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Land use transformations and tenure conflicts in the Cerrado-Caatinga frontier: Evidence from Piauí, Brazil

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ABSTRACT

Brazil's Rural Environmental Registry (CAR), established in 2012 under the Forest Code, is a mandatory environmental cadastral system based on self-declaration of property boundaries that plays a central role in environmental enforcement, rural credit allocation, and land-use monitoring. This study develops and applies a hierarchical conflict-resolution framework to systematically identify which portions of the CAR are procedurally reliable and analytically usable for deforestation attribution and regulatory enforcement. We analyzed 310,657 CAR registrations recorded in 2025 in Piauí, Brazil, integrating them with official tenure datasets through a sequence of hierarchical rules for the Cerrado-Caatinga transition, one of the most active agribusiness frontiers. The reconstructed tenure map, derived from the hierarchical framework representing the accumulated state of all property registrations and boundary rectifications, was applied to attribute deforestation recorded between 2013 and 2023. The primary findings indicate that intra-CAR spatial overlaps were detected nearly one-third of the registered area, with boundary conflicts concentrated among larger properties along the Cerrado agribusiness frontier. In terms of deforestation, 94.20% of vegetation loss (1236,100 ha) can be attributable to identifiable actors, of which 86.60% is associated with private properties registered in CAR and official tenure datasets. The top 1% of properties ranked by cumulative deforestation account for 71.50% of total vegetation loss between 2013 and 2023, indicating a pronounced concentration of clearing among a numerically small set of landowners. Of the deforestation associated with private properties, 73.40% is classified as illegal under the Forest Code mandates applied in this analysis, with Legal Forest Reserve deficit violations representing the dominant source of non-compliance. Although over 13 million ha of native vegetation remains on private lands, Legal Reserve deficits are concentrated among large properties in the Cerrado biome, while small properties show the largest number of individual deficit records. These results demonstrate that a hierarchical analytical framework can extract procedurally reliable information from a self-declared registry, providing a scalable basis for spatially targeted enforcement, deforestation attribution, and Forest Code compliance monitoring at the subnational level.

1. Introduction

The increasing awareness of the global climate crisis has driven the adoption of conservation policies aimed at reducing deforestation and promoting ecological transformation (Meinshausen et al., 2022; Cannon, 2025). Within this context, Brazil's Nationally Determined Contribution (NDC) under the Paris Agreement positions territorial and land-use planning at the core of the country's climate ambitions, guiding policy development at national and subnational levels (Dutra et al., 2024; Malecha et al., 2025). Central to this effort is the Rural Environmental Registry (*Cadastro Ambiental Rural* – CAR) established by the Forest Code (Law No. 12,651/2012) as a foundational instrument for

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integrating environmental obligations into land management at the property level.

Brazil is the only country with nationwide compulsory protection of forests and native vegetation on private land, a policy not found in other major forested nations (Curtis et al., 2018; Chiavari, 2025). While some countries have incentives or regional regulations, none mandates protection on a national scale. According to Brazil's Forest Code, rural landowners must maintain a portion of the property area under native vegetation as a Legal Forest Reserve (*Reserva Legal* – RL): 80% for areas within the Legal Amazon and 20% in all other regions of the country. The code also prohibits native vegetation removal from environmentally sensitive areas such as hilltops, riverbanks, and riparian zones, designated as Permanent Preservation Areas (*Área de Preservação Permanente* – APP) (Biggs et al., 2019).

Since 2014, rural landowners in Brazil have been required to self-declare their property boundaries in the CAR system, generating a national georeferenced dataset of nearly eight million registrations (Chiavari, 2025). The CAR underpins Forest Code enforcement by supporting systematic monitoring of illegal deforestation, providing the legal basis for restoration obligations, and facilitating the development of carbon markets when combined with validation and monitoring frameworks (Camara et al., 2023). Public financial institutions now condition rural credit on CAR compliance, making the registry a critical lever for ensuring that commodity supply chains such as beef, soybean, and palm oil, meet Brazil's zero-deforestation commitments (Curtis et al., 2018; Pendrill et al., 2022; Souza et al., 2024; Rocha et al., 2025).

Despite its central role in environmental governance, the CAR was not designed as a land tenure document. Its primary function is regulatory control (Metzger et al., 2019; Pacheco et al., 2021). The self-declaration process creates structural vulnerabilities, and scholars have documented associations between CAR and land grabbing in the Legal Amazon, including fraud and widespread tenure conflicts (Furumo et al., 2024; Horn, 2024; Ferreira, 2026). These vulnerabilities underscore the need for analytical methods capable of distinguishing procedurally reliable registrations from conflicting or speculative ones.

Resolving spatial inconsistencies within CAR is not merely a data quality exercise. When overlapping or conflicting registrations are systematically identified and corrected, the resulting tenure map can serve as an operational basis for directing enforcement effort toward properties with detected violations, strengthening restoration compliance, and improving Legal Reserve monitoring. The causal pathway runs from improved data integrity to spatially targeted inspections, and from inspections to reduced deforestation risk and a more credible legal basis for regulatory action, a mechanism that is directly relevant to Brazil's 2030 deforestation targets under the NDC (Camara et al., 2023; Brazil, Ministry of Environment and Climate Change. 2026).

This article adopts a critical and empirically grounded perspective toward CAR self-declarations. Rather than treating data reliability as a given, the paper develops and applies a hierarchical analytical framework to systematically resolve spatial inconsistencies and assess which portions of the CAR can be considered procedurally reliable and analytically usable. In operational terms, registrations are considered procedurally reliable and analytically usable when they are topologically consistent, free of unresolved overlaps following hierarchical processing, and unambiguously attributable to a single tenure category. Therefore, the central question guiding this study is whether a self-declared land registry, despite its structural inconsistencies, can be rendered analytically tractable for deforestation attribution and regulatory enforcement at the subnational level.

We argue that applying hierarchical conflict-resolution rules to CAR registrations makes it possible to generate a more accurate and updated assessment of land tenure and land use. This approach intensifies the analytical role of the CAR in environmental governance and provides a scalable framework for deforestation attribution at the subnational level. Therefore, it is important to develop and test such analytical techniques to assess the reliability of CAR self-declarations in practice. This study aims to: (*i*) measure land conflicts within the CAR in the state of Piauí, Brazil; (*ii*) produce more reliable tenure maps by integrating CAR with other official sources; and (*iii*) analyze deforestation patterns and Legal Reserve deficits and surpluses across private lands in Piauí.

Building on the methodological framework of Camara et al. (2023), this study extends that approach to a non-Amazonian frontier context, examining land conflicts in the Cerrado-Caatinga transition zone of Piauí, a socio-ecological setting characterized by historical smallholder occupation, recent large-scale agribusiness expansion, and comparatively weaker subnational enforcement capacity. Unlike the Legal Amazon, where frontier governance dynamics have been more extensively studied, Piauí's institutional configuration generates qualitatively different pressures on CAR-based compliance, yielding insights that cannot be derived from Amazonian case studies alone. Focusing on a single state allows a detailed analysis of tenure conflicts between distinct actors, including soy producers, quilombola communities, and smallholders, and permits assessment of the recent soybean expansion trajectory. The methodology developed here is transferable to other Brazilian states, where self-declaration gaps and inter-registry inconsistencies pose comparable challenges to Forest Code implementation, and its application at the national scale represents a direct avenue for future research.

2. Materials and methods

2.1. Study area

This study focuses on the state of Piauí, located in Northeastern

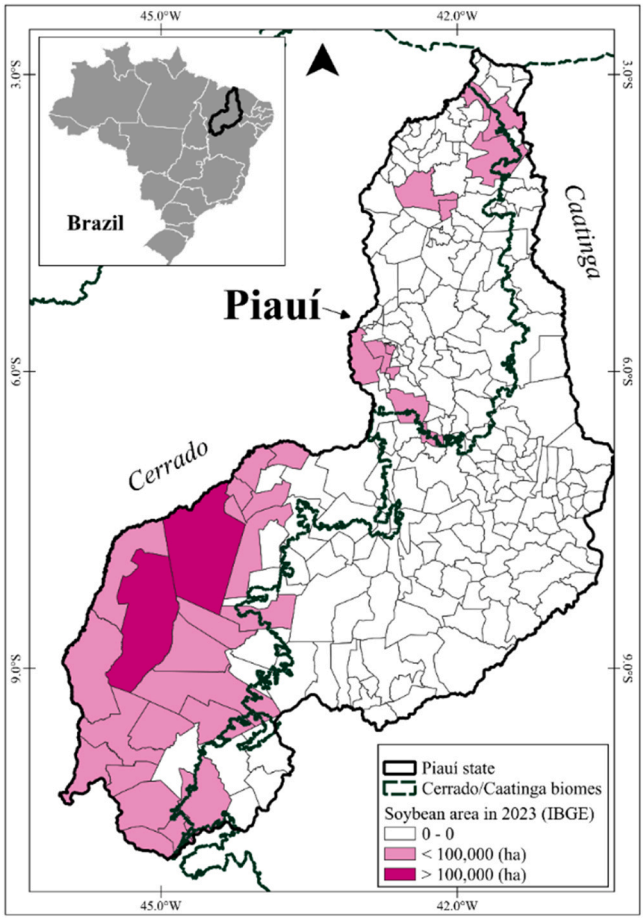


Fig. 1. Location of the state of Piauí, Brazil, indicating the frontiers of the Cerrado and Caatinga biomes and the municipalities with soybean production in 2023.

Brazil, in a transitional zone between the Cerrado and Caatinga biomes (Fig. 1). Recent land use practices have transformed native forests into areas of agricultural expansion and emerging energy development (Espindola et al., 2021). While the Brazilian land governance literature has concentrated largely on states within the Legal Amazon, Piauí offers a distinct socio-ecological setting for examining Forest Code implementation. The state combines historically fragmented smallholder occupations with recent large-scale capitalist expansion, comparatively weaker subnational enforcement capacity, and a biophysical context that challenges remote-sensing-based monitoring.

The state falls within the MATOPIBA agricultural frontier, where rapid soybean and cotton expansion over the past two decades has intensified pressure on native vegetation and heightened tenure conflicts in areas where land regularization remains incomplete. The area has a semiarid climate, with a long dry season and a short rainy season, and its native vegetation is adapted to prolonged water scarcity (Argibay et al., 2020; Sparacino et al., 2021; Sousa Júnior et al., 2023). Such strong and unpredictable climatic seasonality poses a challenge for accurate land use mapping. The spectral responses of land-use and land-cover (LULC) classes vary substantially across seasonal and climatic conditions, directly influencing the accuracy of remote-sensing-based classifications (Sousa Júnior et al., 2022).

2.2. Datasets

In the early 2000s, Brazil, with World Bank support, began developing the precursor of the CAR, prioritizing deforestation monitoring in the Amazon due to severe forest loss (Horn, 2024). Other regions, particularly the Northeast, received limited support and technical investment during this initial phase, as deforestation was less closely linked to major commodity supply chains.

The CAR registration became mandatory with the 2012 Forest Code reform. However, Law No. 13,887/2019 extended the self-declaration deadline to December 31, 2020, allowing landowners to join the Environmental Regularization Program (*Programa de Regularização Ambiental* – PRA). Currently, the entire CAR dataset is publicly available through the National Rural Environmental Registry System (*Sistema Nacional de Cadastro Ambiental Rural* – SICAR). The PRA serves as the primary instrument for addressing environmental liabilities identified through CAR validation, requiring landowners to restore, recover, or compensate for native vegetation illegally cleared after the 2008 legal cut-off date.

Although CAR registration does not grant property rights under the Forest Code, intra-CAR land conflicts are a significant challenge for enforcing forest conservation policies on private lands. Decree No. 10,165/2019 placed the CAR at the center of Brazil's land tenure policy by establishing self-registration as a prerequisite for land regularization. This legal change reinforced the perception that, beyond its environmental purposes, the CAR could also serve as an instrument for land tenure regulation. This ambiguity reinforces the need to address the problems of the CAR and to produce a consolidated, conflict-free land tenure database.

Because the CAR is self-declared, the total area reported in the system actually surpasses the country's real land area, due to overlaps within the CAR itself and with public lands (Chiavari, 2025). Nevertheless, all CAR submissions remain pending until final verification and validation by the respective state environmental agencies.

The National Institute for Colonization and Agrarian Reform (INCRA) manages datasets relevant to land tenure and rural development in Brazil. These include private land tenure cadasters derived from three federal systems: (*i*) the SIGEF (*Sistema de Gestão Fundiária*), covering the period from 2013 to 2025; (*ii*) the SNCI (*Sistema Nacional de Cadastro de Imóveis Rurais*), with entries between 2004 and 2018; and (*iii*) the Terra Legal program, launched in 2009 to regularize smallholder occupations on public lands. INCRA maintains a database of *quilombola* lands, occupied by communities descended from Afro-Brazilian peoples who resisted slavery. INCRA is also responsible for rural settlements created under agrarian reform programs aimed at promoting social inclusion and productive land use practices (Table 1). In Piauí, many such settlements have existed since the 1980s and typically face issues like poor infrastructure and limited technical support (Alencar et al., 2018).

For the purposes of this analysis, registrations not yet validated by state environmental agencies were retained and treated as active entries, given that state-level validation remains largely incomplete across Brazil and their exclusion would substantially reduce the spatial coverage of the dataset. To measure these overlaps and produce an updated assessment of land tenure in Piauí, we used publicly available datasets from Brazilian institutions, as shown in Table 1. The temporal coverage of these datasets varies, as SIGEF spans 2013–2025, while SNCI covers 2004–2018. Where spatial conflicts arose between these two sources, SIGEF registrations were assigned priority, reflecting their more recent coverage and standardized validation procedures. SNCI records without a corresponding SIGEF entry were retained to ensure comprehensive spatial coverage.

The National Foundation for Indigenous Peoples (FUNAI) provides official information on indigenous lands in Brazil. Brazilian law guarantees indigenous communities' permanent possession and exclusive use of their ancestral territories. The Chico Mendes Institute for Biodiversity Conservation (ICMBio) manages conservation units, including fully protected areas, where no settlement or resource use is allowed, and sustainable use areas, where private properties are allowed under strict management (Drummond et al., 2009). The Brazilian Forestry Service (SFB) maintains the National Cadaster of Public Forests (CNFP), which includes forests already allocated to categories such as indigenous lands and conservation units, as well as public forest lands not yet formally designated by authorities, as shown in Table 1.

For Permanent Preservation Areas (APPs), we used data produced by the Brazilian Foundation for Sustainable Development (FBDS). Employing high-resolution digital elevation models and recent satellite mosaics, the FBDS methodology enabled accurate delineation of hydrological APPs by precisely identifying drainage networks and water bodies (see Table 1). FBDS converted the drainage lines into polygons, classified streams by width, and applied buffer zones based on the legal parameters defined in the Forest Code. The resulting dataset combines hydrological and topographic attributes, including riparian zones, hilltops, steep slopes, and escarpments, and provides standardized, legally compliant information that supports the environmental analyses of this study (Fundação Brasileira para o Desenvolvimento Sustentável FBDS, 2024). The FBDS dataset was derived from standardized hydrological and topographic models rather than from the spatial information submitted by individual landowners in their CAR declarations. Where systematic differences exist between these two representations of APP boundaries, the FBDS-derived delineation is treated as the reference layer for legal compliance assessment, given its methodological consistency and independent derivation from high-accuracy elevation models

Table 1
List of datasets used for Piauí, Brazil.

Type	Description	Source	Year
Private lands	CAR (self-declared property boundaries)	SICAR	2019
	CAR (self-declared property boundaries)	SICAR	2025
	SIGEF (rural properties)	INCRA	2025
	SNCI (rural properties)	INCRA	2025
	Terra Legal (rural properties)	INCRA	2025
Public lands	Indigenous lands	FUNAI	2025
	Quilombola lands	INCRA	2025
	Conservation units	ICMBio	2025
	Public forests	CNFP	2025
	Rural settlements	INCRA	2025
APPs	Permanent Preservation Areas	FBDS	2024
LULC maps	PRODES (deforestation)	INPE	2023
	MapBiomas	MapBiomas	2023
Production	Soybean production (PAM)	IBGE	2023

and satellite data.

Brazil's National Institute for Space Research (INPE) monitors annual deforestation caused by clear-cutting in the Brazilian biomes through the PRODES project (*Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite*), which provides consistent, long-term data on forest loss. Since 2015, the community-powered MapBiomas initiative has provided annual maps of land-use and land-cover in Brazil from 1985 onward, enabling comprehensive monitoring of landscape transformations nationwide (Souza et al., 2020). The Brazilian Institute of Geography and Statistics (IBGE) reports data on soybean production in 2023 from the Municipal Agricultural Production (PAM) survey. These records detail the harvested soybean area for each municipality, enabling mapping of agricultural regions and comparisons with the CAR.

2.3. Quantifying intra-CAR overlaps (Rule A)

CAR records contain inconsistencies and errors, including duplicate registrations, geometric mismatches, and spatial overlaps, which affect the analytical reliability of the dataset. Rather than presupposing a degree of accuracy in individual self-declarations, the methodology is designed to identify and quantify these inconsistencies systematically. The procedural reliability of the resulting dataset is an empirical outcome of the workflow, not a premise of the analysis. We set up five hierarchical rules to produce the updated private land tenure map (Fig. 2), described in Table 2. Table 2 summarises the datasets, priority criteria, and output layers for each rule. We applied the first rule (Rule A) to analyze intra-CAR overlaps. We conducted the intra-CAR overlap analysis using two versions of the CAR dataset: 2019 and 2025. We used the 2019 version to evaluate temporal changes, and the 2025 version to quantify current overlaps at the property level. The Legal Reserves within the property boundaries were used to examine the land use practices adopted by the landowners. We applied a series of pre-processing steps to eliminate canceled non-active records.

Based on Camara et al. (2023) and Furumo et al. (2024), we processed a multi-stage spatial validation and cleaning workflow to ensure topological consistency and remove internal overlaps (Rule A). To address intra-CAR conflicts, we identified intersecting parcels with distinct registration codes. Rule A retains the most recently registered polygon in full; where registration dates are identical, the largest polygon takes precedence and overlapping portions of lower-priority records are clipped and discarded. The result is a single, conflict-resolved spatial layer of unique property boundaries that is topologically consistent and procedurally reliable in the sense defined in the Introduction.

To quantify overlaps, we computed descriptive statistics (mean, standard deviation (sd), median, interquartile range (IQR)) for 2019 and 2025. These statistics were calculated for the entire dataset and stratified by property size (small, medium, large) and biome (Cerrado or Caatinga), enabling an assessment of how the magnitude and frequency of spatial conflicts vary across land tenure categories and ecological regions. We also fit Poisson GLMs to relate parcel-level overlap intensity in the 2025 CAR data to property size, property area, soybean production, and landscape context, such as protected lands and deforested regions. We coded size as an ordered factor (small, medium, large) and used municipality boundaries as fixed effects to control spatial heterogeneity. We computed model-based predictions for each parcel and summarized the average by size with 95% confidence interval (CI).

2.4. Building maps of private (Rules B, C, D and E) and public land tenure and quantifying deforestation patterns

After resolving all intra-CAR conflicts, we created an updated map of private land tenure by combining official INCRA datasets (SIGEF, SNCI, and Terra Legal) with CAR records (Fig. 2). Since INCRA datasets are official and validated representations of private land tenure in Brazil, we integrated them in order of importance: first SIGEF and SNCI, then Terra Legal. Rule B addresses any overlaps between SIGEF and SNCI, and Rule C adds Terra Legal records to the dataset.

We applied Rule D to merge the cleaned CAR dataset with the corresponding INCRA records. When spatial conflicts occurred between the two sources, INCRA registrations prevailed, reflecting their legal authority over land tenure information. The analysis quantified the total number of CAR records matching INCRA entries to assess the overall legal coherence between the cadastral and self-declared land datasets. We incorporated rural settlements in the final stage through Rule E. Together, these procedures produced a consistent, up-to-date map of private land tenure for the state of Piauí.

The next step of our analysis considers public land tenure maps that contain protected areas set by law. We implemented a precedence hierarchy as recommended by Camara et al. (2023) and described in Table 1: (*a*) indigenous lands; (*b*) quilombola lands; (*c*) fully protected conservation units; (*d*) military areas; (*e*) sustainable use conservation units; and (*f*) public forests. Table 3 lists the public lands in the state of Piauí. Following Camara et al. (2023), we assigned forest protection mandates to each public land category. Indigenous and quilombola lands, and fully protected conservation units are subject to a 100% forest protection mandate.

Using private and public land tenure maps, we quantified spatial overlaps between private parcels and public lands, as well as with Permanent Preservation Areas (APPs). To assess deforestation across distinct land tenure regimes in Piauí, we applied the conservation requirements defined by the Forest Code. For each parcel in the updated private land tenure dataset, we computed the extent of clear-cuts within its boundaries. Deforestation was classified as illegal when occurring within fully protected areas, indigenous or quilombola lands, regardless of the area affected. For private rural properties, deforestation was deemed illegal when it removed APP or reduced native vegetation coverage below the legally mandated Legal Reserve threshold. This procedure enabled us to systematically compare how private properties comply with their Legal Reserve obligations.

To estimate Legal Reserve deficits and surpluses, APP extents were derived directly from the FBDS dataset. APP areas were subsequently excluded from deficit calculations, so that Legal Reserve compliance was assessed solely based on native vegetation retained outside APP boundaries. Then, the resulting Legal Reserve balance reflects the proportion of native vegetation present outside APPs compared to the statutory thresholds established for each biome. For Piauí, which lies entirely within the Cerrado and Caatinga biomes, the Forest Code establishes a legal reserve requirement of 20% of the property area, excluding APPs.

3. Results

3.1. Trends in intra-CAR overlaps in Piauí state

We assessed temporal trends in boundary rectifications submitted by landowners to the CAR system between 2019 and 2025 and found that 50.38% of the properties changed their boundaries. Large properties (> 15 fiscal modules,[6] Fig. 4B) show a mean increase of 1076.48 ha in registered area compared to 158.57 ha for medium properties (4–15

[6] In Brazil, a fiscal module (*módulo fiscal*) is a unit of land measurement defined by Law No. 6746/1979. Its size varies by municipality (typically between 5 and 110 ha) and reflects local agricultural, economic, and ecological conditions. The fiscal module serves as the reference unit for classifying rural properties by size, as established by Law No. 8629/1993 (art. 4º), which defines small properties (under 4 fiscal modules), medium properties (above 4 up to 15 fiscal modules), and large properties (above 15 fiscal modules). It is also adopted by the Forest Code to calibrate environmental obligations such as Legal Reserve percentages and rules for consolidated rural areas, thereby guiding agrarian, environmental, and land-tenure regulations.

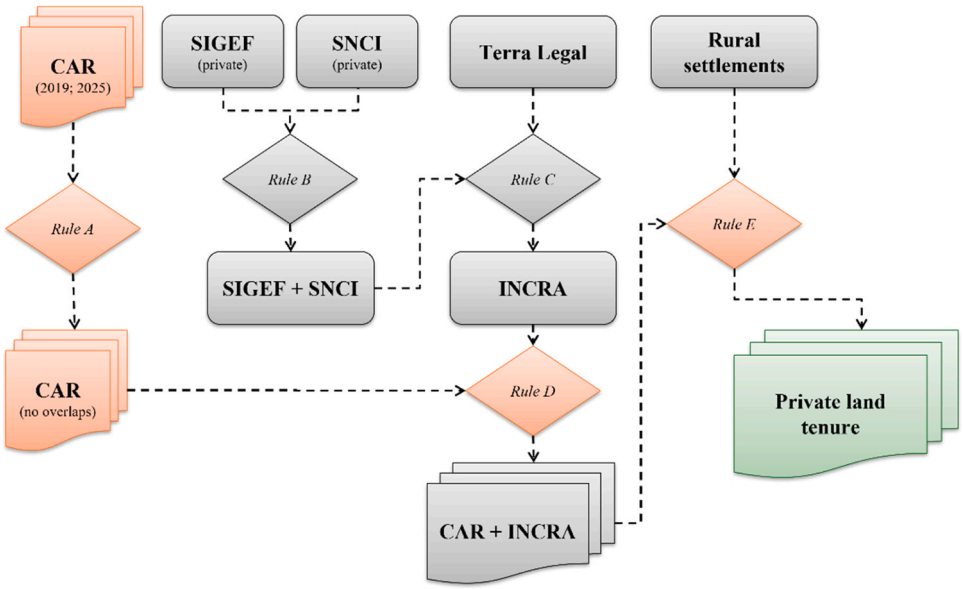


Fig. 2. Hierarchical decision rules (A–E) applied to integrate CAR and official INCRA datasets to generate the updated private land tenure map for Piauí, Brazil.

Table 2
Hierarchical conflict-resolution rules (A–E) applied to integrate CAR and official INCRA datasets and generate the updated private land tenure map for Piauí, Brazil.

Rule	Datasets involved	Priority criterion	Output layer
A	CAR 2019; CAR 2025	Most recently registered polygon is retained in full. Where registration dates are identical, the largest polygon takes precedence. Overlapping portions of lower-priority records are clipped and discarded.	Conflict-free intra-CAR property layer
B	SIGEF; SNCI	SIGEF takes precedence over SNCI where spatial conflicts arise. SNCI records without a corresponding SIGEF entry are retained.	Merged INCRA cadaster (SIGEF + SNCI)
C	SIGEF + SNCI (Rule B); Terra Legal	SIGEF/SNCI layer takes precedence. Terra Legal records are added where no corresponding SIGEF or SNCI entry exists.	Extended INCRA cadaster (SIGEF + SNCI + Terra Legal)
D	CAR (Rule A); INCRA cadasters (Rule C)	INCRA registrations take precedence over CAR polygons where spatial conflicts occur, reflecting their legal authority over land tenure information.	Integrated private land tenure map (INCRA + CAR)

Table 3
Public land tenure in Piauí.

Category	Number of Records	Total Area (ha)
Indigenous lands	1	2113
Quilombola lands	14	128,646
Fully protected conservation units	5	1312,341
Military areas	6	1518,041
Sustainable use conservation units	2	2200
Public forest	638	958,668
Total	672	3922,011

fiscal modules) and 8.72 ha for small properties (< 4 fiscal modules). The proportion of records showing area gains relative to the 2019 baseline reaches 86.54% for large properties, 83.29% for medium properties, and 70.77% for small properties. Although CAR rectification is a legal procedure intended to correct inconsistencies, our results indicate a relatively high degree of flexibility in boundary modification within the SICAR platform, a pattern that bears directly on the procedural reliability of self-declared data as an analytical instrument for environmental governance.

Moreover, analysis revealed substantial and increasing intra-overlaps in CAR (property boundaries) and RL (Legal Reserve boundaries) registrations from 2019 to 2025 (Table 4). Piaui's 2025 CAR database lists 310,657 properties, covering 25,809,770 ha. After removing spatial overlaps using Rule A (Fig. 3), the net conflict-resolved area decreases to 17,297,479 ha, showing that 32.98% of the total registered area overlapped with other registers. The mean number of overlaps per parcel is 1.69 and the median overlap area is 1.23 ha. The mean proportion of parcel area intersected by other registrations is 48.10% (Fig. 4 A). As for Legal Reserves, Piauí 2025 RL dataset includes 267,547 records with 6295,350 ha. Application of Rule A reduces the total area to 5180,195 ha. Thus, 17.72% of the mapped RL area has spatial overlaps. Each RL parcel had an average of 0.65 overlaps with a median of 0.26 ha (IQR = 2.04). On average, 29.58% of each RL parcel was affected by spatial conflicts (Table 4). Rule A prioritizes georeferenced public-domain records (INCRA datasets) over self-declared CAR polygons when spatial conflicts arise, ensuring that the most institutionally verified boundaries take precedence.

Overlap intensity varied across property size and biome (Fig. 4B). Large properties make up 41.38% of the total area overlap when comparing gross and net areas, with a mean of 6.77 overlaps per parcel and a median overlap of 1356.02 ha. Medium-sized properties have intermediate levels of conflict, with 28.38% overlaps, with a mean of 3.46 overlaps per parcel and a median overlap of 51.96 ha (IQR = 366.17). Although small properties were mostly registrations, they have lower overlaps, with a mean of 1.59 overlaps per parcel with a median overlap area of 1.08 ha. Spatial conflicts impacted 47.27% of the small properties.

Considering the biomes, in the Caatinga 32.99% of the mapped area has overlaps, with parcels averaging of 1.90 overlaps with a median overlapped area of 1.18 ha. On average, 41.45% of parcel area has overlaps. In the Cerrado, overlaps accounted for 32.97% of the total CAR area, with parcels averaging 1.42 overlaps with a median overlapped area of 1.32 ha, impacting 56.88% of the parcel's area. Our study found areas with intense land competition and boundary inconsistencies in the agricultural frontier zones of southwestern Piauí, across both the

Table 4
Descriptive statistics of CAR and RL overlaps in Piauí state for 2019 and 2025. The total area of the state of Piauí is approximately 25,152,900 ha. The gross area corresponds to the total area originally registered in the CAR dataset, while the net area represents the effective area after cleaning overlapping records under Rule A. We computed median and mean overlaps exclusively for parcels with spatial intersections. Values exceeding 100% occur when the cumulative area of overlapping registrations exceeds the parcel's own area, reflecting multiple competing claims on the same parcel. RL = Legal Reserve, sd = standard deviation, IQR = interquartile range, and mf = fiscal module.

Data	Num. records	Gross area (ha)	Net area (ha)	Area overlapped	Mean num. overlaps (sd)	Median area overlap (IQR) (ha)	Mean % parcel overlap
CAR 2019	141,011	13,618,659	11,514,879	15.45%	2.06 (2.50)	0.46 (3.26)	17.10%
RL 2019	127,197	3159,319	3015,890	4.54%	0.42 (1.02)	0.09 (0.88)	15.37%
CAR 2025	310,657	25,809,770	17,297,479	32.98%	1.69 (2.19)	1.23 (9.59)	48.10%
RL 2025	267,547	6295,350	5180,195	17.72%	0.65 (1.46)	0.26 (2.04)	29.58%
CAR 2025							
Small (< 4 mf)	299,429	8996,754	6906,893	23.23%	1.59 (1.58)	1.08 (8.14)	47.27%
Medium (4–15 mf)	8109	4085,083	2928,486	28.38%	3.46 (3.31)	51.96 (366.17)	53.05%
Large (> 15 mf)	3119	12,727,932	7462,009	41.38%	6.77 (13.80)	1356.02 (4033.69)	103.86%
Caatinga	168,796	11,794,620	7902,861	32,99%	1.90 (2.36)	1.18 (8.43)	41.45%
Cerrado	141,861	14,015,149	9394,618	32,97%	1.42 (1.93)	1.32 (11.65)	56.88%

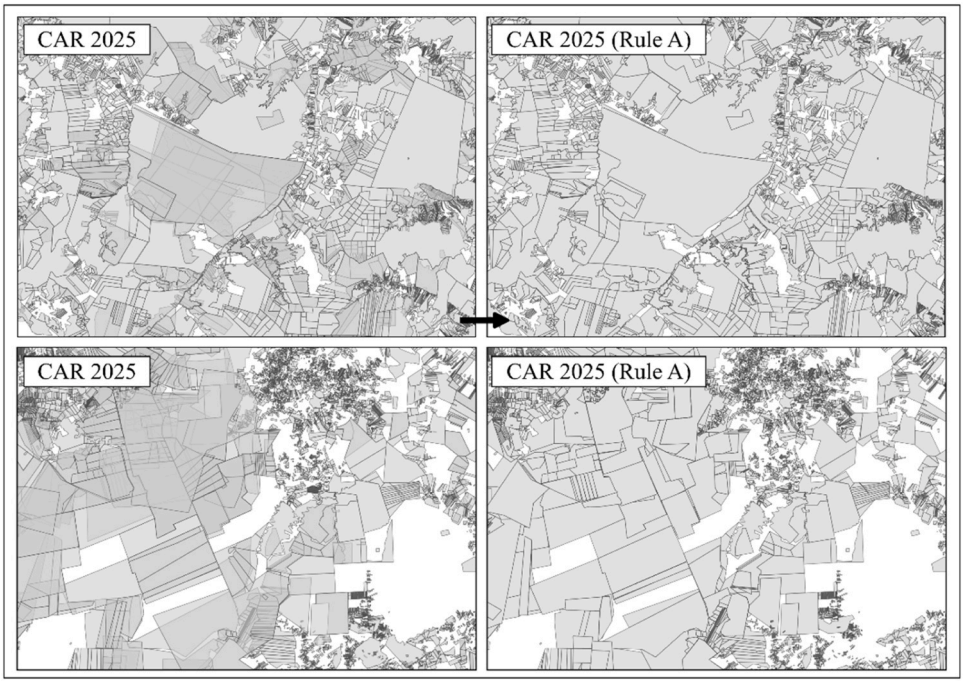


Fig. 3. Illustration of the spatial cleaning process showing intra-CAR overlaps (left) and the cleaned CAR dataset after applying Rule A (right) for two distinct areas.

Cerrado and Caatinga biomes (Fig. 4 A and 4B), where institutional enforcement capacity is comparatively weaker and cadastral conflicts are most persistent.

Statistically, we analyzed property overlaps in the 2025 CAR dataset and found they were more common in larger properties and areas with deforestation, as shown in Fig. 5. Poisson GLMs fitted to the 2025 dataset identifying property size as the strongest predictor of overlap intensity (Fig. 5A). The marginal effect of property area (Fig. 5B) showed a positive gradient within each size class, and the number of overlaps increased with parcel area ($p < 0.001$), even after centering by class means. Our findings show that size heterogeneity within property categories contributes to overlap persistence. Larger self-declared polygons are more closely associated with geometric inconsistencies or boundary disputes, a pattern consistent with strategic behavior rather than accidental boundary manipulation in high-value frontier land.

Areas with higher soybean production (Fig. 5C) showed no statistically significant association with overlap intensity ($p = 0.250$), indicating that the data do not support a systematic relationship between soybean production and overlap intensity in the 2025 CAR dataset. Protected lands (Fig. 5D) have a clear negative association with overlap intensity ($p < 0.01$). Properties in municipalities containing more conservation units or officially designated public lands tend to have less overlap. Deforested areas (Fig. 5E) have a strong positive association with overlap numbers ($p < 0.001$). Municipalities with more deforestation showed higher overlap intensity, indicating that land clearing and spatial conflicts tend to co-occur along agricultural frontiers.

3.2. *Updated land tenure map and land conflicts*

After applying Rules B – E, the consolidated private land tenure map comprises 272,671 parcels covering 18,453,366 ha. This tenure map was produced after resolving inter-dataset conflicts and harmonizing spatial and attribute information across CAR, SIGEF, SNCI, Terra Legal,

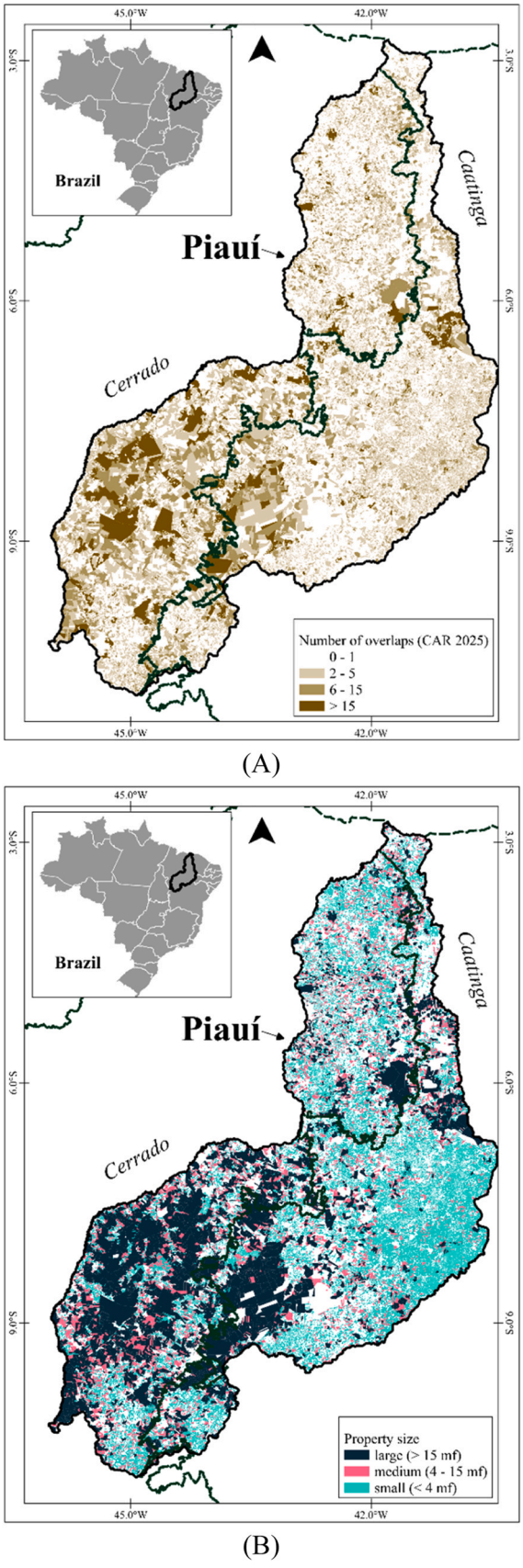


Fig. 4. (A) Number of competing land claims on self-declared properties in the state of Piauí in 2025. (B) CAR parcels in Piauí in 2025 classified by property size: large (> 15 fiscal modules), medium (4–15 fiscal modules), and small (< 4 fiscal modules).

and rural settlement datasets (Table 4). Together, SIGEF (27,036 parcels; 8.48 million ha), SNCI (640 parcels; 1.13 million ha), and Terra Legal (431 parcels; 7478 ha), along with legally established rural settlements (312 units; 824,442 ha), outline the formal and legally recognized structure of land tenure in Piauí. Our results show that 56.58% of the CAR area in 2025 (after applying Rule A) overlapped with INCRA's official land tenure datasets.

Despite such positive results, CAR-based properties that are not present in INCRA's database comprise 244,252 parcels and 8.0 million ha (Table 5). Although this CAR-only subset is proportionally smaller in area than the officially recognized datasets, its high number of self-declared records in the CAR-only dataset poses substantial challenges for validation, as each parcel requires individual assessment for spatial accuracy and legal consistency.

We compared our land tenure map with the public lands listed in Table 2 and found that large private properties contained a higher proportion of public lands (mean =19.20%; sd = 39.27%) than smaller ones. Large private properties are more likely to overlap with quilombola lands, conservation units, and other public domains. The combination of large territorial claims and uncertain cadastral boundaries produces land conflicts in which public areas constitute a significant share of the declared parcel. These patterns underscore the need to prioritize registration validation in areas where agricultural expansion and land-tenure disputes coincide.

Medium-sized properties show an intermediate public-land overlap (mean = 10.97%) with a high degree of dispersion (sd = 31.23%), while small properties had the lowest overlap (8.56%), though variability remained considerable (sd = 28.82%). Taking together, these patterns suggest that, despite lower mean proportions in small and medium properties, the wide standard deviations reflect heterogeneous conditions, ranging from parcels with no overlap to cases where public lands represent a substantial share of the property. These differences are consistent with the interpretation that land tenure uncertainties mainly affect larger properties, though the variability observed across all size categories warrants consideration within any Forest Code compliance framework.

The proportion of Permanent Preservation Areas (APPs) within private properties varied systematically across size categories (Table 5). Large properties showed the highest concentration of APP overlap, with a median of 10.15% of the parcel area affected (IQR = 10.16%), indicating high heterogeneity in how riparian buffers and other protected features intersect large private lands. Medium-sized properties presented intermediate values, with a median of 4.86% (IQR = 6.44%), and small properties showed a similar but slightly lower pattern, with a median of 4.22% (IQR = 5.78%).

3.3. *Deforestation patterns in Piauí, Brazil 2013–2023*

Between 2013 and 2023, PRODES data recorded a total of 1312,100 ha of native vegetation loss in Piauí across the Cerrado and Caatinga biomes. Using the updated private land tenure map produced after applying Rules A–E, we found that 94.20% of this loss (1236,100 ha) is associated with identifiable actors registered in at least one of the official land tenure datasets (Table 6, Fig. 6A). An unmatched 159,500 ha (12.20%) of PRODES-recorded deforestation could not be assigned to any registered tenure category. Cumulative attributed and unattributed shares marginally exceed the PRODES total because of residual geometric mismatches between the tenure and deforestation layers. Unattributed deforestation is concentrated along active deforestation frontiers where land regularization remains incomplete. Our results indicate that the reconstructed tenure map provides a consistent analytical basis for linking deforestation outcomes to specific categories of landowners across the state.

Among all identifiable actors, private properties registered in CAR, SIGEF, SNCI, and Terra Legal account for 86.60% of total PRODES deforestation (1135,800 ha). An additional 59,600 ha (4.50%) is

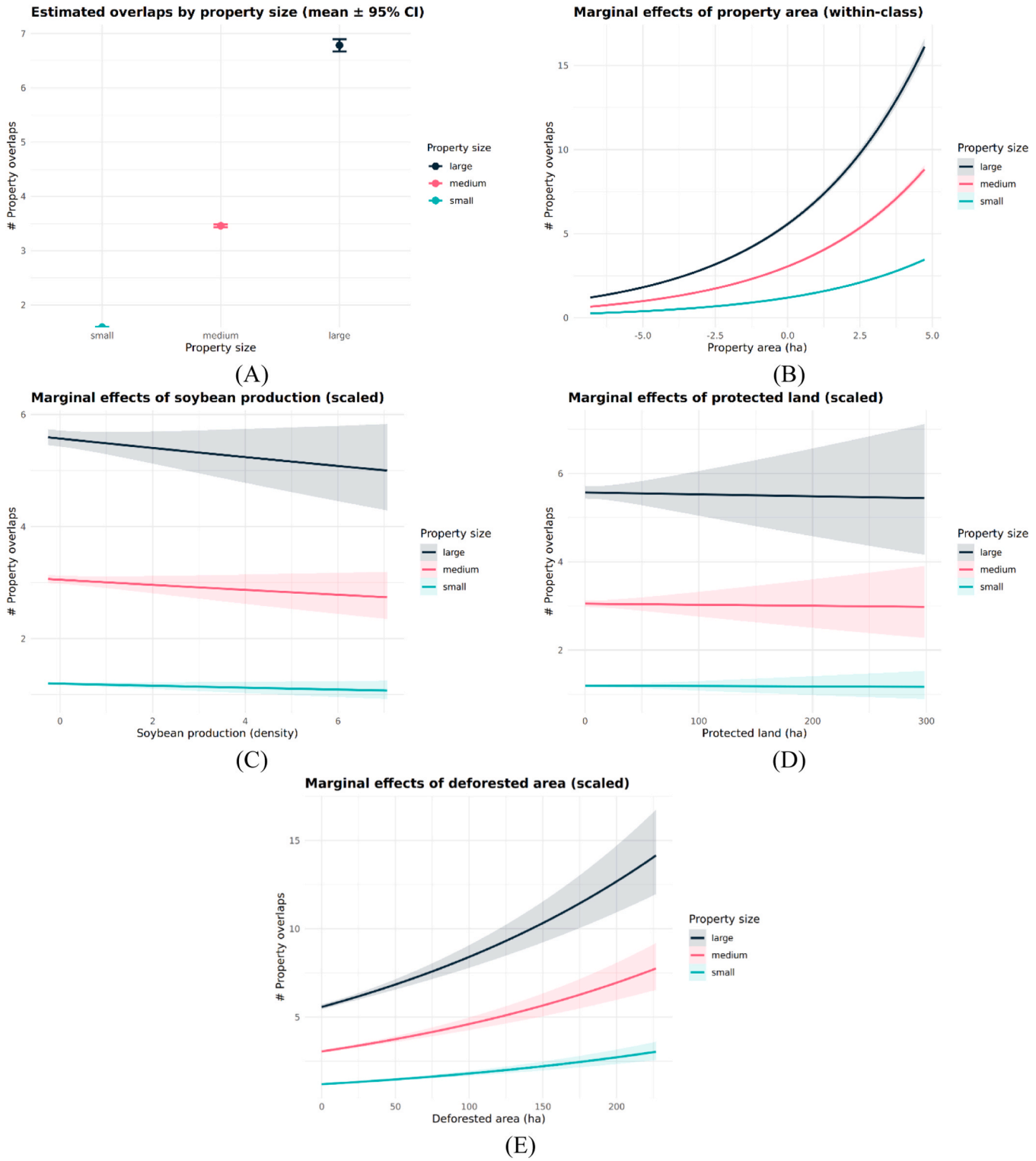


Fig. 5. Marginal effects of property area, soybean production, protected land, and deforested area on predicted overlaps in the 2025 CAR dataset (Poisson GLM). In panel (A), predicted number of property overlaps, with points showing averages and bars showing 95% CI. In panels (B – E), the predicted number of overlaps per property as a function of continuous predictors. The lines represent model-predicted marginal means, and the shaded regions indicate 95% confidence intervals.

associated with private properties overlapping conservation units, 24,200 ha (1.80%) with rural settlements, 14,900 ha (1.10%) with conservation units, and 1600 ha (0.10%) with indigenous and quilombola lands (Table 6). Breaking down private properties by data source, SIGEF-registered parcels are associated with 739,079 ha (56.33% of total PRODES loss), despite comprising a small fraction of total matched properties (26,232 out of 249,481), a pattern consistent with the concentration of larger agribusiness parcels among formally georeferenced records. CAR-only registrations, which represent most matched parcels (222,253), are associated with 341,964 ha (26.06% of total PRODES loss), reflecting their smaller average parcel size.

Disaggregating by property size (Table 7), large properties (> 15

Table 5
Distribution of rural properties and settlements in Piauí across categories in the final land tenure map, and corresponding distribution of APPs by property size. IQR = interquartile range, and mf = fiscal module.

Category	Number of Records	Total Area (ha)
CAR	244,252	8011,109
SIGEF	27,036	8476,876
SNCI	640	1133,459
Terra Legal	431	7478
Rural settlements	312	824,442
Total	272,671	18,453,366
Permanent Preservation Areas (APPs)		
	Median area overlap (%)	IQR (%)
Small (< 4 mf)	4.22%	5.78%
Medium (4–15 mf)	4.86%	6.44%
Large (> 15 mf)	10.15%	10.16%

Table 6
Attribution of PRODES deforestation in Piauí (2013–2023) by land tenure category. Percentages are calculated relative to total PRODES-recorded native vegetation loss in Piauí between 2013 and 2023 (1312,100 ha). The sum of category-level values (1395,600 ha) marginally exceeds the PRODES total because of residual geometric mismatches between the reconstructed tenure layer (Rules A–E) and the PRODES deforestation polygons; consequently, attributed and unattributed shares cumulatively exceed 100%.

Category	Deforestation (ha)	Deforestation (%)
Private lands (CAR, SIGEF, SNCI and Terra Legal)	1135,800	86.60%
Private lands overlapping conservation units	59,600	4.50%
Rural settlements	24,200	1.80%
Conservation units	14,900	1.10%
Indigenous and quilombola lands	1600	0.10%
Unattributed lands	159,500	12.20%
Total	1312,100	100%

fiscal modules) account for 49.20% of deforestation attributed to private properties over the study period (601,097 ha), comprising only 2702 records, fewer than 1.10% of all registered properties in the tenure map. Medium properties (4–15 fiscal modules) account for 22.10% (270,286 ha) across 7856 properties, while small properties (< 4 fiscal modules) account for 28.60% (349,237 ha) across 238,923 properties. A concentration analysis shows that the top 1% of properties ranked by cumulative deforestation (approximately 2495 properties) account for 71.50% of all vegetation loss recorded within private land between 2013 and 2023 (873,191 ha), while the top 5% account for 85.80% (1047,808 ha) (Fig. 6B). Our findings indicate a pronounced concentration of vegetation loss among a numerically small set of large properties, consistent with the tenure structure of Piauí's agricultural frontier.

Of the total deforestation associated with private properties, 73.40% (834,000 ha) is classified as illegal under the Forest Code framework applied in this analysis. Legal Reserve deficit violations represent the dominant source of illegality, accounting for 98.40% of all illegal deforestation in private land, with APP violations contributing 5.10%, and protected lands violations 0.78%. The share of illegal deforestation within each size category is broadly consistent. Large properties show an illegal rate of 53.50%, medium properties 51.70%, and small properties 56.50%. These results indicate that non-compliance with Forest Code requirements is not confined to a specific tenure category but is a widespread pattern across the private land sector in Piauí.

PRODES identifies 14,093,364 ha of native vegetation in Piauí, while MapBiomas estimates 14,752,414 ha, a difference of 659,050 ha. This divergence reflects intrinsic methodological differences between the two monitoring systems, compounded by the challenges of classifying seasonally dynamic vegetation in semiarid and savanna landscapes. In regions where phenological cycles drive rapid transitions between green and senescent states, spectral signals fluctuate in ways that complicate the separation between native vegetation and non-forest land covers (Spera et al., 2016; Parreiras et al., 2025). All deforestation attribution results presented in our results rely on PRODES as the primary reference dataset, consistent with its designation as the official deforestation monitoring system underpinning Brazil's 2030 deforestation targets.

Furthermore, PRODES data indicate that 13,107,567 ha of native vegetation remain on private lands in Piauí, substantially higher than the 5180,195 ha self-reported as Legal Reserve area in 2025 CAR declarations after applying Rule A (Table 5). Disaggregated by property size, large properties account for 5606,524 ha, medium properties for 2784,576 ha, and small properties for 4689,380 ha of PRODES-estimated native vegetation. The discrepancy between remotely sensed vegetation cover and self-declared RL area is consistent across all size categories, indicating that a substantial share of native vegetation on private land is not formally declared under the RL mechanism in the CAR system. This pattern is consistent with the practice of declaring only the minimum legally required RL area, with additional native cover remaining unreported within the cadastral system.

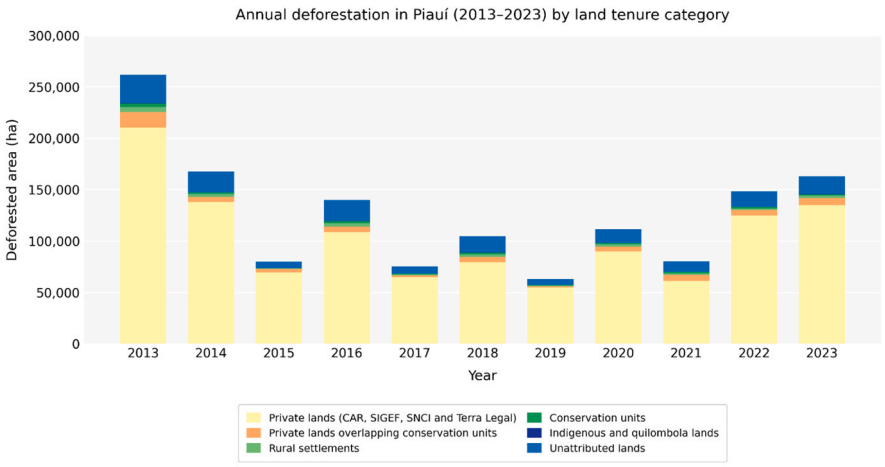
Table 8 shows the distribution of Legal Reserve deficits and surpluses across biomes and property size categories in Piauí. In the Caatinga biome, small properties account for the largest number of RL deficit records, with 64,442 properties presenting a cumulative shortfall of 2305,817 ha. Medium properties in the Caatinga contribute 1818 deficit records (893,091 ha), while large properties account for 631 deficit records but a disproportionately high cumulative shortfall of 2179,169 ha. In the Cerrado biome, small properties represent the largest share of deficit records (46,882 records; 1886,209 ha), while medium and large properties show fewer deficit records but substantially larger per-property shortfalls. Cerrado large properties in deficit account for 3855,627 ha of unfulfilled RL obligation, the largest single shortfall category across both biomes. These results indicate that, while RL non-compliance is widespread across all size categories, the aggregate area of unfulfilled legal obligation is concentrated among large properties, particularly in the Cerrado, mirroring the deforestation concentration reported in Table 7 and underscoring the centrality of large-property governance for Forest Code implementation in Piauí.

4. Discussion

4.1. From intra-CAR overlap trends to policy implementation

The central finding of this study is that cadastral inconsistencies and deforestation attribution are separable problems. Overlaps can be resolved through a hierarchical conflict-resolution framework, and the resulting tenure map remains sufficiently reliable to attribute 94.20% of vegetation loss to identifiable actors. Thus, a substantial portion of CAR declarations match legally recognized properties, and INCRA's records provide a useful spatial baseline for validating CAR land claims. Our result indicates that, although the CAR has been associated with land grabbing risks and inconsistencies, a significant share of its self-declared polygons is spatially coherent and consistent with officially recognized land records, a finding that supports the analytical usability of the reconstructed dataset for environmental governance and the implementation of the Brazilian Forest Code. Therefore, CAR's limitations are not a reason to dismiss it as a governance instrument, but rather a reason to invest in the methodological infrastructure needed to extract its analytical potential.

In Brazil, the CAR system has reshaped how deforestation is monitored and controlled at the property level. Although CAR operates as the official environmental self-declaration registry and plays a central role in regulating the distribution of ecological service benefits within emerging green-economy markets, relevant trade-offs persist (Freitas et al., 2018). The large volume of information generated through a self-declared mechanism often comes at the expense of data quality and



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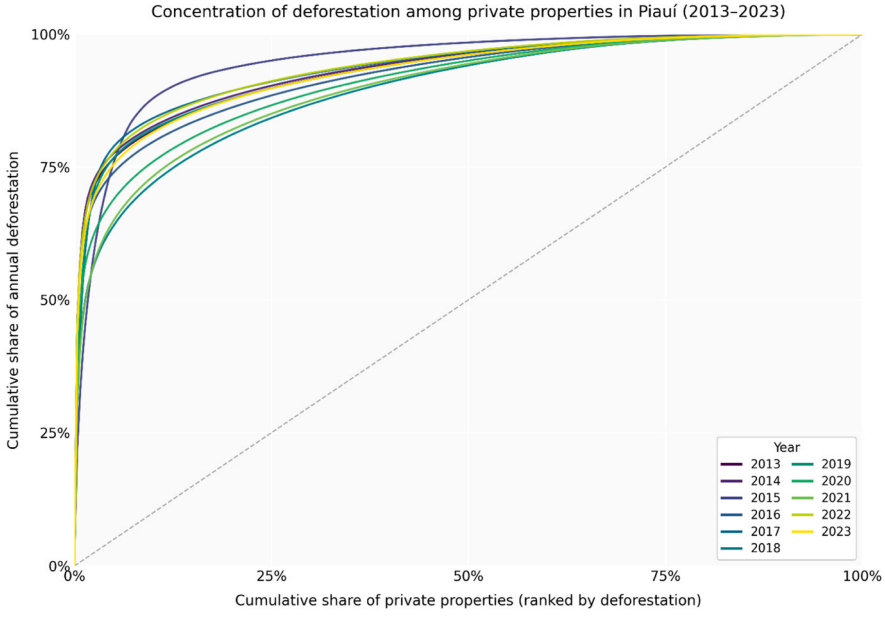

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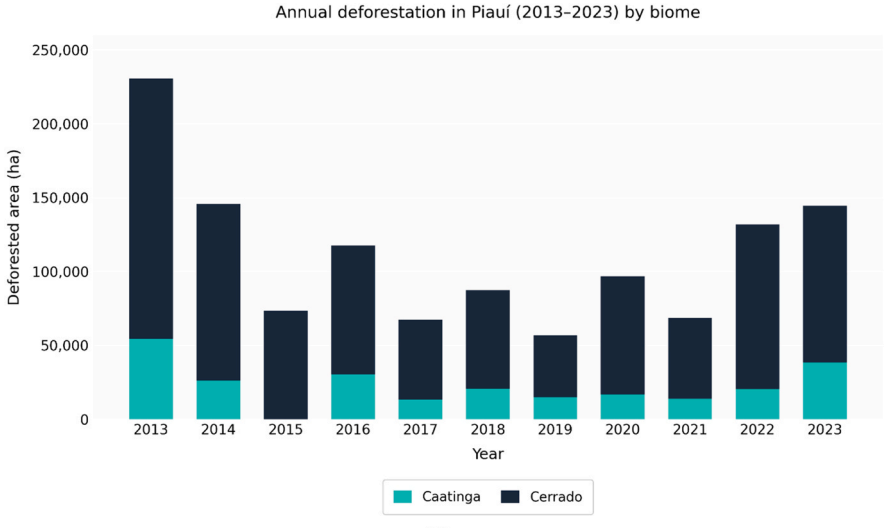

(C)

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Fig. 6. Annual deforestation in Piauí (2013–2023) attributed to private properties, disaggregated by land tenure category (A), concentration among private landowners (B), and biome (C). (A) Stacked bars show deforestation by land tenure category: private lands (CAR, SIGEF, SNCI, and Terra Legal), private lands overlapping conservation units, rural settlements, conservation units, indigenous and quilombola lands, and unattributed lands. (B) Lorenz curves of deforestation concentration among private properties, with one curve per year; properties are ranked by cumulative vegetation loss, and the distance from the line of equality indicates the degree of concentration within a small fraction of landowners. (C) Annual deforestation disaggregated by biome (Cerrado and Caatinga), highlighting the predominance of forest loss in the Cerrado's agricultural frontier along the MATOPIBA corridor.

Table 7
Deforestation attributed to private properties in Piauí (2013–2023), disaggregated by property size category. Illegal deforestation includes violations of Legal Reserve, APP, and protected lands requirements under the Forest Code. Property counts (n) refer to records with at least one PRODES deforestation event detected between 2013 and 2023, and do not correspond to the total number of records in the land tenure map (272,671 records in Table 5).

Category	Properties (n)	Deforestation (ha)	Deforestation (%)	Illegal deforestation (ha)	Illegal rate (%)
Small (< 4 mf)	238,923	349,237	28.60%	197,386	56.52%
Medium (4–15 mf)	7856	270,286	22.10%	139,775	51.71%
Large (> 15 mf)	2702	601,097	49.20%	321,833	53.54%
Total	249,481	1220,620	100%	659,994	54.07%

Table 8
Legal Reserve deficits and surpluses across private properties in Piauí, disaggregated by biome and property size category. Surplus and deficit status reflects the Legal Reserve balance as of 2023. RL = Legal Reserve.

Biome	Property size	RL	Records	Area (ha)
Caatinga	Small (< 4 mf)	Deficit	64,442	2305,817
		Surplus	73,072	1660,328
	Medium (4–15 mf)	Deficit	1818	893,091
		Surplus	767	399,022
	Large (> 15 mf)	Deficit	631	2179,169
		Surplus	255	925,194
Cerrado	Small (< 4 mf)	Deficit	46,882	1886,209
		Surplus	54,527	1173,822
	Medium (4–15 mf)	Deficit	4233	1934,575
		Surplus	1038	483,797
	Large (> 15 mf)	Deficit	1586	3855,627
		Surplus	230	625,982

consistency (Azevedo et al., 2017; Freitas et al., 2017). These trade-offs, however, do not render the system analytically intractable.

Temporal trends in boundary rectifications reveal a pattern that is difficult to reconcile with a purely technical interpretation based on measurement error. The magnitude and directionality of the changes observed, systematically skewed toward area gains, and concentrated among larger properties, are consistent with strategic boundary manipulation in a context where cadastral validation is weak and land values are rising rapidly. Our results suggest that regions with established farming activities, stronger market connections, and more structured land ownership tend to have clearer property boundaries and fewer spatial disputes. Furthermore, well-defined institutional boundaries help stabilize the cadastral system by reducing ambiguity in land allocation and discouraging speculative claims. In Piauí's Cerrado frontier, where the MATOPIBA corridor has driven sustained soybean expansion, the incentive to register and expand landholdings ahead of regularization is particularly strong. The Cerrado–Caatinga transition zone that characterizes Piauí creates distinct cadastral dynamics relative to the Legal Amazon, as the absence of FUNAI-enforced indigenous territory boundaries and the comparatively recent arrival of capital-intensive agriculture produce a landscape in which boundary manipulation is both possible and economically rewarding (Costa et al., 2024).

Furthermore, the patterns documented here extend beyond Piauí's specific frontier context. Furumo et al. (2024), reported persistent overlaps in CAR records throughout the Legal Amazon, a region with a substantially different land tenure history and institutional landscape. The convergence of evidence across such distinct socio-ecological settings suggests that spatial inconsistencies in self-declared registries are a structural feature of Brazil's land governance architecture, rather than a regional artifact. The attribution framework developed here provides a direct operational response to this structural challenge. By linking deforestation events to specific tenure categories and data sources, the method enables agencies to prioritize field inspections toward properties with detected cadastral conflicts and associated vegetation loss, concentrating enforcement capacity where regulatory risk is demonstrably highest. This mechanism operates through a clear pathway: improved CAR data quality leads to spatially targeted inspections, which in turn reduce deforestation risk and strengthen the evidentiary basis for legal action. This pathway is directly relevant to the enforcement instruments established under Brazil's Climate Plan 2024–2035, which designates CAR-based property attribution as a key action for achieving the country's 2030 deforestation targets under the NDC. In this sense, the present study contributes not only to an analytical method but also a scalable implementation pathway for subnational enforcement agencies.

In 2025, the Brazilian federal government introduced a new platform called My Rural Property (*Meu Imóvel Rural*), which integrates all properties registered in the SIGEF, SNCR, and CAR systems into a single, consolidated interface. This initiative directly addresses the type of inter-registry inconsistency documented in this study. By consolidating the same authoritative data sources used in the tenure reconstruction framework developed here, the platform creates institutional conditions for systematic overlap detection and resolution at the national scale. The adoption of consistent georeferencing standards across registries is expected to reduce the parcel overlaps documented above, which are currently concentrated among larger properties in frontier expansion zones. As emphasized by Mastrangelo et al. (2026), the elimination of such overlaps is a precondition for strengthening land tenure security and increasing compliance with the Forest Code, objectives that are also central to Brazil's 2030 deforestation targets (Brazil, Ministry of Environment and Climate Change. 2026).

Piauí has become a major soybean exporter, with export-driven agricultural expansion sustained over the past decade, primarily directed toward Chinese markets. In 2024, soybean farms covered 1080,496 ha, reinforcing the dominance of large-scale monoculture systems across the state. This trajectory of rapid agricultural growth is associated with growing pressures on Forest Code compliance, as agribusiness frontiers expand into areas where cadastral regularization remains incomplete. The convergence of expanding commodity production and unresolved tenure conflicts, documented here through overlap patterns and deforestation attribution, underscores the importance of aligning Piauí's agrarian development trajectory with the legal obligations of the Forest Code.

Previous studies establish that deforestation in Brazil's agricultural frontiers is typically associated with land clearing for speculation or extensive cattle ranching (Lambin et al., 2018; Silva et al., 2023; Oliveira et al., 2025). These initial stages of land conversion tend to exploit the vulnerabilities of frontier regions, where tenure insecurity due to

cadastral uncertainties are most pronounced, and institutional governance is at its weakest. As multiple claimants compete for newly opened lands that lack legal enforcement, cadastral conflicts and vegetation loss tend to intensify simultaneously. Soybean production moves into these landscapes only after they become consolidated and regularized for mechanized cultivation (Macedo et al., 2012; Ermgassen et al., 2020; Villoria et al., 2022). These dynamics are consistent with the patterns documented in this study, in which overlap intensity and deforestation rates are both concentrated in areas of incomplete cadastral regularization. Therefore, reliable land tenure records and consistent CAR validation are operational prerequisites for effective deforestation governance in Brazil's agricultural frontier zones.

4.2. Linking trajectories of land use in land tenure

Our analysis reveals that CAR inconsistencies and tenure conflicts in Piauí are spatially concentrated along the agribusiness frontier. Particularly, the patterns identified across our results reflect a compound dynamic of cadastral weakness, rapid land conversion, and incomplete regularization, precisely the conditions under which the reliability of the CAR system is most contested.

Brazil faces considerable challenges in addressing deforestation across its biomes under pressure from expanding agricultural frontiers. Public authorities need to ensure comprehensive land tenure regularization and systematic validation of CAR data at the subnational level. In states like Piauí, where frontier expansion intersects with heterogeneous tenure structures, the effectiveness of environmental policy depends on the capacity of state agencies to reconcile enforcement, monitoring, and cadastral infrastructure (Costa et al., 2024; Martins et al., 2024). This coordinated approach is vital for ensuring that regulatory efforts align with on-the-ground realities, thereby enhancing both land governance and conservation outcomes.

Unlike the Legal Amazon, where frontier governance dynamics have been more extensively examined in the literature, Piauí's Cerrado–Caatinga transition zone presents a distinct institutional configuration: historical smallholder occupation overlapping with recent large-scale capitalist expansion, comparatively weaker subnational enforcement capacity, and a land market structure that creates qualitatively different pressures on CAR-based environmental compliance.

Our results show that land tenure arrangements are a central determinant of land use policy in Piauí. Deforestation is concentrated in private properties, which accounted for 86.60% of total vegetation loss between 2013 and 2023, and forest loss is concentrated on large holdings along the corridors of agribusiness activity. Vegetation conversion is strongly associated with ownership patterns and to the economic strategies that drive territorial expansion (Faria et al., 2025). Our findings align with broader evidence from Brazil's agricultural frontiers. Deforestation surges are driven by capital-intensive producers operating in contexts of fragile regulatory control and comparatively low land prices. In these frontier regions, the acquisition of large tracts at reduced cost creates strong incentives for rapid conversion of native vegetation. Such practices are often employed both to establish ownership claims and to expedite the economic appreciation of recently acquired properties (Carneiro et al., 2024; Monaco et al., 2024). Critically, our attribution analysis indicates that 94.20% of deforestation between 2013 and 2023 is associated with identifiable actors registered in the CAR system, and that the top 1% of properties by area account for 71.50% of total vegetation loss, a distributional pattern that reveals the systemic rather than incidental character of large-scale deforestation in Piauí. These figures constitute associations grounded in the spatial overlay of PRODES data and CAR registrations, rather than direct causal attributions.

The ongoing interplay between frontier expansion, land accumulation, and the resulting loss of native vegetation highlights the importance of effective CAR-based regulation. As agricultural frontiers advance and land markets become increasingly active, particularly in areas marked by tenure uncertainties, the strategic clearing of native vegetation emerges as a significant risk. In this context, a fully operational and consistently validated CAR system, rigorously enforced, is indispensable for preventing such opportunistic behavior and for upholding the integrity of environmental compliance mechanisms. Ensuring the effectiveness of CAR-based regulation is not only essential for curbing illegal deforestation but also for maintaining the credibility of Brazil's wider conservation policy framework, especially in regions where land market activity and unclear tenure arrangements heighten the risk of environmental non-compliance. Strengthening this regulatory architecture requires coordinated action across governance levels, including enhanced state-level enforcement capacity, interoperability between federal and subnational cadastral systems, and rural credit conditionalities tied to verified CAR compliance.

5. Conclusion

On a global scale, forest governance relies on different regulatory frameworks. Most of these regulations are driven by commercial concerns and not by the need for mitigating greenhouse gas emissions and preserving biodiversity. Brazil's Forest Code stands out as a powerful regulation designed to promote sustainability and to protect the environment. Its adoption in 2012, following a contested legislative process, reflected competing interests among agribusiness, conservation advocates, and smallholder representatives, and its implementation has since revealed structural tensions between land governance capacity and enforcement demands. The Forest Code distinguishes itself by establishing mandatory conservation requirements for private landholders, including quotas that ensure the preservation of native vegetation and the protection of riparian zones as well as other ecologically sensitive areas. These legal safeguards function as foundational mechanisms for stabilizing carbon stocks across the country's diverse biomes. Despite the challenges posed by its overlaps and inconsistencies, CAR is a unique legal instrument, providing a nationwide platform capable of integrating property-level information, land tenure governance, and environmental regulation. By linking individual landowners to conservation obligations, the CAR provides the structural capacity to address emissions from land-use change, reinforcing Brazil's strategy for balancing agricultural expansion with environmental stewardship. Our results indicate that, despite documented inconsistencies, a substantial share of the CAR dataset in Piauí remains procedurally reliable and analytically usable, providing a functional basis for environmental monitoring and Forest Code compliance, provided that targeted validation efforts are directed toward high-conflict frontier zones.

Our analysis investigated the implementation of the Forest Code at the subnational level, focusing specifically on the state of Piauí. We assessed the extent and spatial distribution of intra-CAR overlaps and identified the magnitude of conflicts between CAR registrations and other public land datasets. Our work also tracked the trajectories of deforestation across different categories of private lands. By integrating these perspectives, our study shows how cadastral inconsistencies, land tenure disputes, and ongoing agricultural expansion collectively influence the effectiveness of the Forest Code in Brazil. This multidimensional approach highlights the complexity of land governance in frontier regions, where overlapping claims and rapid land use changes can undermine regulatory compliance. The persistence of such inconsistencies is not exclusively a technical or methodological problem. Speculative CAR registration, strategic use of regularization instruments, and unequal access to land governance mechanisms may reflect deliberate rather than accidental dynamics, underscoring the importance of addressing the institutional and political dimensions of land governance alongside data quality improvements.

The attribution framework developed in this study demonstrates that the analytical limitations of a self-declared land registry need not preclude its operational use for deforestation governance. By combining hierarchical conflict resolution with spatially explicit tenure

reconstruction, the methodology enabled the attribution of 94.20% of vegetation loss to identifiable actors, revealing a highly concentrated distributional structure in which the top 1% of properties ranked by deforestation account for 71.50% of total vegetation loss between 2013 and 2023. This concentration pattern provides enforcement agencies with a tractable basis for spatially targeting inspections and directing regulatory action toward the numerically small set of landowners responsible for the bulk of non-compliance. The approach is directly applicable to the enforcement instruments established under Brazil's Climate Plan 2024–2035, which designates CAR-based property attribution as a key mechanism for achieving the country's 2030 deforestation targets under the NDC. Therefore, analytical tools for interpreting CAR data, such as those presented in this work, are critical for improving land-tenure governance and supporting the implementation of the Forest Code, not only in Piauí but also throughout Brazil. Strengthening the analytical infrastructure underpinning CAR is not merely a data quality objective; it is a precondition for translating environmental legislation into verifiable compliance outcomes across Brazil's diverse frontier landscapes.

This study contributes theoretically by demonstrating how a self-declared land registry with structural inconsistencies can be rendered analytically tractable through a hierarchical conflict-resolution framework. From a practical perspective, it provides a scalable method to reconstruct land tenure and attribute deforestation to specific actors, offering a basis for more targeted enforcement and monitoring under the Brazilian Forest Code. By identifying spatial concentrations of both cadastral conflicts and deforestation, the framework supports the prioritization of validation efforts in high-risk areas, enhancing the effectiveness of land governance in frontier regions.

CRediT authorship contribution statement

Rolf Simões: Writing – review & editing, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Gilberto Câmara:** Writing – review & editing, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Giovana Mira de Espindola:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Daihana Soledad Argibay:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Vicente de Paula Sousa Júnior:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All funding sources acknowledged in the manuscript were provided through institutional research agreements that did not involve any role in the study design; data collection, analysis, or interpretation; writing of the manuscript; or the decision to submit the article for publication. The authors affirm that no conflicts of interest, whether financial, institutional, or personal, influenced the conduct or reporting of this research.

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Data availability

The data that support the findings of this study are openly available at the following URL: https://doi.org/10.5281/zenodo.17712678

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