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Meio Ambiente, Paisagem e Qualidade Ambiental

The ineffectiveness of the Triunfo do Xingu Environmental Protection Area in curbing deforestation in the Brazilian Amazon

A ineficácia da Área de Proteção Ambiental Triunfo do Xingu em conter o desmatamento na Amazônia brasileira

La ineficacia del Área de Protección Ambiental Triunfo do Xingu para frenar la deforestación en la Amazonia brasileña

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ABSTRACT

The Triunfo do Xingu Environmental Protection Area (APATX) exhibits the highest deforestation rates within the Brazilian Legal Amazon (BLA) when compared to other protected areas (PAs). Our study, utilizing geospatial and statistical techniques coupled with data from PRODES and Mapbiomas, scrutinized landscape transformations from 2001 to 2022 to assess the efficacy of APATX in curtailing deforestation. The findings underscore that the primary driver of deforestation within APATX was the conversion of land for pasture. The deforestation rates observed within APATX mirrored the broader trend within BLA, with notably higher rates within the São Félix do Xingu area compared to areas outside it, while Altamira exhibited no significant differences. Our study revealed that APATX exhibited a deforestation trend closely aligned with the overall pattern observed in the biome, showing deforestation levels that exceed legally expected values based on available data. This suggests that the PA is responding similarly to the rest of the Brazilian Amazon to the factors driving deforestation. Consequently, APATX, a crucial area for conservation in the Amazon, has failed to effectively curb deforestation in a critical region of agricultural expansion, where the conversion of forests into pastureland is the primary driver of deforestation.

Keywords: Terra do Meio; ranching; pasture; land use and land cover change (LUCC); protected areas; conservation unit; governance

RESUMO

A Área de Proteção Ambiental Triunfo do Xingu (APATX) apresenta as maiores taxas de desmatamento dentro da Amazônia Legal Brasileira (ALB) quando comparada a outras áreas protegidas (APs). Nosso estudo, utilizando técnicas geoespaciais e estatísticas juntamente com dados do PRODES e Mapbiomas, examinou as transformações da paisagem de 2001 a 2022 para avaliar a eficácia da APATX em conter o desmatamento. Os resultados destacam que o principal fator de desmatamento dentro da APATX foi a conversão de terras para pastagem. As taxas de desmatamento observadas dentro da APATX refletiram a tendência mais ampla dentro da ALB, com taxas notavelmente mais altas na área de São Félix do Xingu em comparação com áreas fora dela, enquanto Altamira não exibiu diferenças significativas. Nosso estudo revelou que a APATX exibiu uma tendência de desmatamento estreitamente alinhada com o padrão geral observado no bioma, mostrando níveis de desmatamento que excedem os valores legalmente esperados com base nos dados disponíveis. Isso sugere que a AP está respondendo de maneira semelhante ao resto da Amazônia Brasileira aos fatores que impulsionam o desmatamento. Consequentemente, a APATX, uma área crucial para a conservação na Amazônia, não conseguiu conter efetivamente o desmatamento em uma região crítica de expansão agropecuária, onde a conversão de florestas em pastagens é o principal motor do desmatamento.

Palavras-chave: Terra do Meio; pecuária; pastagem; mudança de uso e cobertura da terra (LUCC); áreas protegidas; unidades de conservação; governança

RESUMEN

El Área de Protección Ambiental Triunfo do Xingu (APATX) exhibe las tasas más altas de deforestación dentro de la Amazonía Legal Brasileña (ALB) en comparación con otras áreas protegidas (APs). Nuestro estudio, utilizando técnicas geoespaciales y estadísticas junto con datos de PRODES y Mapbiomas, examinó las transformaciones del paisaje de 2001 a 2022 para evaluar la eficacia de la APATX en frenar la deforestación. Los resultados subrayan que el principal impulsor de la deforestación dentro de la APATX fue la conversión de tierras para pastos. Las tasas de deforestación observadas dentro de la APATX reflejaron la tendencia general dentro de la ALB, con tasas notablemente más altas en el área de São Félix do Xingu en comparación con áreas fuera de ella, mientras que Altamira no exhibió diferencias significativas. Nuestro estudio reveló que la APATX exhibió una tendencia de deforestación estrechamente alineada con el patrón general observado en el bioma, mostrando niveles de deforestación que exceden los valores legalmente esperados según los datos disponibles. Esto sugiere que la AP está respondiendo de manera similar al resto de la Amazonía Brasileña a los factores que impulsan la deforestación. En consecuencia, la APATX, un área crucial para la conservación en la Amazonía, no ha logrado frenar efectivamente la deforestación en una región crítica de expansión agrícola, donde la conversión de bosques en pastizales es el principal impulsor de la deforestación.

Palabras-clave: Terra do Meio; ganadería; pastizales; cambio de uso de la tierra (LUCC); áreas protegidas; unidades de conservación; gobernanza

1 INTRODUCTION

Deforestation in the Brazilian Amazon is a complex and highly significant environmental problem faced for decades. Forest loss occurs mainly through the expansion of economic activities such as livestock, agriculture, mining, and land speculation (Margulis, 2004; Fearnside, 2005; Messias et al., 2021). Up to 2022, the Brazilian Legal Amazon (BLA) lost 838,625.43 km² of forest, totalling 20.99% of its original forest area (3,944,675.15 km²) (INPE, 2024a). This loss has led to significant effects on biodiversity, local livelihoods, hydrological cycles, carbon storage, and climate change (Brawn, 2017; Coomes et al., 2020; Brandão et al., 2021; Gatti et al., 2021; Albert et al., 2023) and the resilience of forests with drastic local, regional and global effects (Lovejoy; Nobre, 2019).

Protected areas (PAs) are crucial in the Amazon for preserving biodiversity and maintaining essential ecosystem services, while acting as a barrier against deforestation (Nepstad et al., 2006; Pellin et al., 2022; Soares-Filho et al., 2023). Among the 12 categories of PAs established in Brazil by the National System of Protected Areas (SNUC; Law No. 9,985/2000), a legal framework created to regulate the creation and management of protected areas in the country, Environmental Protection Areas (APA in Portuguese) are categorized as sustainable use units and aim to protect the natural and cultural environment in territories where human activities occur (either public or private lands) and, at the same time, guarantee sustainability and ecological balance. APAs are managed by government agencies (state or federal) in partnership with local communities. It stands as the most flexible category among sustainable use PAs, as it can accommodate a broad spectrum of productive activities, including private properties, as long as they adhere to sustainable practices and do not compromise environmental conservation.

The APA Triunfo do Xingu (hereafter APATX), established by the government of Pará (State Decree number 2612 in 2006) in the municipalities of Altamira and São Félix do Xingu, is listed as a high-priority area for conservation in the Amazon (MMA, 2021). Both municipalities are located in the Brazilian Amazon 'Arc of Deforestation', in the region known as Terra do Meio, and are among those with the highest rates of deforestation in BLA (INPE, 2024a). APATX was supposed to act as a buffer zone to mitigate the impacts of agro-pastoral and logging activities inside other protected areas and Indigenous Lands in Terra do Meio.

However, APATX has been listed for years as the PA with the highest deforestation rates in the Amazon (Doblas, 2015; Araújo et al., 2017). Nonetheless, studies that have described land use and land cover changes within APATX (e.g., Pinho et al., 2017; Gama et al., 2019; Azevedo; Barbosa, 2020; Souza et al., 2020) did not consider what was happening outside of the PA, limiting the comprehension of its internal dynamics. Understanding the external context is relevant to assess the efficacy of a PA in reducing or ending deforestation also in its surroundings (spillover benefits) (Barber et al., 2012; Pfaff; Robalino, 2017).

Given these limitations and aiming to understand why APATX has the highest deforestation rates in the Amazon, this study analyzes changes in land use and cover both inside and outside the PA from 2001 to 2022, and seeks to answer the following questions: (1) How has deforestation and land use evolved within APATX? (2) Do land uses explain the observed deforestation? (3) Is deforestation within the PA lower than before its establishment? (4) Is internal deforestation in the PA lower than external deforestation? (5) Are there differences in deforestation and land use within the PA between the two municipalities? Our study analyzes a longer time series than the previous ones, providing a better description of the temporal deforestation pattern and land use and land cover changes (LULCC) within APATX. Our findings measure the efficacy of APATX in achieving its objectives and its impact on deforestation within and beyond its borders.

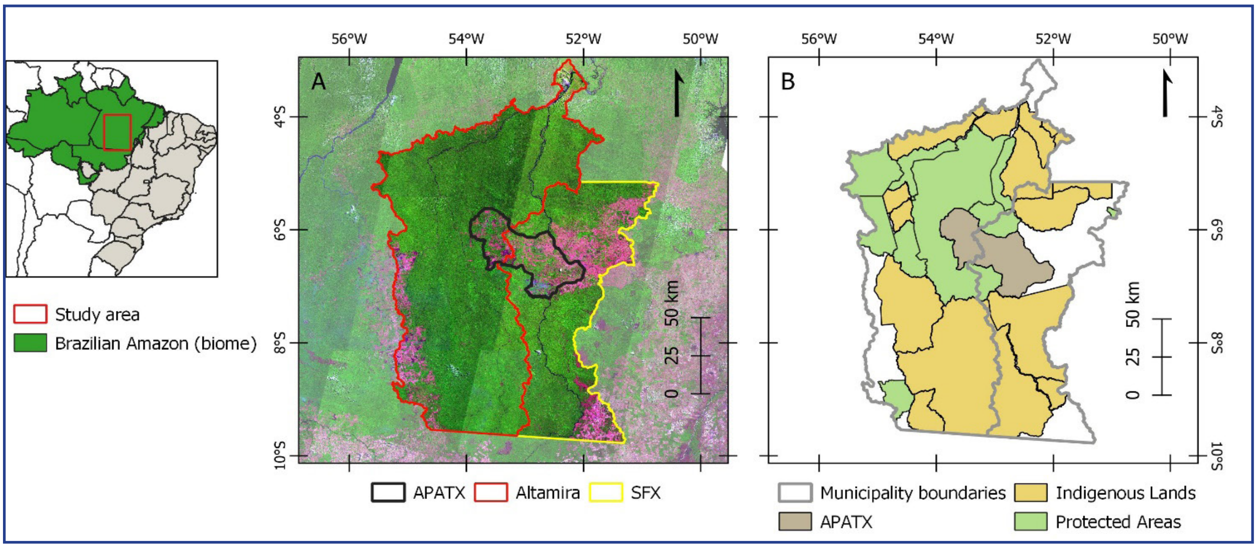
2 MATERIALS AND METHODS

2.1 Study Area

APATX is situated in the southeastern region of Pará, encompassing the municipalities of Altamira and São Félix do Xingu (SFX) (Figure 1). It spans a total area of 16,792.8 km², with 11,027.79 km² located in SFX and 5,765.01 km² in Altamira. Originally, the predominant land cover within APATX consisted of forests (16,346.73 km², 97.34%), with a smaller portion occupied by savannas (424.02 km², 2.53%) (IBGE, 2022). This region, known as Terra do Meio, covers about 79,000 km² and hosts federal and state PAs and Indigenous Lands to safeguard the socio-biodiversity of the Xingu River basin. The region faces challenges such as illegal logging, cattle ranching expansion, and land titling (Doblas, 2015; Gama et al., 2019; Souza et al., 2020). Altamira is the largest municipality in Brazil in terms of territorial area (159,533.31 km²) and has a population of 126,279 inhabitants in 2022 (0.79 hab/km²) (IBGE, 2023). Its economy is based on livestock production (904,271 heads in 2021), as well as large scale soybean and corn agriculture (IBGE, 2023). A percentage of 91.4% of its territory is enclosed within nine PAs (42.1%) and twelve Indigenous Lands (49.3%) that together account for 145,757.75 km².

SFX is the second largest municipality in Pará and the sixth largest in Brazil (84,212.9 km²) with a population of 65,418 inhabitants in 2022 (0,78 hab/km²) (IBGE, 2023). The local economy is centered on cattle ranching, being SFX the Brazilian municipality with the largest bovine herd in the country (2,468,764 heads) (IBGE, 2023). In agriculture, the cultivation of cocoa, banana, and corn is noteworthy (IBGE, 2023). The territory of SFX includes 25 villages and four districts and most of its extension is within six Indigenous Lands (54.2%) and six PAs (19.3%), including APATX.

Figure 1 – Study area



Source: Authors (2023)

Legend: (A) The Triunfo do Xingu Environmental Protection Area (APATX) location relative to the municipalities of Altamira and São Félix do Xingu (SFX) in Pará, Brazil. (B) The Protected Areas and Indigenous Lands surrounding APATX in Altamira and partially in SFX. In the background of A, a false color composition of Sentinel 2 images from 2021 using RGB composition SWIR 2, SWIR 1, and Red Edge 4, respectively

2.2 Data

Polygons of the APATX and the two municipalities were obtained from the TerraBrasilis website (INPE, 2024b). Deforestation within APATX was analyzed using data from the Brazilian Amazon Satellite Monitoring Program (PRODES) (INPE, 2024a). The total accumulated deforestation up to the year 2001 and the annual increments for the period from 2001 to 2022 were extracted from this data. This period is chosen based on the availability of annual data. Before 2000, PRODES data is aggregated into a single period, limiting the ability to conduct detailed historical analyses.

Land use and forest cover data (for 2001 to 2022) were obtained from Mapbiomas collection 8.0 at level 3 of its legend (MapBiomas, 2023). Although Maurano and Escada (2019) found discrepancies between m and PRODES data, they concluded that MapBiomas historical series can provide a good basis for past land use analyses. MapBiomas classifies land use/cover into five main classes and 26 subclasses. Its collection 8.0 data at its most detailed legend level (level 3) has an accuracy of 85,4% for the Amazon region (MapBiomas, 2023). Within the agriculture subclass, MapBIomas classify soybean cultivation apart from the class ‘Other temporary crops’. Annual changes in incremental area for each land use/cover class were calculated from MapBiomas annual accumulated data by simply subtracting the values of the subsequent year from the previous year (e.g., 2002 increment = 2002 value - 2001 value).

To determine whether the total deforestation within APATX exceeded legal expectations, we used data from the Rural Environmental Registry (CAR) available until August 2021 (Brasil, 2021). As per the Brazilian Forest Code (Brasil, 2012), properties spanning up to four Fiscal Modules (Fiscal Module dimensions vary nationwide; see Landau, 2012) are permitted a Legal Reserve area of 50% of the original forest cover, instead of the obligatory 80% stipulated by the Brazilian Forest Code (Brasil, 2012) for forested regions in the Legal Amazon. Given that the Fiscal Module for SFX and Altamira is defined as 75 hectares, properties covering up to 300 hectares are expected to allocate 50% of their area to the remaining forested region, as of July 22, 2008 (see details in Brasil, 2012). Hence, we calculated the combined area of properties exceeding 300 hectares and their potential legal deforested area (20% of the area). Out of the properties with a registration in CAR system up to 2021, 189 (45%) had an area larger than 4 fiscal modules (total area value 7,061.34 km²). Inside them, an estimated deforested area of 1,412.27 km² would be expected according to the Forest Code. The estimated deforested area was summed to the total area of properties smaller than 300 hectares (230 properties, 55%, 236,6 km²), which theoretically could present 50% of their area deforested (118,3 km², excluding permanent preservation areas, which was disregarded due to the scale of analysis). Thus, the expected deforestation could reach 1,530.57 km². Although the analysis is conservative and has limitations in terms of land regulation issues within APATX, it provides insights into the extent of illegal deforestation within the PA.

2.3 Geospatial analysis

A PostgreSQL database was created using the PostGIS spatial extension with vector files standardized in EPSG 102033 (Sirgas 2000 - South America Albers Equal Area). QGIS 3.22 software, spatial queries using SQL language were built to quantify and compare deforestation, land uses and forest cover, all inside and outside APATX (enclosed in the municipalities), and also to analyze CAR data. As other PAs and indigenous lands exist within the two municipalities, with their own land use dynamics due to restrictive land use regulations, the area covered by these areas was excluded from the total area of the municipalities. Thus, the geospatial comparative analysis evaluated the area of APATX and only the area of the municipalities outside any other PA and Indigenous Land.

2.4 Statistical analysis

The statistical analyses were performed using R software (R Core Team, 2023). Due to non-normal distribution, Spearman's Rank Correlation Test (*stats* package in base R) was used to analyze the correlation between deforestation and land use increments for the evaluated years. Simple and multiple linear regression models (using *stats* package in base R) were used to evaluate the contribution of land use increments within APATX in explaining deforestation increments. The selection of the best model was based on the Akaike Information Criterion (AIC; *stats* package in base R), which is justified by its ability to select the model that best balances data fit and model complexity, avoiding overfitting, and enabling reliable inferences (Bozdogan, 1987). The normality of the model residuals was analyzed by the Shapiro-Wilk test (*stats* package in base R), and homoscedasticity was evaluated by graphical analysis and the Levene's test (car package; Fox; Weisberg, 2019). Since the residuals were not normally distributed and were heteroscedastic, the dependent variable (deforestation increments) was transformed using the natural logarithm to meet the model assumptions (as suggested by the Box-Cox analysis). Finally, the model coefficients were back-transformed through exponentiation.

Due to the non-normal nature of deforestation and land use data, the null hypothesis of differences in deforestation and land use inside and outside APATX in each municipality for the post-establishment period of the PA (2007-2022) was evaluated using the Approximative Two-Sample Fisher-Pitman Permutation Test with 1000 repetitions provided by the coin package (Hothorn et al., 2008) for R. The deforestation and land use increment values were standardized by the respective areas of the municipalities outside PAs and Indigenous Lands, and by the area of APATX in each municipality.

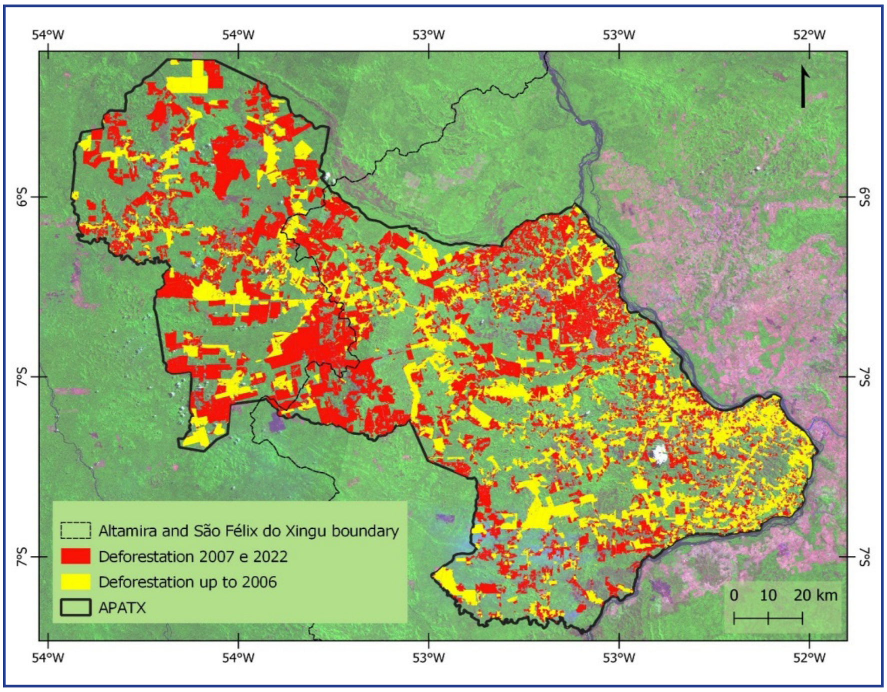
3 RESULTS

3.1 How has deforestation and land use changed within APATX?

Figure 2 shows deforestation within APATX separated into two periods, before and after its establishment in 2006. Between 2001 and 2022, forest-covered areas declined from 95% to 63.1% (≈32%) within it. The accumulated deforestation within the PA until 2001 was 1037.86 km² (6.37% of forest areas). Between 2002 and 2022 deforestation increased by 6067.25 km² (37.25% of forest areas), totaling a deforested area of 7105.11 km² (42.3% of its total area and 43.62% of the forest area). Based on our estimation using the reported area of rural properties in the CAR, a total of 1,530.57

km² of legal deforestation would be expected within APATX. The observed difference from the actual deforestation indicates that 5,574.54 km² were illegally cleared.

Figure 2 – Map of deforestation within the Triunfo do Xingu Environmental Protection Area (APATX)



Source: Authors (2023)

Legend: Map of deforestation within the Triunfo do Xingu Environmental Protection Area (APATX) divided into two periods, pre- (deforestation up to 2006) and post-establishment (deforestation 2007-2021) of the protected area. Sentinel-2 color composition from 2021 using RGB composition with SWIR 2, SWIR 1, and Red Edge 4

The temporal trend in deforestation observed inside APATX and BLA (Figure 3a) exhibited a strong positive correlation ($r = 0.75$; $p < 0.0001$). The most substantial spikes in deforestation took place in 2002 (608.99 km²) and 2022 (555.95 km²), while the lowest level was recorded in 2012 (70.9 km²), as depicted in Figure 3a. In 2016 there was a sudden peak (422.1 km²) in the deforestation trend, following the same pattern observed in BLA, whose increase started in 2013, with a higher value than the previous year (2015 = 176.75 km²) and the following year (2017 = 209.84 km²).

From Figure 3a, three distinct periods can be identified in the annual deforestation increments series within APATX area. The first (2002 to 2007), which includes the years prior to the creation of APATX, had deforestation values above 300 km² per year with an average of 426 km². The second period (2008 to 2012) showed a sharp and continuous decline in deforestation, dropping from 432.0 km² in 2007 to 71.0 km² in 2012 (83.6% reduction). The third period (2013 to 2022) evidenced a resumption of deforestation growth, surging by 783% in 2022 compared to 2012 and returning to levels akin to those seen in the initial period.

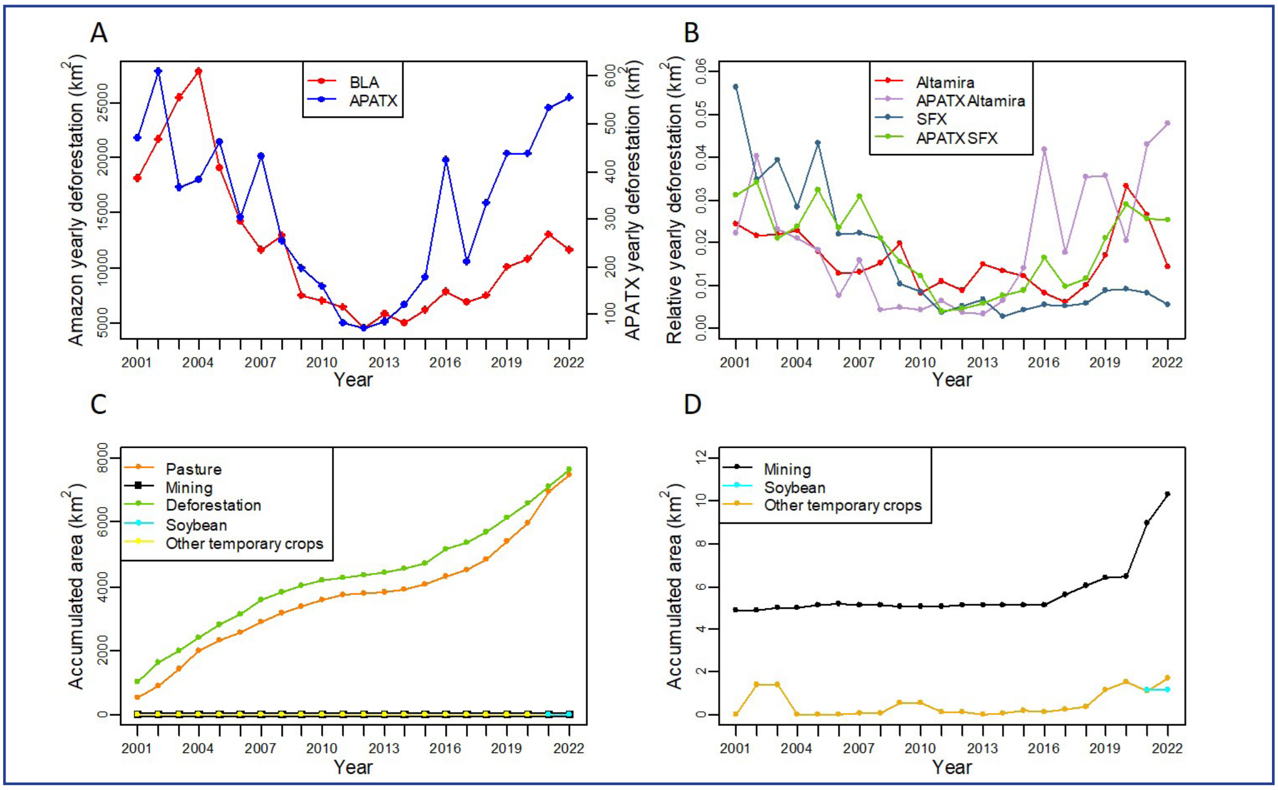
Pasture, mining, soybean, and other temporary crops were observed inside APATX (Table 1; Figure 3c). Pasture had the highest percentage of change in terms of area (1468%) during the analyzed period, occupying approximately 510.00 km² in 2001 and 7,849.00 km² in 2022. Standardizing by the respective area of each locality, inside APATX pasture had a larger area in SFX than in Altamira ($Z = -2.2889$; $p = 0.0204$), reflecting the larger area of pasture in the municipality of SFX when compared to Altamira ($Z = -4.7496$; $p < 0.001$). Mining constituted the second-largest land use within APATX, spanning an area of 10.29 km² and an expansion of 215% in the period. This was consistently documented throughout the entire analysis period, but a noticeable increase has been observed since 2016, intensifying after 2020 (Figure 3d). Despite Altamira having a smaller mining area in general, it exceeded SFX in terms of mining area within APATX (Table 1). While other temporary crops were also observed in our time series starting from 2001, they occupied only 1.73 km². Soybean cultivation, on the other hand, was detected solely in 2021 (Figure 3c-d), encompassing an area of 1.18 km², exclusively within APATX in SFX (Table 1).

Table 1 – Land use/cover (from Mapbiomas) and accumulated deforestation (PRODES) in 2022 inside the Triunfo do Xingu Environmental Protection Area (APATX), Altamira, and São Félix do Xingu (SFX). Units in km²

Localities	Total deforested area	Forest	Pasture	Soybean	Other temporary crops	Mining	Silviculture	Urban area
Altamira	7,310.54	7,717.19	7,015.30	74.33	98.14	42.85	0	32.72
APATX in Altamira	2,600.97	3,351.16	2,416.40	0	0.51	8.26	0	0
APATX in SFX	5,047.47	5,797.10	5,068.60	1.18	1.22	2.03	0	0
SFX	14,195.96	8,111.15	13,443.00	85.58	20.17	100.00	0.27	15.10
APATX (total)	7,648.44	9,148.26	7,485.00	1.18	1.73	10.29	0	0

Source: Authors (2023)

Figure 3 – Land use and land cover change inside the study area



Source: Authors (2023)

Legend: (A) Historical series of yearly deforestation in the Triunfo do Xingu Environmental Protection Area (APATX) and in the Brazilian Legal Amazon (BLA) and (B) inside the two sections of APATX in the municipalities of Altamira and São Félix do Xingu (SFX) and in the respective municipalities. Additionally, (C) yearly increments of the main land uses inside APATX and their relationship with yearly deforestation and (D) expanded description of the minority land uses within APATX observed in C

3.2 Do land use dynamics explain deforestation inside APATX?

As deduced from Figure 3c, yearly deforestation increments exhibited a robust and noteworthy correlation ($r = 0.75$) with increases in pastureland and a moderate correlation ($r = 0.45$) with the expansion of agricultural crops (encompassing Other temporary crops and Soybean in a single variable) and mining activities ($r = 0.51$). In the multiple regression model for annual deforestation increments within APATX, only yearly increases in pastureland were significant ($p < 0.05$; Table 2), indicating that mining and agricultural crops do not explain deforestation rates. A simple linear model focusing solely on pasturelands provided a better fit (AIC = 22.6 vs. 23.5 for the multiple model) and accounted for 69% of the annual deforestation variability within APATX. For every 1 km² of pastureland quantified by Mapbiomas data, there were approximately 1.96 km² (pasture coefficient log-back transformed) of annual deforestation identified by the PRODES Amazonia program.

Table 2 – Results of simple and multiple linear regression models evaluating the impact of different land uses on deforestation within the Triunfo do Xingu Environmental Protection Area

Land uses	Estimate	Std. Error	t value	Pr(>|t|)
Multiple Linear Model				
Intercept	1.9448	0.5885	3.304	0.00394
Pasture	0.6631	0.1095	6.054	0.0000101
Agricultural crops	0.1894	0.1141	1.661	0.1141
Mining	-0.1046	0.1517	-0.69	0.49924
$R^2 = 0.70$; $F_{3,18} = 17.32$; $p = 1.527e^{-05}$; AIC = 23.5				
Simple Linear Model				
Intercept	1.8973	0.5441	3.487	0.00232
Pasture	0.6716	0.0976	6.882	0.0000011
$R^2 = 0.69$; $F_{1,20} = 47.36$; $p = 1.099e^{-06}$; AIC = 22.6				

Source: Authors (2023)

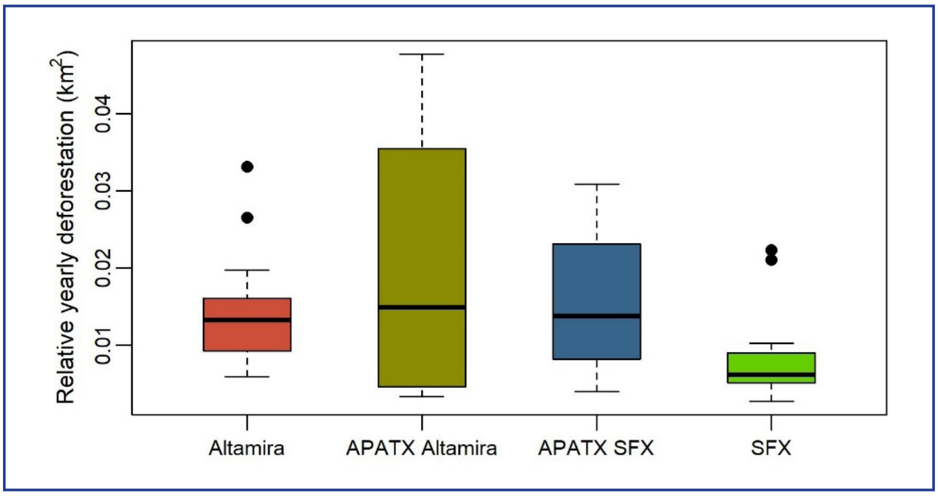
3.3 Was the establishment of APATX successful in controlling deforestation in the region?

As shown in Figure 3a, after APATX was established in 2006, following a year with the lowest deforestation rate since 2001, 2007 saw a sudden spike in deforestation. This was followed by a continuous decline until 2012, when deforestation began to rise again. This upward trend continued until 2022, the last year we analyzed. A significant peak in deforestation, particularly noticeable in 2016, surpassed the deforestation rates in 2006. After 2017, deforestation within APATX rapidly increased, approaching the levels observed in 2002, which marked the highest point in our historical dataset. Both municipalities showed deforestation inside APATX exceeding the 2006 level in 2016 and 2019, respectively, remaining above that threshold until our last data point in 2022 (Figure

3b). Throughout the study period, 41.12% (3,145.08 km²) of deforestation occurred up to 2006, while 58.87% (4,503.36 km²) occurred after the establishment of APATX.

From 2007 to 2022, although deforestation in Altamira exceeded that in SFX (Z = 2.467; p = 0.009; Figure 4), there was no significant difference between the two municipalities within APATX (Z = 0.764; p = 0.488). However, a notable contrast emerged when comparing deforestation rates inside and outside of APATX within these municipalities. In Altamira, no significant difference was observed between the rates inside and outside APATX (Z = -1.036; p = 0.310). In contrast, the municipality of SFX experienced higher deforestation rates and a statistically significant difference inside APATX compared to outside (Z = 2.490; p = 0.009).

Figure 4 – Relative yearly deforestation (2007 – 2022) in the municipalities of Altamira and São Félix do Xingu (SFX), and inside Triunfo do Xingu Environmental Protection Area (APATX) in both municipalities



Source: Authors (2023)

4 DISCUSSION

Our study showed that since APATX establishment in 2006 up until 2022, it had no significant influence on controlling deforestation in the area. This was evidenced by the similar levels of deforestation inside and outside the PA in the municipality of

Altamira, the higher deforestation values inside than outside in SFX, and the correlation with the overall trend of deforestation in the BLA.

The high deforestation values observed between 2001 and 2006 were a consequence of historical uncontrolled occupation of the Terra do Meio, involving wood extraction, corporate and small-scale gold mining from the 1970s-1990s, together with illegal appropriation of public lands by squatters and land grabbers who opened roads for logging (Escada et al., 2005; Doblas, 2015; Souza et al., 2020). Small farmers then occupied the region in the 1990s, resulting in deforestation values increasing from hundreds to thousands of km² by the end of the decade. Large cattle farms also contributed to deforestation between 2000-2005 (Escada et al., 2005; Doblas, 2015; Souza et al., 2020).

Deforestation reduction inside APATX (2007-2012) can be associated to former environmental policies and to the drop in agricultural commodity prices. ARPA (established in 2002) produced significant results in areas with high anthropic pressure, notably in the Deforestation Arc (Soares-Filho et al., 2023). The PPCDAm program, launched in 2004 (Brasil, 2004), aimed to prevent and control deforestation in the Amazon, with the governmental, non-governmental and the private sector actively participating to achieve relevant results in curbing deforestation (West; Fearnside, 2021). The so-called List of Priority Municipalities in the Amazon also played a key role in reducing illegal deforestation (Assunção; Rocha, 2019). Law enforcement actions, government restrictions, and lawsuits by the Federal Public Ministry against companies and landowners, along with the PPCDAm second phase (2009-2011), were critical to deforestation reduction in the region and in the biome in general (Assunção et al., 2012; Nolte et al., 2013).

In this same period, the reduced demand for beef and soybean that occurred led to a decrease in their prices, which may have contributed to the reduction in deforestation as of 2005 (Assunção et al., 2012). This price decline resulted in reduced area used for temporary crops and fewer bovines in BLA from 2005 to 2007 (Messias et al., 2021). Additionally, the Soy Moratorium and the Cattle Agreement, the latter implemented in 2009 to prevent slaughterhouses from purchasing beef from deforested areas, contributed to the decrease in deforestation rates until 2012 (Macedo et al., 2012; Nepstad et al., 2014). These political and economic factors are estimated to have caused a ~80% reduction in deforestation between 2004 and 2012 (West; Fearnside, 2021).

Mirroring the Amazon's trend, deforestation inside APATX began to rise in 2012, reaching pre-PA levels. In this period, deforestation within PAs and Indigenous Lands in the Brazilian Amazon increased 3.6 times, compared to 1.6 times outside of them (Qin et al., 2023). Between 2017 and 2021, the Near Real-Time Deforestation Detection System (DETER/INPE) issued 3,244 alerts for APATX, with approximately 65% for SFX (Merêncio; Vieira, 2021). Among the factors for this increase may be the growing value of soybeans in this period that led to the sale of pasture areas in states with better logistical infrastructure for the product, such as Mato Grosso, and the migration of pastures to the active deforestation frontier (Macedo et al., 2012; Song et al., 2021). Additionally, international demand for meat has led to an increase in the cattle herd in Altamira and SFX. During this period, the cattle population in Altamira increased from 668,541 to 904,271 heads, and from 2,143,760 to 2,468,764 heads in SFX (IBGE, 2023). The construction of the Belo Monte Hydroelectric Plant near Altamira caused a surge in demand for timber and directly contributed to deforestation in Terra do Meio and the surrounding region (Jiang et al., 2018; Silva Junior et al., 2018). It led to an increase in illegal logging activities from 20,000 to 70,000 hectares between 2011 and 2012 (Doblas, 2015).

Political decisions played a major role in escalating deforestation in the country. Changes to the Forest Code in 2012, including amnesty for deforestation prior to 2008, and other bills aimed at easing environmental licensing, may have encouraged deforestation in anticipation of further legislative changes due to political pressure from the ruralist caucus in the National Congress (Ferrante; Fearnside, 2019; Pereira et al., 2020; Rajão et al., 2020). The deforestation peak inside APATX in 2016 compared to previous and subsequent years coincided with the political uncertainty caused by the impeachment of former President Dilma Rousseff, which provided legislative initiatives for weakening environmental legislation in the country (Fearnside, 2022). The peak of deforestation was also observed for the Legal Amazon as a whole and for the state of Pará itself, where deforestation reached one-third of that observed for the entire BLA (INPE, 2024b). The political influence on deforestation in the Amazon and the APATX increased significantly during the period of 2018-2021, likely due to the incentives and rhetoric of President Jair Bolsonaro at the time and the limited enforcement actions imposed to IBAMA and ICMBio, the federal agencies responsible for environmental oversight outside and inside protected areas, respectively (see Ferrante; Fearnside, 2019; Ramos, 2021).

The lack of a statistical difference in deforestation within the APATX in Altamira and SFX seems to stem from the rapid escalation of deforestation within the PA in Altamira after 2015, surpassing that within it in SFX, which has tended to be higher since its establishment. Deforestation in the PA in Altamira has increased in line with the overall trend in the municipality, whereas deforestation in the municipality of SFX has decreased, been lower than that observed within APATX. The reasons for the differences between the two municipalities are still to be investigated. One possible explanation for the higher deforestation within APATX than outside it in SFX is the historical process of occupation in the area. Figure 1 indicates that the non-protected area in SFX has reached an advanced stage of deforestation and fragmentation, with only large forest patches remaining inside PAs, including APATX. Fearnside (2003) observed a similar trend in the state of Mato Grosso. Therefore, the greater deforested area within APATX may be solely due to the availability of large forested areas still vulnerable to clearance. Also, the deforestation within APATX occurs in an east-west direction, starting from the already deforested areas of SFX, while its area in Altamira is surrounded by different PAs.

The similarity in deforestation within APATX in both municipalities may be due to the same land use practices. SFX had a larger area of pasture than Altamira within APATX, possibly due to more intense deforestation in SFX prior to Altamira within the PA (Pinto et al., 2011; Doblas, 2015) and the municipality having the largest cattle herd in the country in 2021 (IBGE, 2023). Pasture explained most of the deforestation within APATX and is also the main driver of forest loss in Terra do Meio (Mertens et al., 2002; Neves et al., 2014), reflecting the fact that cattle ranching is the primary economic activity in both municipalities (Escada et al., 2005; Castro, 2007; Macedo et al., 2013). During this period, the cattle herd in Altamira increased from 668,541 to 904,271 heads, and from 2,143,760 to 2,468,764 heads in SFX (a 19.93% increase considering the joint herd of both municipalities) (IBGE, 2023). Due to the simple technological package required and the guaranteed economic return, ranching is one of the main drivers of deforestation in the Amazon (Margulis, 2004; Barona et al., 2010). It takes advantage of roads opened by illegal logging in frontier zones or uses this activity as a means to capitalize on the beginning of pasture establishment, which also serves as a way for land grabbing by small, medium, and large landowners (Escada et al., 2005; Castro, 2007; Souza et al., 2017).

While pastureland dominates within APATX, agricultural crops and mining did not significantly contribute to explaining deforestation within APATX. In fact, the area cultivated with agricultural crops within APATX was trifling compared to pastureland. For instance, soybean cultivation only appeared in 2021, covering only 1.18 km² within the PA. The lack of significance of agricultural crops in explaining deforestation in APATX may stem from their potential establishment in areas previously used for pasture. The establishment of high-capital crops tends to occur in already consolidated areas with good infrastructure for production flow (Costa et al., 2001; Fearnside, 2007) and, as of the establishment of the Soybean Moratorium, it has not been common in the deforestation frontier in the Amazon (Rudorff et al., 2011). In addition, many properties within APATX lack land ownership registration, which hinders investment in crops and limits access to agricultural credit (Garrett et al., 2013; Dias et al., 2021). Consequently, the high financial returns of livestock production in these frontiers and in illegal areas have become a safety net for many small and medium-sized farmers, hindering the diffusion of other uses within APATX (Salisbury; Schmink, 2007; Siegmund-Schultze et al., 2007).

Information about mining activities within APATX remains limited. In the municipality of SFX, (Costa et al., 2019) identified a staggering 700% increase in mining areas between 2008 and 2017, leading the municipality to hold the highest number of permits for such activities in 2013 within a region recognized as one of the state's major mining business centers (Costa, 2013). Although Costa (2013) acknowledged the presence of mining activities within APATX, the precise extent was not quantified. According to the author, these activities are predominantly concentrated along the Canopus Road (or Transiriri), constructed by a mining company in the 1980s. The limited influence of mining areas in explaining deforestation detected by the PRODES program might be attributed to their existence in previously deforested regions inside PRODES mask of exclusion (see PRODES methodology in Almeida et al., 2022). Nevertheless, a thorough investigation of the specific locations of these mining activities could yield a more comprehensive understanding of the dynamics of mining within APATX

Regarding the similarities between APATX and BLA's deforestation trends, Doblas (2015) points out that deforestation dynamics in the Terra do Meio region have been regarded as an early indicator for the Brazilian Amazon. The ineffectiveness of APATX in curbing deforestation becomes evident through the resemblance of deforestation rates both inside and outside the PA in the municipalities, with higher values observed inside than outside in SFX. The lack of control over deforestation within APATX is apparent when the deforestation in both Altamira and SFX sections exceeds the levels recorded at the time of its establishment in 2006, as seen in 2016 and 2019, respectively. Considering that the creation of a PA should lead to the cessation or the reduction of deforestation rates below those outside its boundaries (Barber et al., 2012), it is evident that APATX has not achieved this objective.

However, deforestation in PAs (UCs and TIs) is on the rise in Brazil. The ineffectiveness of APATX, which has become the leading PA in deforestation in the Amazon for consecutive years (Araújo et al., 2017; INPE, 2024b), epitomizes the challenges faced by PAs in the Brazilian Amazon when it comes to preventing anthropogenic activities within their boundaries. Between 2000 and 2021, PAs in the Brazilian Amazon lost an average of $0.08 x 10^{6}$ $ha.yr^{-1}$ (0.04% yr_{-1}) (Qin et al., 2023). Within the biome, both strict protection and sustainable use PAs, as well as Indigenous Lands, are facing illegal practices such as deforestation, mining, and timber extraction (Araújo et al., 2017; Rorato et al., 2021; Qin et al., 2023). Moreover, in the Terra do Meio region itself, several PAs and Indigenous Lands are also under immense pressure, primarily due to land speculation and illegal timber extraction (Doblas, 2015; Araújo et al., 2017).

The increasing deforestation within APATX may also be a result of spillover effects originating from the extensive protected area in the two municipalities. Deforestation spillovers occur when the establishment of protected areas to safeguard a specific region leads to deforestation occurring in adjacent or even distant locations beyond their boundaries (Pfaff; Robalino, 2017). According to Doblas (2015), efforts to curb deforestation in SFX have inadvertently caused deforestation to “leak” into APATX, facilitated by the lack of governance in territorial management within the protected area. The limited area outside of protected areas and indigenous territories in both municipalities (26.5% in SFX and 8.6% in Altamira) means that APATX, with fewer usage restrictions and various management shortcomings, serves as an escape zone for deforestation in the Terra do Meio region of both municipalities. This helps explain the similar deforestation rates observed within APATX in both municipalities. This phenomenon can be observed by the clearly defined boundaries between the protected areas and indigenous territories with APATX.

Sustainable use areas, which include Environmental Protection Areas (APAs) (BRASIL, 2000), are more sensitive and vulnerable to impacts compared to strict use PAs and Indigenous Lands in terms of preventing deforestation (Nepstad et al., 2006; Françoso et al., 2015; Soares-Filho et al., 2023). A global analysis covering a 12-year period (2000-2012) showed that strict protection areas achieved an 81% reduction in deforestation, while sustainable use areas achieved a 67% reduction (Shah et al., 2021). This lower efficacy of sustainable use areas can be attributed to their location in regions under greater pressure (Nepstad et al., 2006; Nelson; Chomitz, 2011; Nolte et al., 2013). Because of that, despite of the results, some researchers suggest that, in relative terms, sustainable use areas can be more effective than strict protection areas (Nolte et al., 2013; Pfaff et al., 2014).

However, APAs have limitations compared to other categories of sustainable use. As they do not require land expropriation, resulting in lower social, political, and economic costs, in certain regions they constitute the largest established PAs (Françoso et al., 2015). Consequently, APAs predominate among State PAs (69%) (Rylands; Brandon, 2005). A large-scale assessment concluded that, in general, they are not effective in reducing deforestation in the Amazon (Siani et al., 2019). For instance, in the state of Acre, two APAs were among the three most deforested PAs from 2007 to 2019 (Reis; Rocha, 2022). The Tapajós APA in Pará lost approximately 191 km² of forests to agriculture and ranching (~150 km2), and mining (~40 km²) (Cunha; Ferreira, 2022), ranking among the most threatened PAs in the Amazon (INPE, 2024b).

The limitations of APAs extend beyond the Amazon, as various studies have documented similar impacts in other biomes such as the Cerrado, Caatinga, and Atlantic Forest (Feitosa, Araújo, 2016; Rodrigues et al., 2017; Oliveira et al., 2019). APAs, which allow for diverse productive activities as outlined in their management plan and primarily encompass private lands (BRASIL, 2000), naturally face the risk of both legal and illegal deforestation, along with other typical anthropogenic activities outside of PAs. In the Amazon, private properties are legally permitted to clear up to 20% of their land (Brasil, 2012). Moreover, the initial purpose of APAs was primarily for land use planning in buffer zones around PAs rather than solely for biodiversity conservation (Rylands; Brandon, 2005), which could further constrain their efficacy.

The low efficacy of APAs is influenced by multiple factors beyond their inherent characteristics. Research indicates that deforestation in PAs is driven by a combination of territorial and management contexts, influenced by external forces like infrastructure projects and agricultural expansion, rather than solely relying on the efficiency of PA management (Giehl et al., 2017; Shah et al., 2021; Pellin et al., 2022). For example, in Pará, the state with the highest deforestation rates (INPE, 2024b), the PAs within it also experience the most significant deforestation levels (Pellin et al., 2022). Inadequate management, enforcement, and governance of protected areas, their spatial location in relation to areas under higher anthropogenic pressure, jurisdictional complexities (state-level PAs tend to experience greater impacts; see Vitel et al., 2009; Herrera et al., 2019), land use practices, stakeholder dynamics, lack of benefits from PAs, opportunity costs for local communities to preserve forests, as well as land regularization both inside and outside them, are identified as combined factors that contribute to various anthropogenic processes occurring within PAs and their buffer zones (Nolte et al., 2013; Costa; Reis, 2017; Shah et al., 2021; Cunha; Ferreira, 2022; Pellin et al., 2022).

The lack of a management plan, deficiencies in land titling, and even the occurrence of fraudulent land records, combined with deficiencies in the management, enforcement, and monitoring systems observed in APATX (Doblas, 2015; Araújo et al., 2017; Costa; Reis, 2017), hinder the management and enforcement of PAs (Herrera et al., 2019; West et al., 2022). The increasing deforestation within APATX has triggered the encroachment into adjacent PAs, such as the Serra do Pardo National Park (Doblas, 2015; Pinho et al., 2017). The lack of a management plan is a recurring feature in APAs with significant environmental impact (e.g., Rodrigues et al., 2017; Oliveira et al., 2019; Cunha; Ferreira, 2022), further exacerbated by APATX location in the eastern region of Pará, within the Deforestation Arc, one of the most heavily affected regions by deforestation (Pfaff et al., 2015). Inadequate enforcement within APATX plays a crucial role in these findings, as studies have emphasized the pivotal contribution of government enforcement institutions in curbing deforestation in APAs (Siani et al., 2019) and other PAs in the Amazon (Assunção et al., 2012; Nolte et al., 2013; West, Fearnside, 2021). In the absence of State regulation of land use within APATX, the proliferation of unofficial roads, stretching over 407,693 km, has facilitated the expansion of deforestation into less impacted areas of APATX (Pinho et al., 2017).

5 CONCLUDING REMARKS

Our study revealed that APATX exhibited a deforestation trend closely aligned with the overall pattern observed in the biome and showed deforestation levels that exceed what would be legally expected based on the available data. This suggests that the PA is responding in a similar way to the Brazilian Amazon to internal and external factors that led to a decline in deforestation between 2007 and 2012, followed by a subsequent increase until the final year of analysis (2021). Surprisingly, APATX exhibited deforestation rates that were similar to or even higher than those observed in areas outside of it. This indicates that APATX, a highly important area for conservation in the Amazon, failed to effectively curb deforestation in a critical region of agricultural expansion, where the conversion of forests into pastureland serves as the primary driver of deforestation.

The inadequate governance of APATX, exemplified by the absence, thus far, of a management plan that integrates its conservation objectives with the landowners' aspirations, as well as the limited land regularization in the region, renders the management of an area characterized by intense anthropogenic pressure and socio-environmental conflicts unfeasible. Considering the purpose of an APA, defined as a "sustainable use PA aimed at protecting biodiversity, regulating land occupation, and ensuring the sustainable use of natural resources" (Federal Law No. 9985/2000), in light of the presented and discussed results, including studies that demonstrate a similar situation in other APAs in the Amazon and other biomes, there are grounds to question APATX efficacy and this PA model in achieving such objectives in regions where the opportunity cost of maintaining the forest intact is high.

We underscore the existing literature on APATX, highlighting that the government of Pará must address the challenges hindering the efficient management of the protected area. Prioritizing land regularization and the development of a comprehensive management plan is crucial. This plan should guide the permissible types of land use, ensure environmental compliance of properties, and establish acceptable limits for landscape changes, all aimed at achieving long-term sustainability. It is essential to engage local representative organizations, strengthen the management capacity of APATX, and establish strategic partnerships with various sectors to fulfill these objectives. Additionally, regular monitoring of land use and land cover within the area (which can be done with data provided by Amazon's official monitoring programs such as PRODES and DETER) is vital to assess progress and make informed decisions.

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