lighter tones and areas with older transitions in darker tones. This approach provides a synthetic view of the temporal dynamics of landscapes, offering insights into the persistence and evolution of changes over time.

Assessing Land Use Conversion Trends with the Mann-Kendall Test

To assess the temporal trends in land use class conversions (C1 and C2) both within the Mapinguari National Park (MNP) and its buffer zone (BZ), the Mann-Kendall test was applied. This non-parametric method was chosen for its effectiveness in detecting monotonic trends in time series without making assumptions about data distribution.

Given the small number of observations (with data from 2009 to 2021), the Mann-Kendall test proved particularly suitable. Parametric methods, such as linear regression, would be less robust due to the need for data normality and the potential presence of outliers. Moreover, the Mann-Kendall test has been widely used in studies of environmental trends and land use changes, as it is less sensitive to gaps or small samples in time series.

The test was applied to the data on hectares for each class (C1 and C2) over the different years evaluated, allowing the identification of trends in the increase or decrease of native vegetation areas (C1) and the expansion of anthropogenic areas (C2).

Results

Within the limits of the Mapinguari National Park (MNP), during the analyzed period, significant changes in land cover were observed, particularly regarding the Native Formation class (C1). This class lost a total of 43,784.08 hectares by 2021. This reduction corresponds to 2.43% of the area originally occupied by C1 in 2009, highlighting the increasing pressure on the park's natural ecosystems. The analysis revealed that this loss did not occur in isolation but was directly associated with the conversion of areas from C1 to the Anthropogenic Area class (C2), reflecting the expansion of human activities over the native vegetation. As a result of this dynamic, the proportion of the C2 class grew substantially, registering an increase of approximately 174% between 2009 and 2021, providing clear evidence of the impact of human activities within the park (Table 1).

An interesting aspect was observed in 2013, when the C1 class recorded an increase of 1,437.21 hectares compared to 2011. This recovery, although temporary, suggests that conservation actions, natural regeneration, or changes in land use may have contributed to the restoration of native vegetation in certain areas of the park (Table 1).

In addition to the changes within the limits of the MNP, even more pronounced transformations were identified in the park's buffer zone (BZ), a critical area for mitigating the impacts of human activities on protected areas. According to the data presented in Table 1, the Native Formation class (C1) in the buffer zone suffered a substantial loss of 96,470.05 hectares by 2021, representing a 9.93% reduction compared to the area occupied in 2009. Conversely, the Anthropogenic Area class (C2) in the buffer zone experienced a significant increase, with its proportion growing by 135% over the same period.

These findings indicate a concerning trend of land conversion from native vegetation (C1) to anthropogenic use (C2) both within the park and in its buffer zone. Within the limits of the MNP, the C1 class experienced an average annual reduction of 647 hectares during the analyzed period, while the C2 class increased at the same rate. Both trends were found to be statistically significant ($p<0.05$), underscoring the seriousness and consistency of the data obtained. This dynamic highlights the growing pressure on the park's natural resources and emphasizes the urgent need for more effective and comprehensive conservation policies.

The situation in the buffer zone is even more critical. Between 2009 and 2021, Mann-Kendall statistical tests indicated an average annual reduction of 16,078 hectares for the C1 class ($p=0.0027$), while the C2 class exhibited a proportional increase over the same period. These results demonstrate an accelerated process of land cover transformation in the buffer zone, with areas originally covered by native vegetation being replaced by anthropogenic uses. This change reflects a systematic and growing pressure on the MNP's protected ecosystems, making it evident that coordinated actions are required to control and mitigate such impacts.

Table 1. Temporal distribution of areas between the Native Formation class (C1) and Anthropogenic Area class (C2).

Year	MNP				BZ of MNP			
	Class 1 (C1)		Class 2 (C2)		Class 1 (C1)		Class 2 (C2)	
	ha	(%)	ha	(%)	ha	(%)	ha	(%)
2009	1,801,186.38	99.61	7,132.59	0.39	1,095,522.21	93.86	71,682.21	6.14
2011	1,801,178.28	99.61	7,140.69	0.39	1,088,303.67	93.24	78,900.75	6.76
2013	1,802,615.49	99.68	5,703.48	0.32	1,084,842.00	92.94	82,362.42	7.06
2015	1,800,811.17	99.58	7,507.80	0.42	1,067,075.82	91.42	100,128.60	8.58
2017	1,800,222.30	99.55	8,096.67	0.45	1,041,037.29	89.19	126,167.13	10.81
2019	1,799,517.24	99.51	8,801.73	0.49	1,026,430.83	87.94	140,773.59	12.06
2021	1,757,402.30	98.90	19,528.50	1.09	999,052.16	85.59	168,152.26	14.41

Detailed spatial analysis revealed that pressures on the MNP are most intense in the southern and southeastern portions of the park. In these areas, the buffer zone is almost entirely occupied by anthropogenic activities, resulting in direct impacts on the park's boundaries. In the southern portion, in particular, human activities have already reached the MNP's limits, with most analyzed pixels clearly indicating signs of anthropogenic use within the protected area (Figure 3). This situation highlights a concerning advance of human activities into previously intact areas, demanding urgent measures to preserve the park's ecological integrity and ensure the maintenance of its ecosystem services.

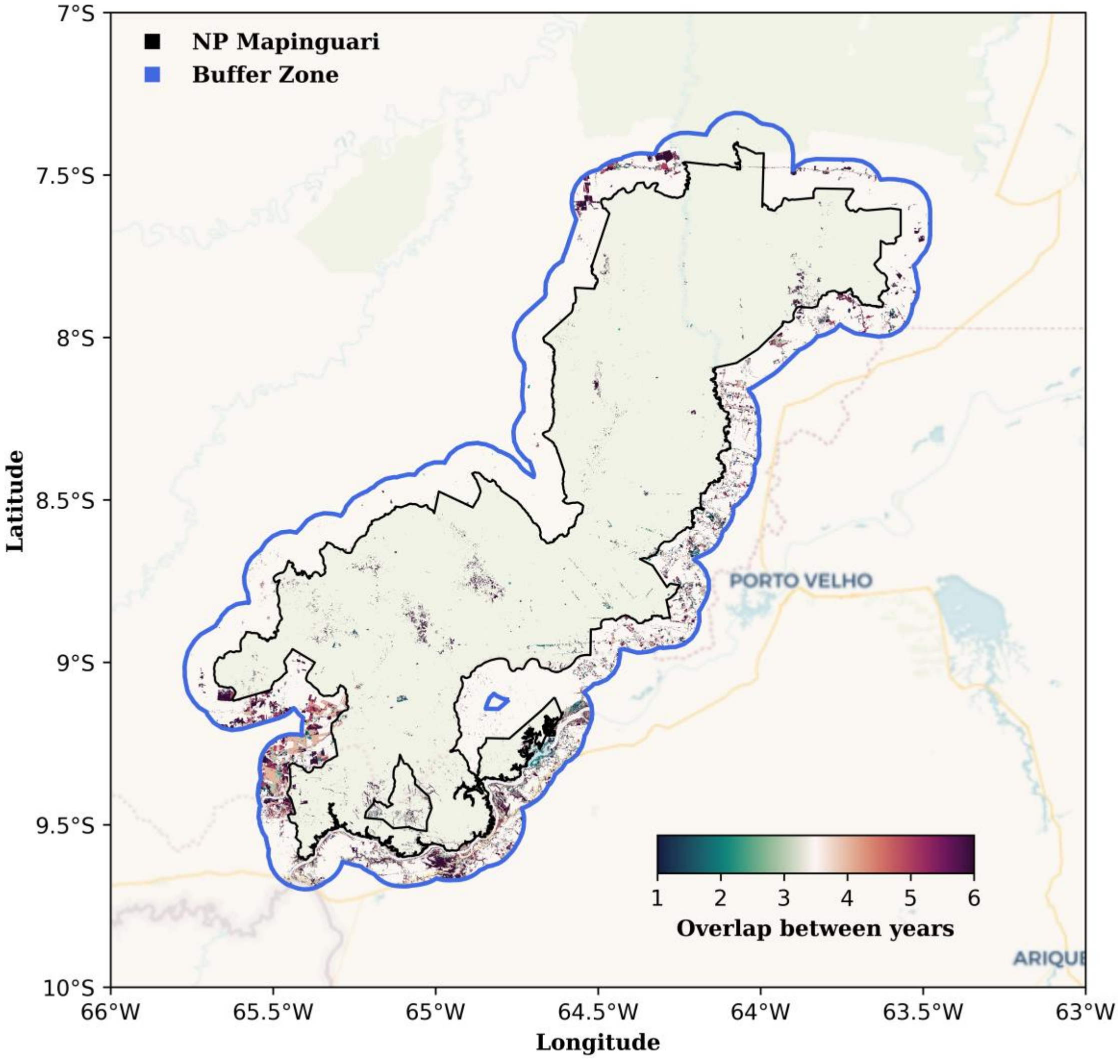

Figure 3. Progression of the conversion of C1 areas into C2 areas inside and within the BZ of the Mapinguari National Park, where blue shades indicate older changes and violet areas represent recent changes.

Within the limits of the MNP, excluding the buffer zone (BZ), there are 304,343.17 hectares designated as private properties, considering the three municipalities bordering the MNP and disregarding any overlaps (Figure 4). Of this total, 123,467.16 hectares are located in the municipality of Canutama, 119,985.86 hectares in Lábrea, and 60,923.15 hectares in Porto Velho, with the area extending throughout the park. Further verification of the acquisition dates of these occupied areas within the MNP is necessary, as any acquisitions made after the park's decree was issued would not be legally valid, and therefore, potential expropriation would not require financial compensation.

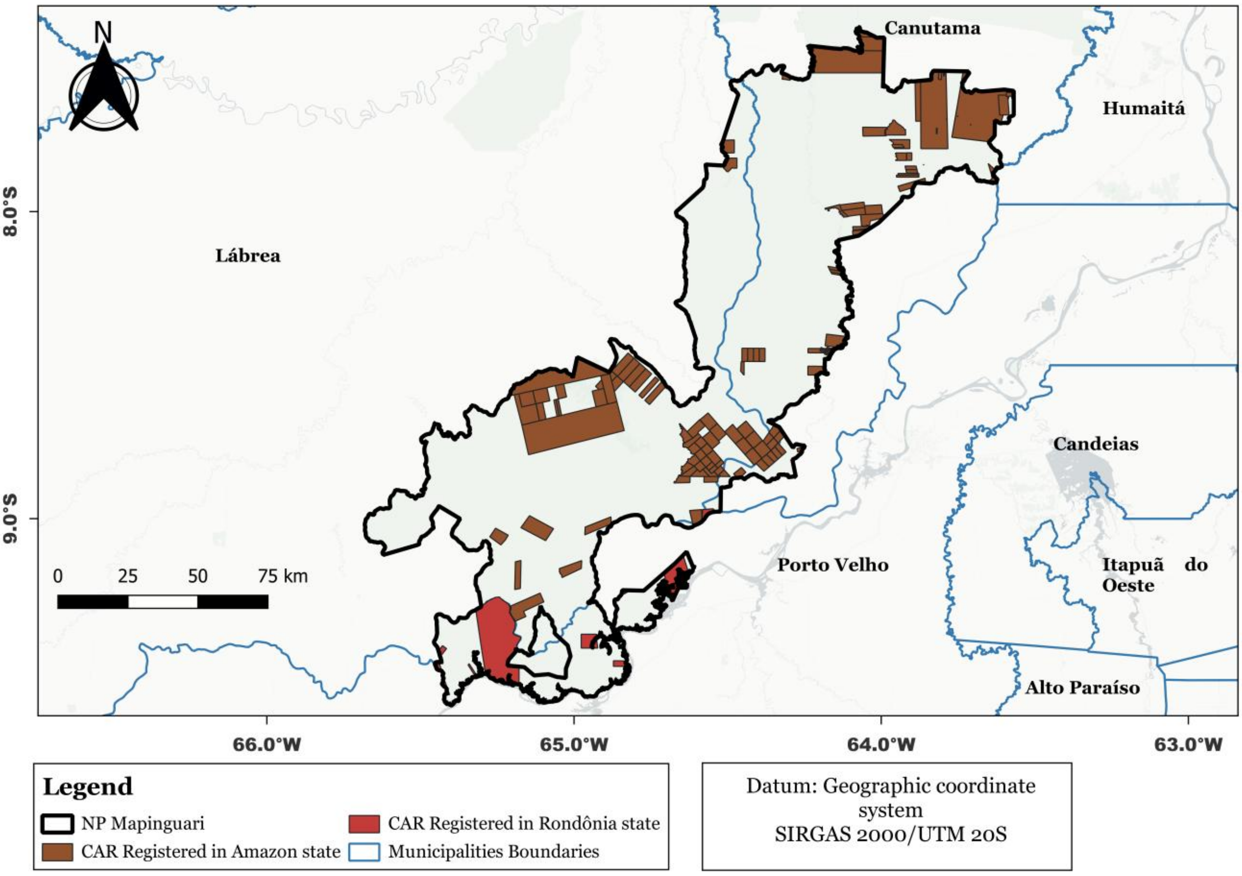

Figure 4. Map illustrating the distribution of registered properties in the SICAR that are demarcated within the Mapinguari National Park area.

Discussion

The results of this study clearly show the progression of deforestation both within the Mapinguari National Park (MNP) and its buffer zone (BZ), suggesting the need for greater control and monitoring. The creation of the MNP, formalized by an unnumbered Decree of June 5, 2008, and later amended by Laws No. 12.249 of June 11, 2010, and No. 12.678 of June 25, 2012, aimed to protect the ombrophilous forests and their interfaces with the Cerrado and Campinarana biomes, recognized for their unique ecological characteristics (MMA, 2018b). However, the results indicate that even after the park's establishment, significant areas continue to be converted to anthropogenic use, highlighting the lack of an effective BZ and adequate restrictions in the management plan (Bernardi et al., 2020).

This suggests that, although the park has been partially effective in containing deforestation, especially in the early years when the formalization of the park's boundaries led to the recovery of initially deforested areas (MMA, 2018a), after 2013, the conversion of native vegetation areas into anthropogenic land began to increase again. This demonstrates the ineffectiveness of monitoring and enforcement due to financial constraints and the lack of adequate policies in the management of the Conservation Unit (Young & Castro, 2021a; Young & Castro, 2021b).

Recent studies indicate that protected areas play a crucial role in mitigating deforestation (Heilmayr et al., 2020; Spanholi & Young, 2023).

For example, Koskimäki et al. (2021) evaluated the impact of conservation units in the state of Acre and found that, although most protected areas have prevented significant forest loss, there was substantial variation among them in terms of effectiveness in preventing deforestation and the associated carbon emissions.

Furthermore, Nogueira et al. (2018) estimated that, in 2014, approximately 57% of the carbon stored in the Brazilian Legal Amazon was contained within protected areas, highlighting the importance of these areas for carbon conservation and climate change mitigation.

Our results detected that external pressures occur mainly from the south and southeast of the Mapinguari National Park (MNP) and are advancing rapidly. The BR-364, BR-319, and BR-230 highways present within the MNP, as well as their branches, have been the main drivers of deforestation and illegal occupation (MMA, 2018a; Young & Castro, 2021a). This phenomenon reflects trends observed in other protected areas in Brazil and globally (Nascimento et al., 2021; Silva et al., 2021).

Previous studies indicate that the expansion of highways is closely associated with increased deforestation and illegal occupation, leading to habitat fragmentation and biodiversity loss (Garcia et al., 2017; Lecina-Diaz et al., 2019; Montibeller et al., 2020; Moraes et al., 2017; Silva et al., 2016). The dynamics observed in the MNP follow a similar pattern, with highways facilitating access to protected areas and encouraging illegal activities such as timber theft. To curb this trend, it is crucial to implement stricter enforcement measures and apply effective monitoring tools (Bogoni et al., 2023; Feng et al., 2022; Kleemann et al., 2022; Wolf et al., 2021).

The expansion of highways is indeed a determining factor in the advance of deforestation in the Amazon. Barber et al. (2014) identified that nearly 95% of all deforestation occurred within 5.5 km of highways or 1 km of rivers, indicating that proximity to these transportation routes significantly increases the risk of deforestation.

Araujo et al. (2023) developed a model that links market access, facilitated by improvements in transportation infrastructure, to deforestation. The results showed that investments in transportation infrastructure can increase deforestation, especially in previously isolated regions, by facilitating market access and encouraging the conversion of forests into agricultural lands.

Another factor that has significantly impacted the fundamental role of the Mapinguari National Park (MNP) is the presence of hydroelectric plants, such as the Santo Antônio and Jirau dams. In fact, their implementation further complicated the protection of these areas, resulting in the redefinition of the MNP boundaries, the opening of new access routes to construction sites for the dams (Fearnside, 2014), and the displacement of local communities (Fearnside, 2016; Moura et al., 2019). The impact of these projects not only disrupted the ecological balance of the region due to deforested areas but also affected water quality, particularly because the headwaters of the Purus and Madeira river basins are located within the park.

Institutional flexibility, where the administrative sphere appropriates laws and provisional measures, often without adequate technical studies or based on "tailored" studies that justify changes in boundaries, allows for the installation of hydroelectric plants in areas previously designated as conservation units, causing serious problems for the preservation of protected areas (Freitas et al., 2018).

According to the National System of Conservation Units regulated by Law No. 9,985 of June 18, 2000, the responsibility for managing the exploitation and activities that alter land use in the buffer zone lies with the conservation units themselves and must be included in their management plans, which is not the case for the Mapinguari National Park (MNP). However, the National Environmental System established by Law No. 6,938 of August 31, 1981, also stipulates that municipal authorities must preserve and protect the environmental heritage within their territories. Therefore, municipalities should include specific legislation in their Municipal Master Plans to regulate the maintenance of protected areas.

Thus, the monitoring and preservation of the areas surrounding the Mapinguari National Park (MNP) should be carried out jointly by the municipalities and the park administration, improving the allocation of resources and efforts to promote conservation (Lima & Ranieri, 2018). Among the municipalities where the MNP is located, only Porto Velho/RO has a Master Plan that addresses measures for zoning and incentives for conservation within its municipal protected areas (Brazilian Institute of Municipal Administration [IBAM], 2019). Similar information was not found for the municipalities of Lábrea/AM and Canutama/AM.

Pressures on the southern portion of the Mapinguari National Park (MNP) originate from the city of Porto Velho, driven by factors such as urban expansion, agribusiness, and road infrastructure. The urban area of Porto Velho grew from 112 km² to 134 km² between 2010 and 2019, accompanied by a population growth of approximately 22% during the same period (SEMPOG, 2022). This expansion exerts direct pressure on the park's boundaries as the city expands, creating demands for space for urban infrastructure, including roads, housing, and industrial facilities, leading to the invasion or fragmentation of the park's territory. Regarding the expansion of agribusiness, in 2010, Porto Velho had an area of 410,000 hectares with approximately 2,842 agricultural establishments. By 2017, these figures had increased to 778,000 hectares and 5,177 establishments (IBGE, 2017). The growth of agribusiness and related deforestation activities may extend to areas near the MNP, increasing pressure on the biodiversity and ecosystems within the park.

Furthermore, Lábrea has shown the highest deforestation rates in southern Amazonas since 2009. The municipality recorded a deforested area of 315,190 hectares, representing approximately 4.52% of its total area. In contrast, the municipality of Canutama reported deforestation of 89,890 hectares, equivalent to 3.97% of its total area. The high deforestation rates in Lábrea can be attributed to the presence of farms with areas ranging from 5,000 to 10,000 hectares, associated with the accumulation of pastures and areas designated for logging activities (Reis & Leal, 2020).

Another critical issue identified is the overlap of privately owned properties registered in SICAR with the Mapinguari National Park (MNP), reflecting the persistent lack of land regularization in the area. Although the MNP’s Territorial Consolidation Plan includes actions aimed at land regularization, progress has been limited, with only 0.1% of the park's total area currently undergoing expropriation processes (MMA, 2018b). This highlights a failure in the enforcement of protection laws and in the adequate or sufficient allocation of resources for land regularization.

Approximately R$ 12.9 million from the hydroelectric plants installed in the region should have been allocated to land regularization, but this did not occur as planned. The allocation of this environmental compensation was inconsistent and disproportionate to the impacts caused in the park. A significant portion of the funds was, in fact, used to regularize lands belonging to other conservation units in the Amazon, and, in the end, the remaining amount was insufficient to settle the land debts and effectively implement the MNP (MMA, 2018a).

The overlap of privately owned properties registered in SICAR with conservation units is a critical issue that compromises the effectiveness of these protected areas. Recent studies highlight the magnitude of this problem in various regions of Brazil (Tofeti & Campos, 2019). For example, Reydon et al. (2020) advocate for improvements in land governance in Brazil, particularly in the Amazon region. According to the authors, land governance is a necessary condition to reduce or control deforestation, which is strongly observed where property rights are not clearly established and primarily occurs on land directly or indirectly under the responsibility of the State (Reydon et al., 2022).

Pacheco & Meyer (2022) analyzed how different land tenure regimes influence deforestation rates in Brazil, highlighting that undesignated or untitled lands exhibited the highest deforestation rates between 1985 and 2018, surpassing other types of tenure, including private lands. This vulnerability was most evident in remote areas, where government enforcement capacity is limited. On the other hand, Indigenous territories, local communities, and fully protected areas showed the best outcomes in forest preservation, demonstrating the effectiveness of these regimes in environmental conservation (Rajão et al., 2020).

To address these challenges, it is essential to implement environmental management strategies that integrate sustainable urban planning and cooperation between government authorities, local communities, and conservation organizations. The adoption of Agroforestry Systems (AFS) and Payment for Environmental Services (PES) are mechanisms widely recognized as strategies to promote sustainability and environmental conservation in various contexts, including fostering sustainable development in regions with land tenure conflicts.

Agroforestry Systems (AFS) stand out as an environmental management tool that aligns economic activities with environmental conservation, reducing the negative impacts of conventional agricultural and livestock practices. Recognized for providing environmental benefits, AFS contribute to soil integrity (Marsden et al., 2020), carbon sequestration (Hübner et al., 2021; Ronquim et al., 2016; Shi et al., 2018), water quality (Pavlidis & Tsihrintzis, 2018), and the maintenance of biodiversity and its functions (Haggar et al., 2019; Santos et al., 2019).

Payment for Environmental Services (PES), as an environmental management tool, creates a direct financial incentive to promote conservation by integrating economic and environmental objectives (Momedes et al., 2023).

It is an economic mechanism that encourages landowners or communities to adopt sustainable use practices that generate environmental benefits, including forest and water resource conservation (Pissarra et al., 2021), greenhouse gas emission reductions, and biodiversity protection (Pissarra et al., 2022; Young & Castro, 2021b).

However, for the success of both agroforestry systems and the implementation of PES, it is essential to develop an incentive plan tailored to local socioeconomic characteristics (Bispo et al., 2020). Additionally, PES should be implemented considering land use and land cover (LULC) characteristics, as well as the conservation and restoration of local water resources (Wunder et al., 2020). This will ensure an adequate financial quantification for the payment, avoiding both underestimations and overestimations.

These mechanisms have already proven effective in other regions of Brazil, as highlighted by Souza et al. (2021), and can be adapted to the local needs of the MNP. Aza et al. (2021) raise the possibility of implementing PES with multiple projects operating in the same area. According to the authors, this increases the benefits and provides solutions to some of its challenges. This integration should offer an optimal combination of short- and long-term ecosystem services, ensuring resilience to environmental and social changes.

Additionally, the "Adopt a Park" Program, established by Law No. 10,623 of February 9, 2021, can offer a temporary solution to increase financial resources for the conservation and monitoring of protected areas. This program aims to promote the conservation, restoration, and improvement of federal conservation units through contributions from individuals and private legal entities, both national and foreign. The program seeks to enhance infrastructure and services in parks to boost ecotourism, attract resources for environmental protection, and, most importantly, provide financial resources for the execution of appropriate services, the development of new instruments, and the supervision of conservation units.

Although the program's name suggests only the word "park", it encompasses 41 Fully Protected Units and 91 Sustainable Use Units, totaling 132 conservation units and covering an area of 64,369,569 hectares. By adopting a park, individuals and companies contribute to the legal protection of the environment, committing to pay fifty reais or ten euros per hectare of land over a one-year period.

Between February and April 2021, eight conservation units were adopted (Table 2) (Campos, 2021). Initially, this involved a total investment of approximately 6 million reais, an amount that can be used to strengthen environmental conservation, improve infrastructure, promote sustainable tourism, and enhance the efficient management of the conservation units. However, it requires more transparent implementation and integration with local communities.

Indeed, a detailed analysis of the decree that established this program reveals significant shortcomings, particularly the lack of provisions for transparent processes and consultation with traditional communities in the conservation units, violating constitutional principles and international agreements. Furthermore, the program was launched without the involvement of the conservation unit councils or civil society in dialogue or consultation. At the time when eight companies submitted adoption proposals to the Ministry of the Environment (MMA), the Letter of Intent was signed between the adopters and the MMA, and the announcement was made. If eight companies expressed interest in adopting a park within three months, it demonstrates that the initiative is promising but requires the immediate correction of identified flaws to achieve full effectiveness.

This program can serve as a strategy to accelerate the territorial consolidation of the internal boundaries of the Mapinguari National Park (MNP), considering that the "Adopt a Park" Program also aims to promote the conservation, restoration, and improvement of federal conservation units. Directing these resources toward territorial consolidation could significantly contribute to advancing expropriation and land regularization processes within the MNP. This strategy would not only align available resources with the specific needs of the conservation unit but also leverage private sector initiatives to collaborate in environmental preservation.

Therefore, resolving the issue of overlapping private properties within conservation units requires an integrated approach that combines land regularization, the implementation of sustainable practices, and the strengthening of environmental governance. Only through coordinated actions will it be possible to ensure the effective conservation of protected areas and the sustainable development of local communities.

Table 2. Conservation Units adopted by partner companies through the 'Adopt a Park' Program.

Conservation Unit	State	Area (ha)	Investment (R$)	Adoptive company
WRESEX do Lago do Cuniã	RO	75,877	3,793,850.00	Carrefour Comércio e Indústria Ltda
ARIE Dinâmica Biológica Fragmentos Florestais	AM	3,180	159,000.00	Genial Investimentos Corretora de Valores Mobiliários S.A
RESEX São João da Ponta	PA	3,408	170,400.00	Coopecredi Guariba - Cooperativa de Crédito
RESEX Chocoaré Mato-Grosso	PA	2,783	141,000.00	Geoflorestas Soluções Ambientais Ltda.
ARIE Seringal Nova Esperança	AC	2,574	128,700.00	Coplana – Cooperativa Agroindustrial
RESEX do Quilombo Flexal	MA	9,338	466,900.00	HNK BR Indústria de Bebidas Ltda. –Heineken
RESEX Marinha Cuinarana	PA	11,017	550,850.00	MRV Engenharia e Participações S.A.
ARIE Javari Buriti	AM	13,177	658,850.00	Coca Cola Indústrias Ltda.

Finally, and equally important, the Amazon Now Plan, created by the government of the state of Pará, also highlights the essential need to consolidate Protected Areas (PAs) (Brito & Prizibisczki, 2021; Yang et al., 2021). It suggests faster ways to cancel improper registrations in SICAR, as well as improving the system to prevent new registrations with such overlaps. The consolidation of PAs is essential to ensure the effectiveness of these areas in environmental preservation and biodiversity protection.

Addressing issues related to improper registrations and overlaps in SICAR is an important step to ensure the integrity of these areas and prevent conflicts that may arise from inconsistencies in cadastral data. Therefore, initiatives such as the Amazon Now Plan, from the state of Pará, which tackle these issues and propose solutions for the consolidation and improvement of environmental records, are crucial for the sustainable management of protected areas in the Amazon region.

Thus, the challenges for the conservation of the Mapinguari National Park (MNP) and its buffer zone (BZ) require coordination among different levels of government, local communities, and the private sector. Only through a collaborative approach will it be possible to reduce anthropogenic pressures, restore degraded ecosystems, and ensure the integrity of protected areas.

Final Considerations

This study demonstrated that the existence of the Mapinguari National Park, located in the deforestation arc, has partial effectiveness in minimizing deforestation. Although the park has managed to contain the loss of vegetation cover within its boundaries, deforestation is advancing at an alarming rate in the buffer zone, especially in the southern and southeastern portions, due to proximity to Porto Velho and the expansion of agricultural and urban areas. The presence of anthropogenic pressures in these areas reinforces the need for more robust control and enforcement measures to preserve the integrity of the conservation unit and its surrounding areas.

The results indicate the urgency of additional instruments for the effective management of protected areas. Innovative solutions, such as agroforestry systems, Payment for Environmental Services, and the adoption of parks by the Brazilian government not only facilitate the creation of a financial transfer mechanism for local management but also enable sustainable management, carbon emission reduction, protection of water resources, and biodiversity conservation. These combined instruments are essential to mitigate deforestation and promote the restoration of degraded areas, contributing to a sustainable development model that can be replicated in other regions.

Finally, this study makes a significant contribution by highlighting the need for more integrated and specific policies for buffer zones, as well as emphasizing the importance of innovative financing mechanisms to ensure the effective preservation of protected ecosystems. Future research can focus on complementary strategies that strengthen the role of protected areas in curbing deforestation and promoting sustainable practices in their zones of influence.

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