

Article

Land-Tenure Dynamics and Deforestation Pressure in MATOPIBA, Brazil: An Assessment of the Rural Environmental Registry (CAR), 2019–2025

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Abstract

Agricultural expansion in frontier regions is reshaping land-tenure arrangements and accelerating native vegetation loss, posing significant challenges to territorial governance. MATOPIBA, Brazil, epitomizes this dynamic, concentrating long-standing tensions between agribusiness expansion and environmental conservation in the Cerrado biome. This study examines how the Rural Environmental Registry (CAR) reflects these pressures by analyzing property records from 2019 and 2025, mapping overlaps with public lands, and quantifying vegetation change between 1985 and 2024 to evaluate CAR's potential as a territorial governance instrument. We integrated public datasets, applying geometry validation and cadastral hierarchization procedures. Between 2019 and 2025, registered properties nearly doubled, rising from 7734 to 14,231. Overlaps with protected and public lands were identified, and native vegetation declined by 38.12% over the study period, with losses recorded in approximately 75% of the properties analyzed. These findings indicate that CAR holds significant potential for territorial and environmental governance, but its effectiveness depends on continuous data validation, institutional integration, and strengthened conservation policies.

Keywords: rural environmental registry; land use rights; deforestation; social–ecological resilience; agricultural frontier; MATOPIBA

1. Introduction

Changes in land use and the expansion of agricultural areas have become salient topics in international sustainability debates, particularly in regions where rapid economic growth coincides with social and environmental concerns [1,2]. Globally, agricultural expansion tends to intensify pressures on natural ecosystems, reshape land-tenure arrangements, and alter rural livelihoods. These shifts often generate complex territorial configurations and pose challenges for governing these processes in a fair and efficient manner [3–5].

Within this context, frontier regions are critical settings for understanding the interplay among agricultural production, environmental conservation, and social justice. For the purposes of this study, frontier regions can be understood as territories undergoing rapid land-use transitions in which capitalist agriculture advances into areas previously dominated by natural ecosystems or by traditional and smallholder land-use systems, typically under conditions of weak land governance, incomplete tenure regularization,



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and contested property claims [6,7]. Such areas commonly face constraints stemming from institutional fragility, land disputes, and the coexistence of diverse land uses [8–12]. They encompass large-scale agribusiness estates, smallholder family farms, and traditional resource-use practices. Consequently, land governance has become a central issue to ensure more sustainable territorial use and to prevent conflicts over land rights, access, and protection [13–16].

Brazil plays a pivotal role globally due to its agricultural output and extraordinary biological and cultural diversity. In recent years, the country has undergone significant land-use changes, particularly in the Cerrado and the Amazon. Agricultural expansion in these biomes has reshaped landscapes, affected ecosystems, and influenced social relations [17–21]. These transformations have intensified debates on sustainability, environmental conservation, and appropriate pathways for rural development [22,23].

Against this broader context, the MATOPIBA region, comprising portions of Maranhão, Tocantins, Piauí, and Bahia, has consolidated itself as a major agricultural production area in recent years. This expansion has been driven by technological advances, infrastructure growth, and tighter integration with international commodity markets [24–26]. Its relevance as a research subject is grounded in a well-documented set of quantitative markers. Between 2000 and the early 2020s, the soybean-cultivated area in MATOPIBA expanded several-fold, rising from approximately one to more than six million hectares, consolidating the region as the most dynamic agricultural frontier within the Cerrado biome [27,28]. In recent years, MATOPIBA has consistently recorded among the highest annual deforestation rates in the Cerrado, accounting for a substantial share of biome-wide native-vegetation loss reported by PRODES and MapBiomas [27,28]. The region also concentrates a high incidence of documented land-tenure conflicts involving traditional communities, family farmers, and commercial agribusiness fronts. Taken together, these markers justify the selection of MATOPIBA as the empirical focus of the present study. At the same time, the region concentrates multiple land-use systems and social groups, including traditional communities, family farmers, and large agribusiness companies, forming a complex territorial mosaic [29,30].

These dynamics are closely linked to land-tenure regimes, statutory frameworks, and modalities of environmental control. Instruments such as rural land registries, land-use/land-cover (LULC) maps, and environmental management policies have gained prominence for organizing land use and mediating competing interests, understood here as the often-divergent claims and priorities asserted by agribusiness operators, smallholders, traditional and indigenous communities, environmental agencies, and land-tenure authorities over the same territorial space [31–33]. However, their effectiveness is highly context-dependent, varying with governance capacity, institutional arrangements, and local socio-environmental conditions [34].

Concurrently, land-use change in frontier areas is commonly associated with environmental transformations, including vegetation loss, habitat fragmentation, and alterations to ecosystem services [35–38]. These processes directly affect the livelihoods of populations dependent on natural resources and undermine the resilience of local social–ecological systems, especially where communities rely on these resources for subsistence and cultural continuity [39–41].

Understanding these interactions requires an integrated, cross-disciplinary approach that links land governance, environmental change, and social dynamics. Recent scholarship underscores that achieving sustainable development in agricultural frontier regions depends on balancing production, conservation, and social inclusion through adaptive governance and participatory land-management strategies [42–45].

In this context, MATOPIBA offers a salient case for examining how land-use change, land-governance arrangements, and environmental transformations are interrelated. By analyzing both historical trajectories and current dynamics, one can obtain a clearer view of the challenges and opportunities involved in reconciling agricultural expansion, environmental stewardship, and the sustainable governance of natural resources in Brazil's Cerrado.

Accordingly, this study aims to characterize land-tenure dynamics and deforestation pressure in the MATOPIBA region by analyzing the temporal evolution of Rural Environmental Registry (CAR) records between 2019 and 2025, identifying land-tenure overlaps with public lands, and quantifying native vegetation loss between 1985 and 2024. In doing so, it assesses the extent to which CAR data, once geometrically validated and integrated with official cadasters following hierarchical rules, can serve as a reliable indicator of territorial governance challenges in an agricultural frontier context. The findings are intended to inform federal and state environmental institutions, land-tenure authorities, researchers working on land-use science and territorial governance, and civil society organizations engaged in Cerrado conservation and in the monitoring of socio-environmental conflicts.

Three limitations bound the scope of this study and should be acknowledged upfront. First, the Rural Environmental Registry is a declaratory instrument, which means that the reliability of its records depends on the information self-declared by landholders and on the institutional capacity of the competent environmental agencies to validate those declarations; registered boundaries may therefore not correspond exactly to on-the-ground occupation. Second, the six municipalities analyzed were purposively selected for representing the consolidated soy-expansion core of MATOPIBA in Maranhão and Piauí and should not be read as capturing the full internal heterogeneity of the MATOPIBA region, which also encompasses distinct dynamics in Tocantins and Bahia. Third, the cross-referencing of CAR with SIGEF, SSCI, CNFP, and protected-area boundaries is sensitive to the temporal alignment of each database; consequently, the overlaps reported here are to be interpreted as indicators of potential irregularities rather than as definitive evidence of illegal occupation, since technical georeferencing errors, administrative inconsistencies, and substantive land-tenure conflicts cannot always be distinguished without case-by-case investigation.

2. Materials and Methods

2.1. Study Area

This study was conducted across six municipalities in the states of Maranhão and Piauí, within the region known as MATOPIBA, which in recent years has emerged as one of Brazil's most dynamic frontiers of agricultural expansion. In Maranhão, the municipalities examined were Balsas (approximately 101,767 inhabitants), Riachão (approximately 22,145), and Tasso Fragoso (approximately 8862). In Piauí, the study encompassed Baixa Grande do Ribeiro (13,272 inhabitants), Ribeiro Gonçalves (6164), and Uruçuí (approximately 25,203), as shown in Figure 1. The selection of these locations was purposive: all exhibit significant export-oriented soybean production and are undergoing substantial territorial reconfigurations driven by the influx of farmers seeking fertile soils and new economic opportunities.

Migration flows and large-scale agribusiness investments have driven profound changes in landscapes and in local socio-environmental relations. The study area lies in an ecological transition zone (ecotone) between the Cerrado and Caatinga biomes, characterized by vegetation types that include savannas, dry forests, and seasonal forests. The climate is tropical, with average temperatures ranging from 27 °C to 42 °C throughout the year. Precipitation exhibits a well-defined seasonality: the wet season extends from November to April, whereas the dry season spans May to October. These climatic conditions, together with regional topography and vegetation, have shaped local agricultural

practices, favoring rainfed soybean cultivation (non-irrigated), according to 2022 data from the Brazilian Institute of Geography and Statistics (IBGE).

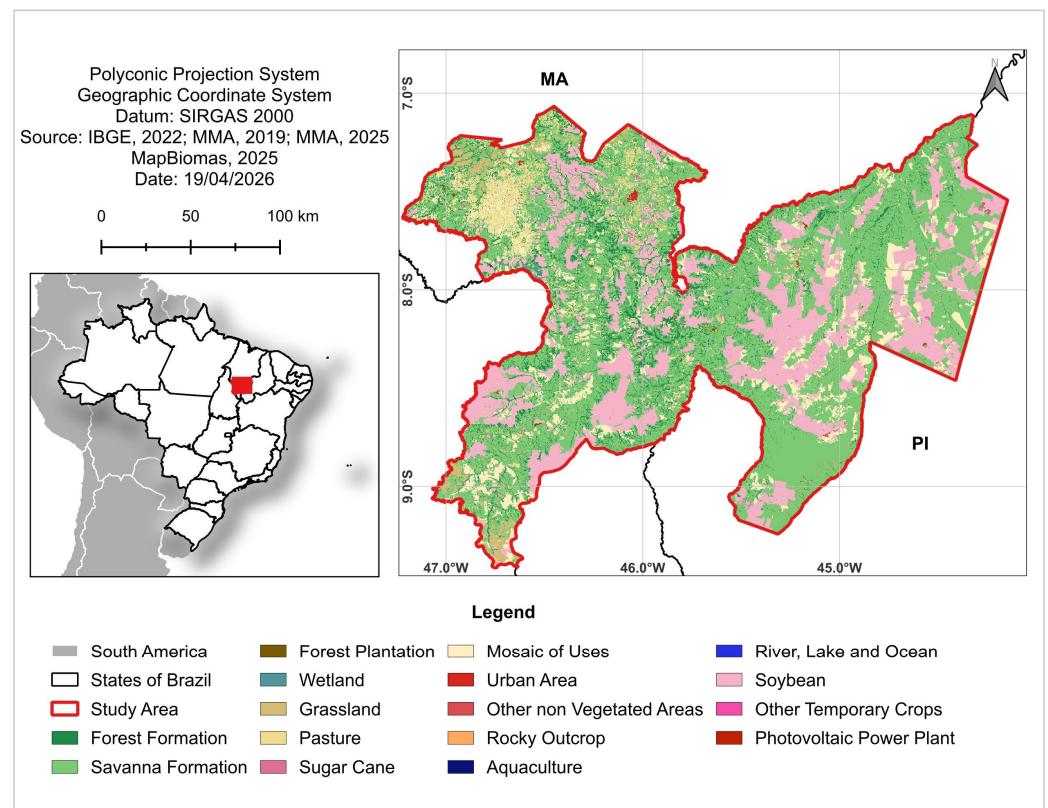


Figure 1. Study area location map with land-use/land-cover (LULC) data from the MapBiomass Project (Collection 10) for 2025.

The Parnaíba River, present across most of these municipalities, has been instrumental to the region's agricultural development, supplying water for irrigation and facilitating territorial occupation. Besides soybean, a variety of crops adapt to local conditions, including rice, maize, beans, cashew, cotton, and sugarcane [46]. Alongside mechanized agriculture, local communities continue to practice traditional forms of natural resource extraction. Products such as babassu oil [47], carnauba wax, and buriti fruits [48] illustrate the region's cultural and ecological richness. In addition, activities such as timber extraction, charcoal production, and apiculture remain important sources of income for rural residents [46].

2.2. Data Collection

To assess land-tenure dynamics and deforestation pressure in the MATOPIBA region, we relied on a suite of public datasets produced by Brazilian institutions, following the methodological approach of Camara et al. [49], as summarized in Figure 2, which presents the public databases used to implement this study's methodology.

Information on political-administrative boundaries, biome limits, and special territories was obtained from the Brazilian Institute of Geography and Statistics (IBGE). Land-tenure data were organized into two major groups: (i) datasets from the National Institute for Colonization and Agrarian Reform (INCRA) and (ii) records from the Rural Environmental Registry (CAR/MGI). For CAR, two temporal snapshots were considered—2019 and April 2025—covering registered rural properties and their respective declared legal reserves. Permanent Preservation Areas (APPs) were compiled through technical cooperation between the Brazilian Forest Service (SFB) and the Brazilian Foundation for Sustainable Development (FBDS) [49].

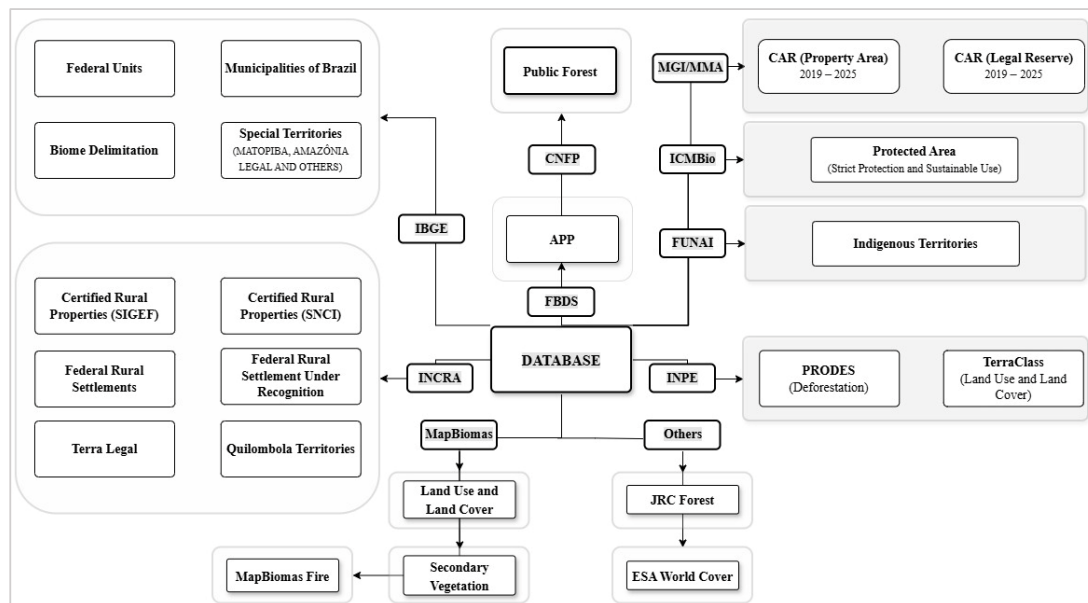


Figure 2. Open datasets used, with detailed sources and data-type classification.

With respect to public lands, we used data on Protected Areas from the Chico Mendes Institute for Biodiversity Conservation (ICMBio); Indigenous Territories from the National Foundation of Indigenous Peoples (FUNAI); Quilombola Territories and Rural Settlements from INCRA; and Public Forests from the National Register of Public Forests (CNFP). These geospatial datasets enable the delineation of public and private properties, as well as the linkage of environmental information declared via CAR to each rural property [49].

Complementarily, land-use/land-cover (LULC) data were obtained from multiple sources. MapBiomass Collection 10 was adopted as the primary dataset for the vegetation-cover and land-use change analyses reported in Section 3.4, for four reasons. First, it provides the longest continuous annual time series available for Brazil (1985 to 2024), which is a necessary condition for the property-level vegetation-change assessment performed in this study. Second, it offers the most detailed thematic classification for the Cerrado and Caatinga biomes that compose the study area, distinguishing native formations (forest formation, savanna formation, grassland formation) from anthropic uses (soy, other temporary crops, pasture, planted forest). Third, its classification methodology is harmonized across years, which avoids the inter-product inconsistencies that would arise if different LULC databases were chained over the study period. Fourth, it is consistent with the methodological framework adopted in Camara et al. [49], thereby preserving comparability with prior CAR-based analyses. TerraClass (INPE) was consulted for cross-referencing specific Cerrado land-cover classes in selected years but was not adopted as the primary source, given its discontinuous release schedule. PRODES (INPE) was used as the official reference for annual deforestation increments, complementing the MapBiomass-based vegetation-cover assessment.

2.3. Data Analysis

For data analysis, we employed open-source software such as RStudio (version 2026.01.2+418 “Apple Blossom”, Posit Software), PostgreSQL (version 18.3) with the PostGIS spatial extension (version 3.6.3), and QGIS (version 4.0.1 “Norfolköping”; long-term release 3.44.9 “Solothurn”), alongside Microsoft Excel (Microsoft 365 Apps, Current Channel, version 2603). All data processing required to generate the results was executed on a virtual machine configured as the working environment.

A local database (DB) was created in RStudio, which was also used to convert geospatial files into formats compatible with PostgreSQL/PostGIS. Within the database, we performed geometry validation, created spatial indexes, and executed other preprocessing and data-organization procedures.

Finally, QGIS was used to produce cartographic outputs and to support the visual exploration of results, whereas Microsoft Excel served as an auxiliary tool for building charts and synthesizing the processed data.

2.4. Rural Environmental Registry (Car)

This study treats CAR as both an object of analysis and a governance indicator. Three analytical dimensions are operationalized as proxies of territorial governance challenges: (i) the temporal evolution of registered properties between 2019 and 2025, which captures the rate of land formalization and the progressive consolidation of rural claims; (ii) the spatial overlap between CAR-registered private properties and legally designated public lands, which serves as an indicator of potential irregularities and land-tenure conflicts; and (iii) land-use/land-cover (LULC) change within registered properties between 1985 and 2024, which provides a long-term measure of deforestation pressure concurrent with the expansion of the registry. Together, these three dimensions allow for an integrated assessment of how land-tenure formalization relates to environmental change in an agricultural frontier context [49].

To allow readers to judge whether the values reported in Section 3 indicate a situation of concern, operational significance thresholds were defined for each of the three analytical dimensions, anchored in the Brazilian Forest Code and in the statutory frameworks that govern public lands in Brazil. For Dimension (i), a growth in the number of registered CAR properties exceeding 25% over the 2019 to 2025 window is treated as substantive, a rate that sits above the nationwide average of CAR formalization reported for comparable periods. For Dimension (ii), any detected overlap between a CAR-registered private property and Conservation Units, Indigenous Territories, Quilombola Territories, or federal military areas is treated as a substantive irregularity, since these land categories are constitutionally or statutorily non-overlappable with private rural properties. Overlap values are reported in both absolute (hectares) and relative (percentage of the total area of the respective public-land category) terms. For Dimension (iii), the minimum legal-reserve requirement of the Forest Code provides the reference: 20% for rural holdings located outside the Amazônia Legal (applicable to the MATOPIBA municipalities analyzed). Properties whose native vegetation cover in 2024 falls below these legal-reserve thresholds are interpreted as presenting significant deforestation pressure, and properties that lost more than 20 percentage points of native vegetation cover between 1985 and 2024 are additionally flagged as having undergone substantial conversion over the study period.

The analysis of registered properties in the Rural Environmental Registry (CAR) was designed to evaluate temporal consistency between 2019 and 2025. Using the “reg_name” attribute, unique identifiers were assigned to individual properties, enabling record linkage across the two periods.

To ensure geometric integrity for the layers corresponding to each year, we applied a minimal-radius buffer (zero-distance buffer) technique to correct invalid geometries. We then computed property areas and quantified the change between 2019 and 2025 by taking the difference between current and previous areas.

This step made it possible to identify properties that underwent area adjustments (both increases and reductions) as well as those that remained stable over the analysis period. Figure 3 depicts the workflow for this temporal consistency assessment.

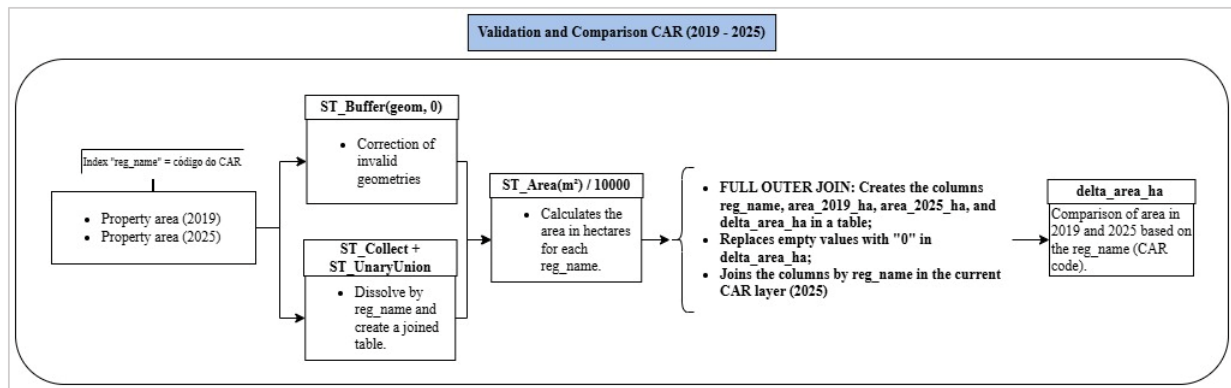


Figure 3. Methodological workflow for the temporal consistency analysis of rural property areas (2019–2025).

The core stage of the methodology consists of cleaning the CAR dataset by removing overlaps among properties, thereby generating a consolidated layer of private and public holdings. To this end, it is essential that the 2025 CAR dataset be free of invalid geometries. Given this requirement, we created two specific correction functions to normalize geometries and ensure the correct execution of subsequent processing steps.

In addition, the MY_Date function was developed to standardize date fields in the attribute tables of the geospatial datasets. This procedure was applied to all input layers, preventing downstream processing issues related to invalid geometries or non-standardized date formats. Figure 4 illustrates, in its initial stage, the methodological workflow outlined above [49]. Accordingly, all vector datasets listed in Figure 3 underwent geometry validation and date-field standardization [49].

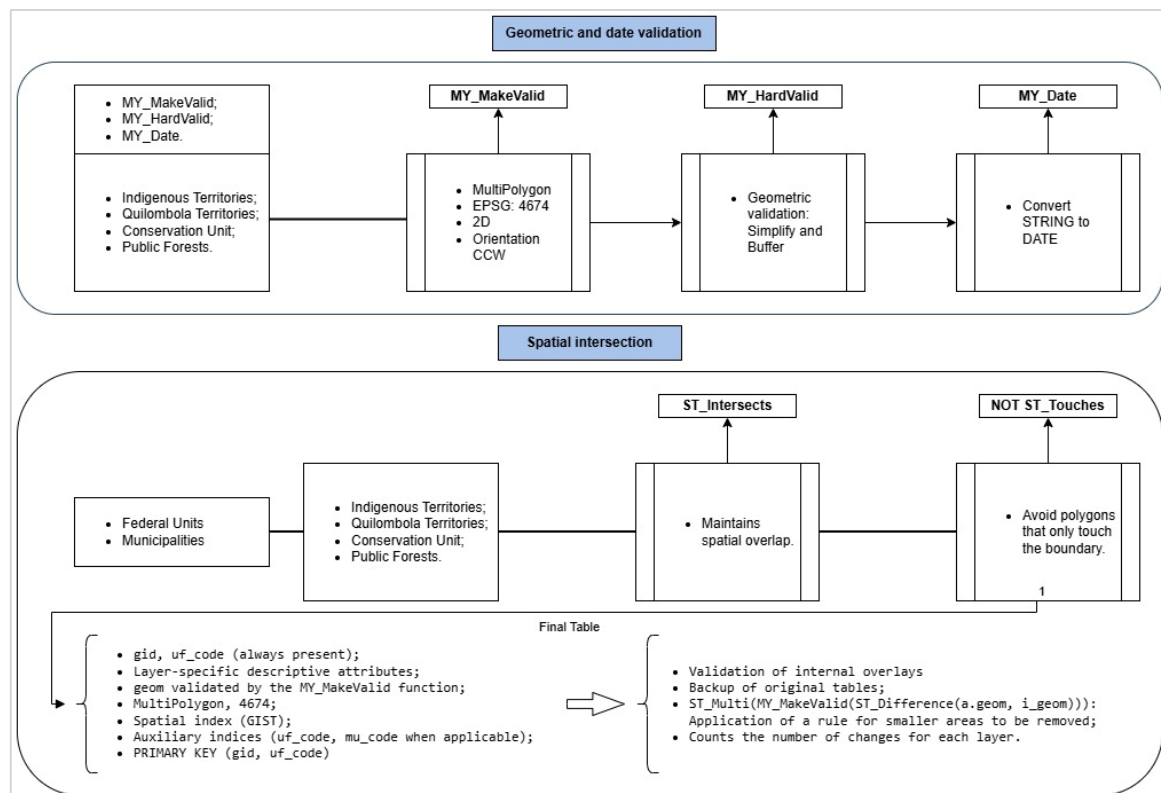


Figure 4. Methodological workflow for geometry validation and date-field standardization of CAR-registered rural properties for 2025 and public lands.

2.5. Preparation of Public and Private Property Maps

Our analysis required maps of public and private lands. To this end, we merged multiple rural property layers based on dataset-specific rules and a cross-layer hierarchy; accordingly, we established five rules [49].

Rule (A) comprised the validation and de-overlap cleaning of the CAR (2025) layer. Rule (B) merged the SIGEF (private) and SNCI (private) layers, applying the same geometry-validation and overlap-removal procedures. At this stage, SIGEF-registered properties take precedence; any overlaps with SNCI result in the exclusion of the latter's geometries.

In Rule (C), the procedure mirrored the previous step, but priority was assigned to the merged SIGEF + SNCI properties over Terra Legal properties. Rule (D) then defines the final hierarchy, granting precedence to SIGEF + SNCI + Terra Legal over overlapping CAR records.

Finally, Rule (E) incorporates Rural Settlements, yielding a consolidated layer representing possession or ownership holdings. Figure 5 depicts the workflow for the application of the above rules.

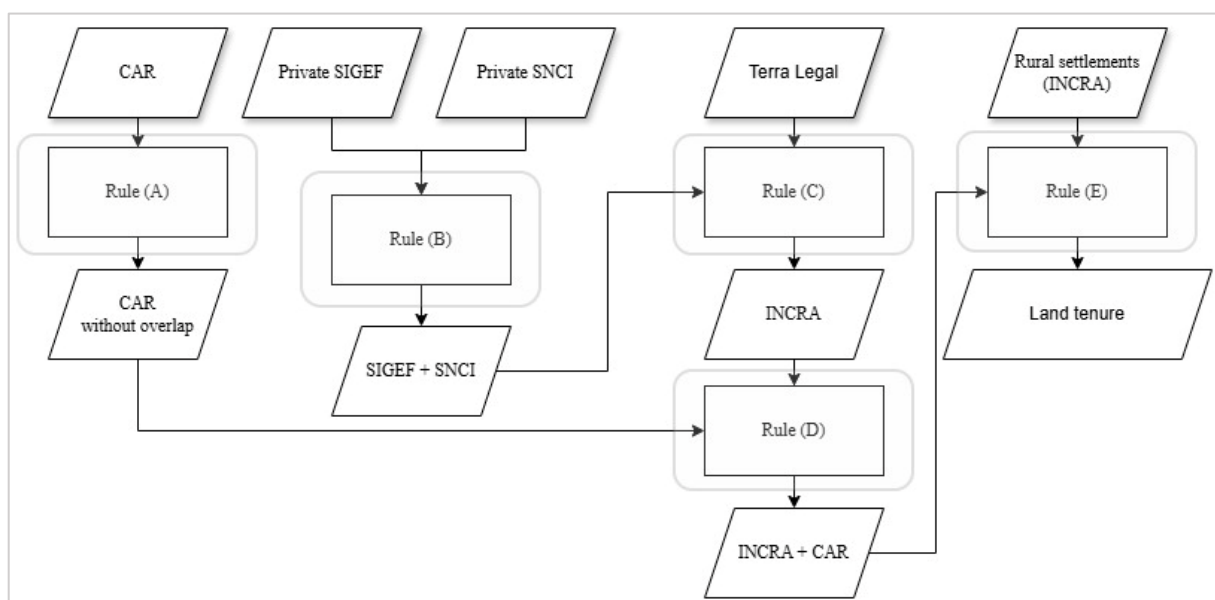


Figure 5. Application of validation, overlap cleaning, and boundary hierarchization rules for rural property layers from SIGEF, SNCI, Terra Legal, CAR, and Rural Settlements for 2025 [49].

3. Results

The results reported here cover four analytical stages applied to rural properties registered in the Rural Environmental Registry (CAR) within the study area: geometry validation and cleaning, land-tenure hierarchization, temporal consistency analysis, and land-use/land-cover change assessment. Specifically, they encompass the evolution in the number of rural properties from 2019 to 2025; the consolidation of the land-tenure database through integration with official INCRA data; the identification of overlaps with public lands; and the characterization of land-use/land-cover (LULC) dynamics between 1985 and 2024.

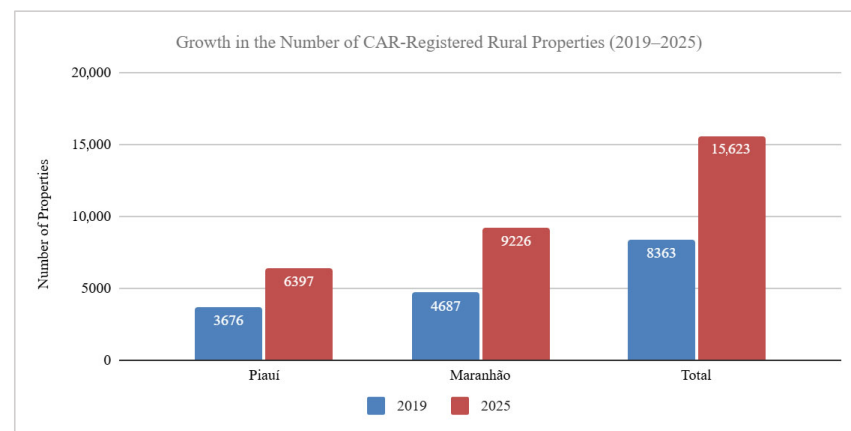
3.1. Consolidation and Evolution of Rural Environmental Registry (CAR) Properties

The raw data from the Rural Environmental Registry (CAR) indicate a marked increase in the number of registered rural properties between 2019 and 2025 across the municipalities analyzed in Piauí and Maranhão. The total rose from 8363 in 2019 to 15,623 in 2025, nearly doubling over the period, and is presented in Table 1.

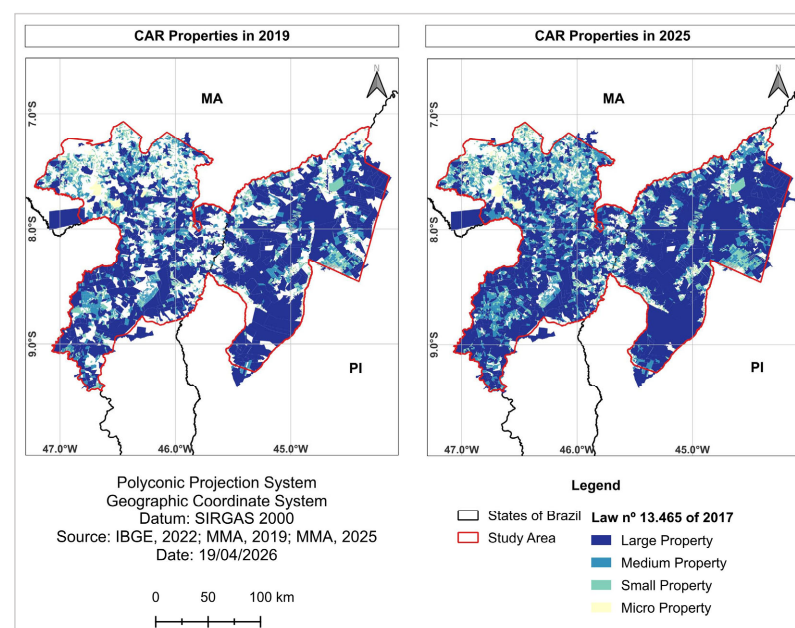
Table 1. Evolution of registered rural properties in CAR by state (raw data), 2019–2025.

Year	Piauí	Maranhão	Total	% Growth in Maranhão	% Growth in Piauí	% Total
2019	3676	4687	8363	57.46%	50.80%	53.53%
2025	6397	9226	15,623			

Maranhão posted the highest absolute values in both years under analysis, rising from 4687 to 9226 properties. In Piauí, the total increased from 3676 to 6397. Although both states substantially expanded their declaratory base, Maranhão maintained a larger relative share, as shown in Figure 6. The growth rates confirm this pattern: Maranhão recorded an increase of 57.46%, exceeding the 50.80% observed in Piauí. Across the set of municipalities analyzed, the aggregate increase was 53.53%.

**Figure 6.** Evolution of the growth in the number of CAR-registered rural properties (2019–2025).

Accordingly, the data point to a general increase in CAR registrations, with Maranhão outpacing Piauí in both absolute numbers and proportional growth. Figures 6 and 7 map these results, while Figure 8 details the 2019–2025 rectifications for CAR properties.

**Figure 7.** Spatial distribution of CAR-registered rural properties by source dataset across the six municipalities, 2025.

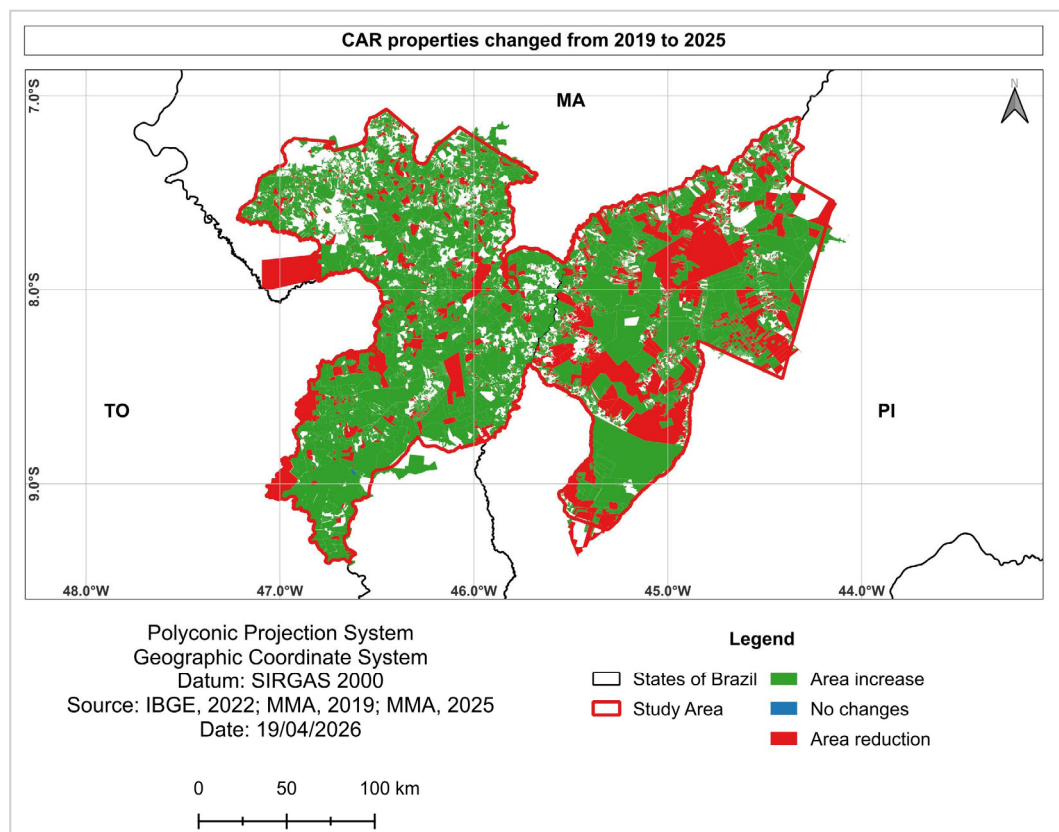


Figure 8. Area rectifications of CAR-registered rural properties between 2019 and 2025, showing increases, reductions, and stable records.

3.2. Internal Cleaning and Geometric Validation of Raw CAR Data (2019–2025)

The combined data-cleaning and geometric validation procedures reduced the total number of CAR rural properties, rendering the database more representative of the land-tenure and environmental situation in the study area. In 2019, the number of properties decreased from 8363 (raw) to 7734 after cleaning; in 2025, from 15,623 to 14,231. This outcome indicates the presence of duplicates, outdated records, and inconsistencies that compromise the initial reliability of the data. Figure 9 presents the data after applying the methodology and Rule A, as demonstrated in Figure 5.

However, the growth rates recalculated from the cleaned database reveal a noteworthy shift: Piauí recorded the highest proportional increase over the period (59.28%), surpassing Maranhão (51.29%). Although Maranhão still holds the largest absolute totals, Piauí showed a stronger relative advance in the registration and updating of records. The comparison between the raw and cleaned datasets for 2019 and 2025 is presented in Tables 2 and 3.

Table 2. Evolution of validated rural properties in CAR by state (cleaned data), 2019–2025.

Year	Piauí	Maranhão	Total	% Growth in Maranhão	% Growth in Piauí	% Total
2019	3229	4505	7734	59.28	51.29%	54.35%
2025	5447	8784	14,231			

Table 3. Percentage reduction in the number of registered properties after data cleaning, by state and year.

Year	% Cleaned (PI)	% Cleaned (MA)	% Total
2019	−13.84%	−4.04%	−8.13%
2025	−17.44%	−5.03%	−9.78%

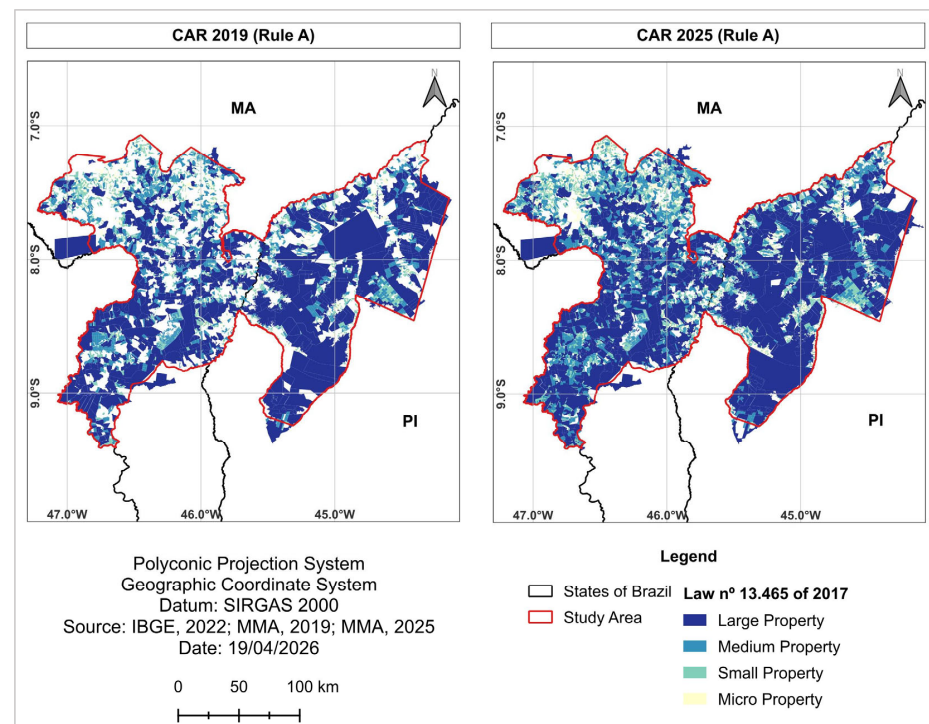


Figure 9. Spatial distribution of validated CAR properties after applying Rule A (internal overlap removal), 2025.

This result indicates that cleaning had an asymmetric effect across states, with larger reductions in Piauí than in Maranhão in both years, reflecting a higher incidence of inconsistent records in Piauí (duplicates/overlaps/obsolescence). Figure 10 displays the origin of properties resulting from the full methodology, as shown in Figure 4.

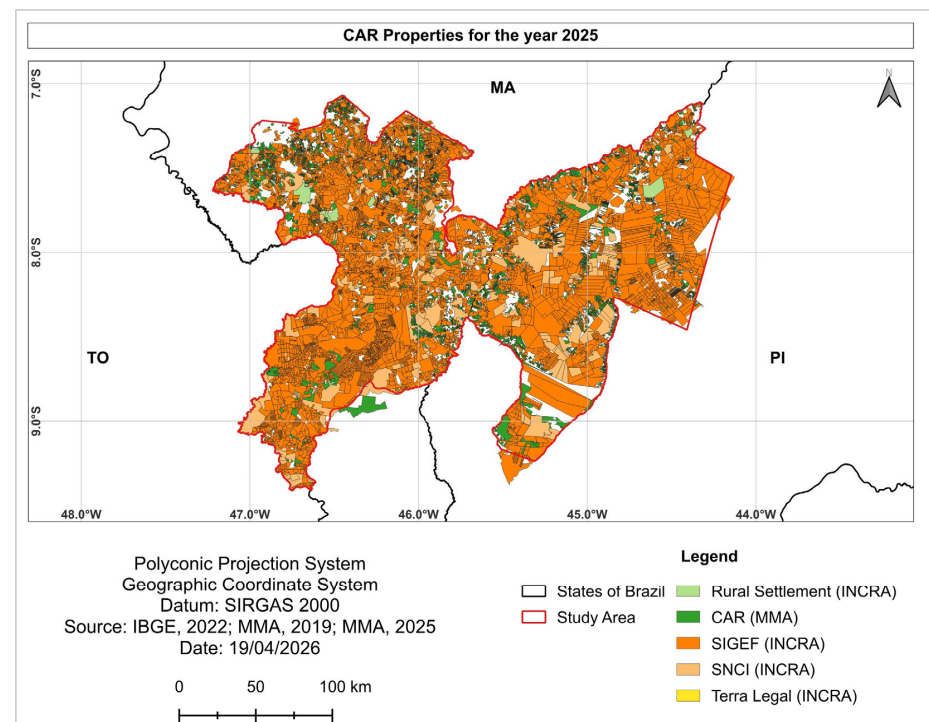


Figure 10. Source of consolidated rural properties by source dataset after applying hierarchical rules (Rules A–E), 2025.

In Maranhão, of the 9697 properties resulting after all consistency rules were applied, 6296 originated from SIGEF, 3180 from CAR, 215 from SNCI, and 6 corresponded to agrarian-reform settlements. In Piauí, among the 5121 validated properties, 2967 derived from CAR, 2026 from SIGEF, 104 from SNCI, 22 from Terra Legal, and 2 from agrarian-reform settlements. Table 4 presents the analysis of this final version shown in Figure 10, alongside the raw data.

Table 4. Percentage change in the total number of registered properties after applying all hierarchical rules (Rules A–E), by state.

% Cleaned (PI)	% Cleaned (MA)	% Total
−24.92%	4.86%	−5.43%
Reduction	Increase	Reduction

The spatial pattern depicted in Figure 9 reveals that validated CAR properties are markedly concentrated along the main soy-production axes of the six municipalities, with dense clusters in the central and southern portions of the study area and sparser coverage in the northern and northwestern sectors. The zones that appear empty in the map correspond to three distinct situations that should not be conflated: (i) polygon surfaces removed by the internal de-overlap procedure of Rule A, which eliminated duplicated or nested CAR declarations over the same parcel; (ii) areas covered by public-land categories, which are excluded from the private-property layer by construction; and (iii) sectors where rural producers have not yet submitted CAR declarations, a pattern particularly visible in the more remote portions of Riachão (MA) and Baixa Grande do Ribeiro (PI). The residual gaps observable within actively occupied sectors further indicate that the declaratory coverage of CAR, although substantial, is not yet exhaustive within the study area, and that the validated layer in Figure 8 should be read as a lower bound of formalized land tenure rather than as a complete map of rural occupation.

Figure 10 disaggregates the consolidated rural property layer by source dataset after the full hierarchical procedure (Rules A to E) and reveals a clear inter-state contrast in the institutional composition of land-tenure records. In Maranhão, SIGEF dominates the consolidated layer, accounting for 6296 of the 9697 validated properties (64.93%), followed by CAR-only records (3180 properties, 32.79%), SNCI (215 properties, 2.22%), and agrarian-reform settlements (6 properties, 0.06%). In Piauí, the composition is inverted: CAR-only records prevail, accounting for 2967 of the 5121 validated properties (57.94%), followed by SIGEF (2026 properties, 39.56%), SNCI (104 properties, 2.03%), Terra Legal (22 properties, 0.43%), and agrarian-reform settlements (2 properties, 0.04%). This contrast reflects a state-level difference in the trajectory of land-tenure regularization. Maranhão exhibits a higher share of formally titled properties registered via SIGEF, indicating a more advanced stage of tenure formalization under the National System of Rural Cadastre; Piauí, in contrast, remains more dependent on the declaratory CAR as the primary territorial record, which increases the relative weight of self-declared polygons and, consequently, the data-quality vulnerabilities quantified earlier in this section (larger proportional reductions in Piauí after the cleaning procedures: 17.39% against 5.00% in Maranhão). The inter-state asymmetry in dataset composition therefore mirrors the inter-state asymmetry in data reliability and suggests that tenure-regularization policy in the MATOPIBA portion of Piauí would benefit from prioritizing the migration of CAR-only records into the SIGEF system.

3.3. Overlap of Consolidated Properties with Public Lands

Overlaps between CAR-registered private properties and legally designated public lands represent a key indicator of land-tenure irregularities, pointing to potential encroach-

ments that may constitute a form of institutional land-tenure conflict. Table 5 reports the overlapping areas (in hectares) for the properties shown in Figure 10.

Table 5. Overlap areas (ha) between consolidated rural properties and public land categories, by state.

Type	Piauí (ha)	Maranhão (ha)	Total (ha)
Indigenous Territories	0	0	
Quilombola Territories	0	0	
Public Forests	0	2571.42	136,124.10
Military Areas	3709.46	6382.22	
Sustainable Use Conservation Units	0	0	
Full Protection Conservation Units	123,461.00	0	

These findings suggest that land-tenure formalization via CAR has not prevented the registration of properties that encroach upon legally protected territories, underscoring the need for systematic cross-referencing of CAR records with other official cadasters as a condition for effective territorial governance.

3.4. Land-Use and Land-Cover Change on Properties (1985–2024)

The analysis of land-use/land-cover (LULC) change on rural properties, based on MapBiomas, reveals significant transformations in native vegetation across the study area. Both the number of properties without native vegetation and the total native-vegetation area changed markedly over this period. Figure 11 depicts the extent of native vegetation between 1985 and 2024.

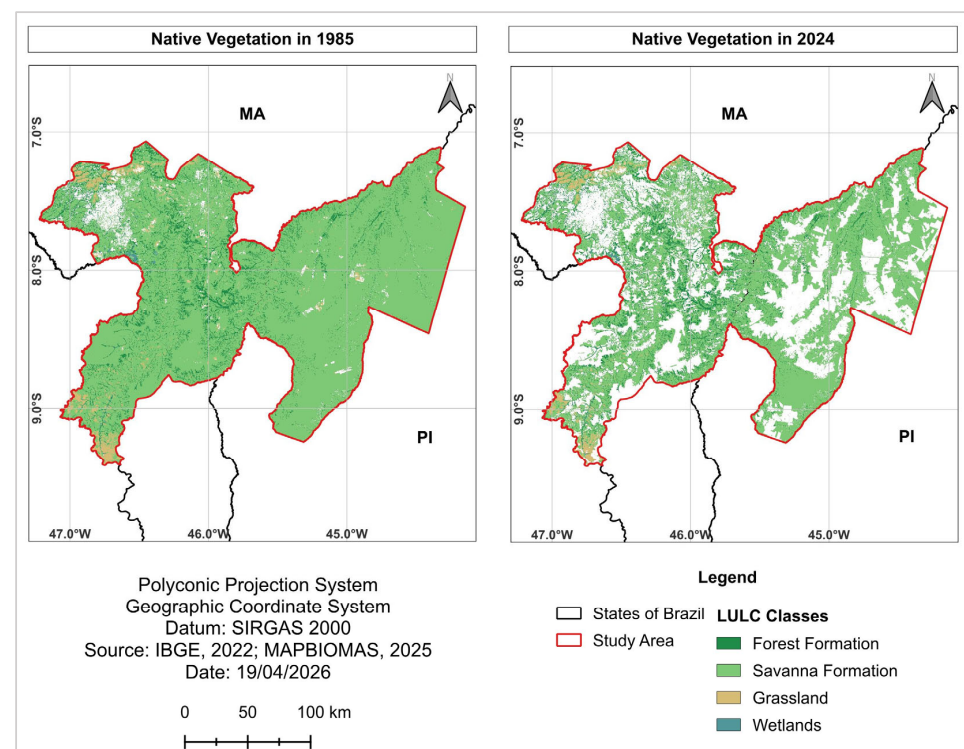


Figure 11. Spatial distribution of native vegetation cover within consolidated rural properties for 1985 and 2024.

In Piauí, the number of properties entirely devoid of native vegetation increased from 74 to 162 (+218.92%), whereas in Maranhão it rose from 34 to 173 (+508.82%). Overall, properties without native vegetation grew from 108 to 335 (+310.19%), indicating the continued expansion of conversion to anthropogenic land uses. The total area of native

vegetation also declined over the period: in Piauí, from 1763,540 ha to 1050,430 ha (−40.44%); in Maranhão, from 2,057,030 ha to 1,313,740 ha (−36.13%). Aggregated over the study area, native vegetation decreased from 3,820,570 ha to 2,364,170 ha (−38.12%). Figure 12 presents the analysis of native vegetation at the property level.

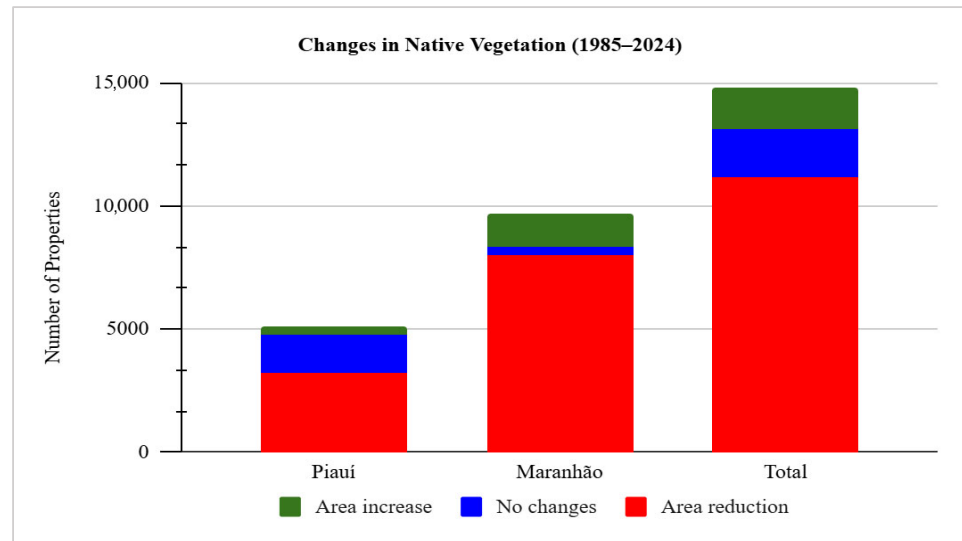


Figure 12. Native vegetation changes at the property level, 1985–2024: proportion of properties with loss, stability, or gain, by state (Piauí and Maranhão).

At the property level, loss is the predominant pattern. In Piauí, 3195 properties (62.39%) showed reductions in native vegetation, 1585 (30.95%) remained stable, and 341 (6.66%) increased. In Maranhão, losses were higher: 7976 properties (82.25%) lost vegetation, 365 (3.76%) remained stable, and 1356 (13.98%) increased. Across the dataset, 11,171 properties (75.39%) exhibited reductions in native vegetation between 1985 and 2024. Figure 13 maps the spatial distribution of these results across the study area.

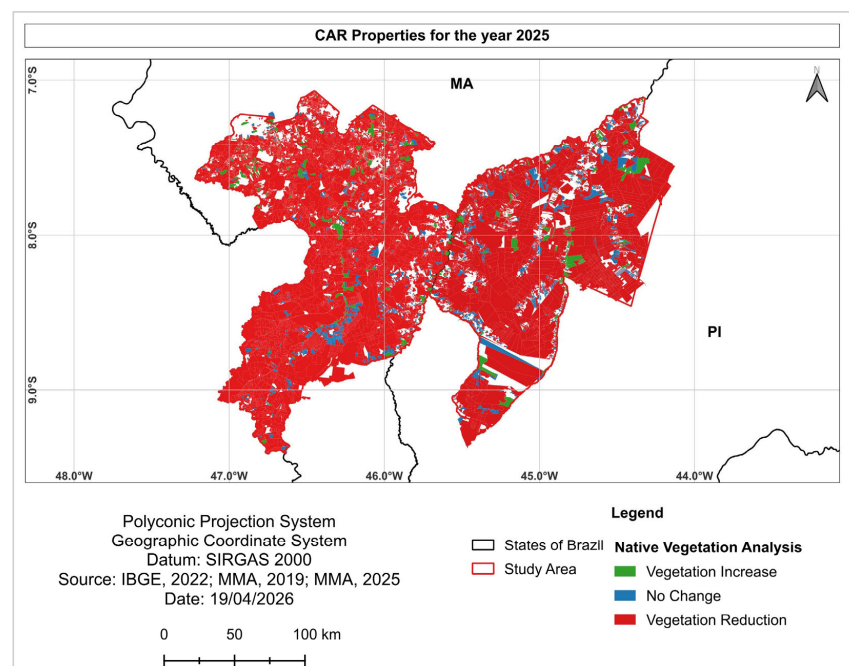


Figure 13. Spatial distribution of native vegetation change (loss, stability, and gain) within consolidated rural properties across the study area, 1985–2024.

Taken together, these results indicate that the expansion of CAR occurred concurrently with a sustained process of native vegetation loss, suggesting that land-tenure formalization alone has been insufficient to curb deforestation pressure within the study area.

4. Discussion

4.1. Land-Tenure Regularization Dynamics in an Agricultural Expansion Area

The data indicate that, between 2019 and 2025, the Rural Environmental Registry (CAR) recorded a substantial increase in the study area, with a rise in the number of registered properties and a progressive consolidation of land tenure. This growth points both to the strengthening of environmental regularization efforts and to greater participation by rural producers, particularly in regions where agricultural and livestock activities are intensifying. This dynamic reflects a broader process of territorial occupation and spatial organization in agricultural frontier areas.

From an analytical perspective, this growth can be understood as part of the global reconfiguration of land use [1,4], in which agricultural expansion is linked to the formalization of land tenure. In this context, CAR functions not only as a technical instrument of environmental management, but also as a mechanism that accompanies, and to some extent legitimizes, the territorial consolidation of agribusiness [8].

An important analytical question concerns the causal direction of this relationship: does the expansion of CAR registrations precede or follow deforestation? The temporal structure of the data does not allow for a definitive causal inference; however, the concurrent trends observed suggest a pattern of co-occurrence rather than sequential causality. The near-doubling of registered properties between 2019 and 2025, alongside the sustained vegetation loss documented since 1985, is consistent with a dynamic in which land formalization and agricultural expansion reinforce each other. This interpretive caution is warranted given the potential for reverse causality: deforestation may precede registration, as landholders clear native vegetation to establish productive use before formalizing their claims via CAR. Future research employing panel data and spatial econometric methods would be needed to disentangle these effects rigorously [49].

Accordingly, the expansion of the registry occurs concomitantly with increased productive occupation, indicating that environmental regularization and agricultural expansion are taking place simultaneously and in an interdependent manner in regions such as MATOPIBA.

4.2. Data Limitations and Challenges in Environmental Governance

Despite the growth in the number of records, the need to perform data cleaning and geometric validation revealed vulnerabilities in the CAR database, such as duplicate entries, inconsistencies, and outdated information. The reduction in the number of properties after this procedure indicates that the original data do not fully represent on-the-ground conditions, underscoring the importance of rigorous validation methodologies for scientific studies and territorial planning.

These results corroborate what the literature has highlighted regarding the limitations of CAR as a declaratory instrument, especially in agricultural frontier areas where database integration is limited and institutional challenges persist [31]. The differences observed between Maranhão and Piauí show that regularization processes are not uniform; rather, they are influenced by historical and institutional factors and by territorial occupation patterns [13,14].

Comparable asymmetries in CAR data quality across Brazilian states have been documented in the Legal Amazon, where the prevalence of self-declared polygons, the incidence of duplicate records, and the magnitude of post-cleaning reductions vary markedly with

the maturity of state-level land-titling infrastructure. Analogous patterns have also been reported for the Cerrado portions of Goiás and western Bahia, where asymmetries in the ratio of SIGEF-titled to CAR-only records track sub-regional differences in the historical consolidation of property rights. The differential quality of CAR records between Maranhão and Piauí documented in the present study, therefore, situates the MATOPIBA portion of Piauí within a broader national pattern rather than as an isolated case and reinforces the argument that improvements in data reliability require structural investment in cross-cadastral integration rather than purely methodological refinement.

In light of this, the data reinforce the importance of more integrated and flexible environmental governance [34], in which interoperability among information systems and the continuous validation of data are essential to enhance the reliability and effectiveness of public policies.

4.3. Land-Tenure Overlap as a Manifestation of Structural Territorial Conflicts

The observation of overlaps between CAR-registered properties and public lands reveals not only technical shortcomings but also structural conflicts related to land tenure and land use. These findings suggest potential irregularities and corroborate the presence of territorial disputes in strategically significant zones.

Such a pattern aligns with debates on land appropriation processes, whereby agribusiness expansion proceeds through the incorporation of public or collective lands [10,11]. At the same time, these overlaps highlight vulnerabilities in public policy implementation and environmental enforcement [31].

The geospatial evidence presented here establishes that the CAR, in its current operational form, does not prevent the formal recording of properties with declared perimeters that intersect public land categories with which they are, by law, non-overlappable. It does not, however, allow a record-by-record attribution of each overlap to one specific mechanism, which would require complementary administrative verification. The overlaps are therefore best interpreted as vulnerabilities in the implementation of public policy and in inter-institutional coordination [31,49], whose material manifestations range from cartographic artifacts to substantive tenure conflicts, among which land grabbing is one plausible but not exclusive interpretation.

The evidence indicates that CAR, when considered in isolation, has limitations as an instrument of territorial governance. It is therefore essential to integrate CAR with other official cadasters and planning datasets to enhance legal certainty and mitigate land-tenure conflicts, consistent with the land-governance literature [27]. The systematic cross-referencing of CAR records with SIGEF, SNCI, and protected-area boundaries, as demonstrated in this study, offers a replicable methodological pathway for identifying such overlaps at scale [49].

4.4. Acceleration of Environmental Change and Constraints on Territorial Regulation

The land-use/land-cover (LULC) analysis for 1985–2024 reveals a persistent decline in native vegetation, concomitant with the expansion of areas occupied by human activities such as agriculture and livestock. The prevalence of properties exhibiting vegetation loss, particularly in Maranhão, points to the intensification of natural ecosystem conversion and reflects a sustained process of landscape transformation.

This pattern aligns with international studies identifying agricultural expansion as a primary driver of deforestation and environmental degradation [2,5], and underscores the vulnerability of the Cerrado, recognized as a biodiversity hotspot under strong anthropogenic pressure [37]. The data also indicate that the expansion of CAR occurred

concurrently with this long-term process of land-use change, suggesting that registry growth alone has been insufficient to guarantee environmental conservation.

Within this context, the results show that land-tenure regularization and security of land rights are essential to curb deforestation and to implement forest-restoration actions, corroborating prior findings reported in the literature. Thus, although the Rural Environmental Registry (CAR) represents a significant institutional advance, its effectiveness depends on integration with robust monitoring, enforcement, and coordinated territorial governance policies [32].

More specifically, the evidence from this study points to three priority actions: (i) mandatory cross-validation of CAR records against protected-area and military-zone boundaries before registration approval; (ii) periodic re-validation of existing records to address the high rate of inconsistencies identified, particularly in Piauí; and (iii) integration of CAR data with LULC monitoring systems such as PRODES and MapBiomas to enable near-real-time detection of deforestation within registered properties.

5. Conclusions

This study shows that, between 2019 and 2025, the expansion of CAR nearly doubled the number of registered rural properties in the study area, contributing to the progressive consolidation of land-tenure records. However, it also revealed significant limitations, such as data-quality issues and record inconsistencies, with cleaning procedures reducing the total property count by up to 17% in Piauí and 5% in Maranhão. Geometric validation was a key step to enhance data reliability and better support territorial planning.

In addition, overlaps between CAR-registered properties and public lands, particularly within Full Protection Conservation Units and military areas, point to challenges in land-tenure governance and potential institutional conflicts. This underscores the need for improved integration across registry systems, including systematic cross-referencing of CAR with SIGEF, SNCI, and protected-area boundaries, as well as more rigorous verification of declared information.

At the same time, the 38.12% decline in native vegetation recorded between 1985 and 2024, affecting approximately 75% of the properties analyzed, indicates that the expansion of the registry occurred amid intense landscape change. The concurrent trends in CAR growth and vegetation loss suggest that land-tenure formalization, while necessary, has been insufficient on its own to curb deforestation pressure in the MATOPIBA region.

Therefore, we argue that CAR holds substantial potential as a tool for environmental and territorial governance. Nevertheless, to be truly effective, it requires three interrelated improvements: (i) mandatory cross-validation of new registrations against protected-area and military-zone boundaries prior to approval; (ii) periodic re-validation of existing records to address data inconsistencies, which are particularly acute in states with higher rates of agricultural frontier expansion such as Piauí; and (iii) integration of CAR data with satellite-based land-cover monitoring systems (PRODES, MapBiomas) to enable near-real-time detection of deforestation within registered properties. These recommendations are directly transferable to other tropical frontier regions facing similar governance challenges, where geospatial cadastral data can serve as a foundational layer for evidence-based environmental policy.

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Abbreviations

The following abbreviations are used in this manuscript:

APP	Permanent Preservation Area (Área de Preservação Permanente)
CAR	Rural Environmental Registry (Cadastro Ambiental Rural)
CNFP	National Register of Public Forests (Cadastro Nacional de Florestas Públicas)
DB	Database
ESA	European Space Agency
FBDS	Brazilian Foundation for Sustainable Development (Fundação Brasileira para o Desenvolvimento Sustentável)
FUNAI	National Foundation of Indigenous Peoples (Fundação Nacional dos Povos Indígenas)
IBGE	Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística)
ICMBio	Chico Mendes Institute for Biodiversity Conservation (Instituto Chico Mendes de Conservação da Biodiversidade)
INCRA	National Institute for Colonization and Agrarian Reform (Instituto Nacional de Colonização e Reforma Agrária)
INPE	National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais)
JRC	Joint Research Centre
LULC	Land-Use/Land-Cover
MATOPIBA	Maranhão, Tocantins, Piauí, Bahia
MGI	Ministry of Management and Innovation (Ministério da Gestão e da Inovação)
PRODES	Program for Deforestation Monitoring in the Brazilian Amazon (Programa de Monitoramento da Floresta Amazônica Brasileira por Satélite)
QGIS	Quantum Geographic Information System
SFB	Brazilian Forest Service (Serviço Florestal Brasileiro)
SIGEF	Rural Land Certification and Management System (Sistema de Gestão Fundiária)
SNCI	National Geospatial Certification System (Sistema Nacional de Certificação de Imóveis)

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