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AVALIAÇÃO DO IMPACTO DO CADASTRO AMBIENTAL RURAL NA REDUÇÃO DO DESMATAMENTO E CONFORMIDADE AMBIENTAL NO CENTRO-OESTE BRASILEIRO

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AVALIAÇÃO DO IMPACTO DO CADASTRO AMBIENTAL RURAL NA REDUÇÃO DO DESMATAMENTO E CONFORMIDADE AMBIENTAL NO CENTRO-OESTE BRASILEIRO

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ABSTRACT

Agriculture and livestock production are fundamental to Brazil's economy and have undergone modernization through advanced technologies, expanding operations via conversion of native vegetation areas. To promote biome preservation, Brazil updated its Forest Code in 2012 and implemented the Rural Environmental Registry (CAR) in 2014. This instrument, operationalized by the National CAR System (SICAR), compiles data on rural properties to create an essential database for environmental and economic monitoring, control, and planning, while also supporting anti-deforestation initiatives. This study evaluated CAR's impact on deforestation and environmental compliance of rural properties in the Central-West agricultural frontier - a strategic grain-producing region encompassing municipalities within the Legal Amazon. Two analyses were conducted using SICAR data: the first on deforestation covered 229,386 properties registered between 2014-2021 across 449 municipalities; the second on compliance analyzed 106,436 properties in 447 municipalities. Annual deforestation data were obtained from Brazil's National Institute for Space Research (INPE), spanning 2008-2023. The analysis employed Callaway and Sant'Anna's (2021) multi-period Difference-in-Differences methodology. Results showed deforestation reduction among small properties registered in 2015 and 2016, with effects intensifying as treatment exposure duration increased. For environmental compliance, an increased probability of regularization was observed only among small properties. These findings demonstrate that CAR's effectiveness varies by property size, and that the identified heterogeneous effects can inform improvements in environmental policies through differentiated strategies that reconcile ecosystem conservation with regional economic development.

Keywords: Rural Environmental Registry. Deforestation. Environmental Compliance. Agricultural Frontier. Public Policy.

RESUMO

A agropecuária é fundamental para a economia brasileira e passou por um processo de modernização com o uso de tecnologias avançadas, expandindo suas atividades por meio da conversão de áreas nativas. Para promover a preservação da vegetação nos biomas, o Brasil atualizou o Código Florestal em 2012 e implementou o Cadastro Ambiental Rural (CAR) em 2014. Esse instrumento, operacionalizado pelo Sistema Nacional de Cadastro Ambiental Rural (SICAR), visa compilar informações dos imóveis rurais, formando uma base de dados essencial para o controle, o monitoramento e o planejamento ambiental e econômico, além de subsidiar ações de combate ao desmatamento. Este estudo avaliou o impacto do CAR sobre o desmatamento e a conformidade ambiental de imóveis rurais na fronteira agrícola do Centro- Oeste, região estratégica para a produção de grãos e que inclui municípios inseridos na Amazônia Legal. Foram conduzidas duas análises a partir de dados do SICAR: a primeira, sobre desmatamento, abrangeu 229.386 imóveis cadastrados entre 2014 e 2021, distribuídos em 449 municípios; a segunda, sobre conformidade ambiental, analisou 106.436 imóveis em 447 municípios. Os dados anuais de desmatamento foram obtidos do Instituto Nacional de Pesquisas Espaciais (INPE), cobrindo o período de 2008 a 2023. O método empregado foi o de Diferenças-em-Diferenças com múltiplos períodos de tempo, conforme proposto por Callaway e Sant'Anna (2021). Os resultados indicaram redução do desmatamento em imóveis pequenos registrados em 2015 e 2016, com intensificação do efeito conforme o tempo de exposição ao tratamento aumentou. Em relação à conformidade ambiental, observou-se aumento na probabilidade de regularidade apenas entre os imóveis pequenos. Esses achados evidenciam que a efetividade do CAR varia conforme o tamanho dos imóveis e que os efeitos heterogêneos identificados podem fornecer subsídios para o aprimoramento de políticas ambientais, com estratégias diferenciadas que articulem conservação ambiental e desenvolvimento econômico regional.

Palavras-chave: Cadastro Ambiental Rural. Desmatamento. Conformidade Ambiental. Fronteira Agrícola. Política Pública.

INTRODUCTION

Since the 1960s, Brazilian agriculture and livestock farming have undergone a profound transformation, driven by the growing global demand for food and raw materials and the industrial development promoted by the governments of that time. This period marked the beginning of agricultural modernization, characterized by significant technological advancements, such as the introduction of tractors, improved seeds, fertilizers, and agricultural pesticides (Vieira Filho, 2022).

This modernization was made possible by instruments such as subsidized credit, financing, rural extension, and agricultural research, with emphasis on the role of the Brazilian Agricultural Research Corporation (Embrapa). State support through incentives and infrastructure facilitated the expansion of agricultural frontiers in Brazil, increasing the productivity of various crops (Contini *et al.*, 2010; Castanho and Teixeira, 2017).

This expansion of agricultural frontiers, where agricultural activities are constantly expanding, has been particularly notable in the Central-West, especially in the Cerrado. Technological advancements and the adoption of modern techniques have led to a significant increase in cultivated areas (Sano, 2011). With the growth of intensive soybean production, there has been an industrial shift to the region and the absorption of migrants, consolidating the importance of this agricultural frontier for the Brazilian agricultural sector (Brito, 2002; Gallo, 2009; Santos Junior, Tesser, and Barcellos, 2009; Vieira Filho, 2016).

In 2017, the Central-West region had 347.2 thousand agricultural establishments, of which 64.3% were family farms. In 2021, the agricultural sector contributed 16.81% to the regional GDP, totaling R$156.7 billion. The area cultivated with soybeans increased from 3.32 million hectares in 1988 to 18.8 million in 2022, while the area of corn reached 10.8 million hectares in the same year. Soybean production reached 62.1 million tons in 2022, a tenfold increase since 1988, and corn saw equally significant growth, with annual rates of 7.07% and 8.7%, respectively. The value of temporary crops, mainly soybeans and corn, reached R$302.3 billion in 2022, with these crops accounting for 81.91% of that total, equivalent to R$247.6 billion (IBGE, 2022).

The agricultural expansion has resulted in 49.37% of the Central-West's area being occupied by agriculture and livestock, favored by ideal climatic conditions for grain cultivation (MapBiomas, 2022). The Cerrado, predominant in the region, holds 5% of global biodiversity but faces significant threats. Mato Grosso, which is part of the Legal Amazon, has observed a concerning increase in deforestation in recent years, intensifying conservation and sustainability challenges.

It is important to acknowledge that agricultural production in the Central-West depends on essential ecosystem services, such as pollination, climate and disease regulation, food and water provision, soil formation, and nutrient cycling (Ferraz, 2019). Agricultural expansion and the opening of new frontiers have raised environmental concerns, particularly regarding deforestation. Agriculture and livestock farming, when not adopting conservation practices, can cause damage to ecosystem services, such as reducing available water, compacting and eroding soil, and losing biodiversity (Faria *et al.*, 2023).

To balance increased agricultural production with environmental conservation, it is essential to adopt strategies that promote productivity in already deforested areas and combat the illegal occupation of protected lands. Among these strategies are the demarcation of public forests, compliance with the Brazilian Forest Code (CFB) through the use of Payments for Environmental Services (PES), and investment in research and sustainable practices (Stabile *et al.*, 2020).

In this context, this study applies the Difference-in-Differences (DiD) method following the Callaway and Sant'Anna framework to evaluate the impact of the CAR on deforestation and environmental compliance. By focusing on an agricultural frontier region under strong environmental pressure, the study contributes to a relatively unexplored literature on the effects of CAR, particularly in dynamic rural territories. The identification of heterogeneous impacts across property categories and over time provides important insights for the improvement of public policy, encouraging differentiated strategies for environmental regularization and enforcement. These findings support biodiversity protection and contribute to more sustainable regional development pathways.

This article is structured into six sections: this introduction, an overview of the CAR, evidence of the CAR's impact on deforestation, methodological aspects, results and discussion, and final considerations.

NEW FOREST CODE AND THE RURAL ENVIRONMENTAL REGISTRY

The importance of maintaining natural environments for human life and productive activities is increasingly recognized. As a result, the protection and proper use of ecosystems have become central topics in environmental discussions, leading to the creation of Brazilian Forest Codes (CFB). Broadly, the new CFB, established by Law No. 12,651/2012, addresses the protection of native vegetation, Permanent Preservation Areas, and Legal Reserve areas, as well as forest exploitation, by providing economic and financial instruments to achieve its objectives.

This law reiterates the country's commitment to the preservation of its areas as a whole, with special attention to biodiversity, which is more sensitive in certain regions. This measure is crucial to ensure the well-being of both present and future generations. Additionally, it highlights the shared responsibility of government levels in formulating policies that meet these objectives (Brazil, 2012).

It is important to highlight that the implementation of the Forest Code can ensure the territorial rights of traditional communities, while also facilitating more effective land governance. The requirement to set aside a percentage of the area is fundamental for preserving native vegetation and reducing the impacts on biodiversity caused by exploitative activities, such as agriculture (IPAM, 2021).

In this context, the Rural Environmental Registry (CAR) emerged as a regulatory tool with the purpose of implementing the guidelines of the Brazilian Forest Code. It is regulated by Decrees No. 7,830/2012 and No. 8,235/2014, as well as Normative Instruction MMA No. 2/2014. The target audience of the CAR consists of landowners and holders of rural properties, while society as a whole benefits from the regulation (MAPA, 2022; SICAR, 2023).

Environmental compliance of the property begins with registration in the National Rural Environmental Registry System (SICAR), which requires information such as details of the owner, rural possessor, or direct responsible party, proof of ownership or possession documents, and georeferenced information. This includes the property's perimeter, areas of social interest or public utility, location of native vegetation, Permanent Protection Areas (APP), restricted use areas, consolidated areas, and Legal Reserve (RL) (SICAR, 2023).

The CAR has emerged as an important tool for environmental compliance, utilizing modern technologies to create an essential database for control, monitoring, environmental and economic planning, as well as combating deforestation, based on information from rural properties. Owners or possessors can easily register their properties online and await approval following an analysis conducted by state or municipal agencies.

The effective implementation of the CAR relies on government actions to establish it as an environmental and economic management tool. Expected outcomes include the simplification of the environmental compliance process, improvements in management, and the provision of information for economic and environmental planning nationwide. In other words, this initiative is expected to generate a national database with detailed information on land use and coverage, enabling a more accurate assessment of sustainability, including agricultural activities (Sambuichi *et al.*, 2014).

Among the challenges related to the CAR, the central issue is the loss of native vegetation on rural properties. Thus, it is essential to question the effectiveness of this tool in combating deforestation, assess whether there has been a reduction in this practice, and verify if the minimum required areas for Permanent Protection Areas (APP) or Legal Reserve (RL) are being maintained.

Non-compliance with the guidelines results in increased carbon emissions and climate changes, impacting all life on the planet. The CAR, as a regulatory instrument, aims to protect society by enforcing rules, contributing to the eradication of hunger, promoting sustainable agriculture, responsible consumption and production, aiding in the fight against climate change, and fostering health and well-being, aligning with the United Nations Sustainable Development Goals (SDGs) (Brazil, 2012).

Therefore, the CAR plays a significant role in understanding the history of land occupation and use, serving as a key element in quantifying the preservation of native vegetation and environmental liabilities. Given the importance of the information obtained through the CAR, there is an opportunity to conduct studies on the characterization of deforestation in Brazil following the implementation of the new Forest Code, questioning whether this deforestation originates from rural properties or not.

STUDIES ON THE RURAL ENVIRONMENTAL REGISTRY AND DEFORESTATION

When analyzing the impact of land registration on short-term deforestation dynamics in the state of Pará, L'Roe *et al*. (2016) observed a reduction in deforestation on properties registered with the CAR, specifically those ranging from 100 to 300 hectares. Garcia *et al*. (2017) investigated the impact of the CAR on deforestation in registered properties in the states of Mato Grosso and Pará, where the Amazon biome predominates. The results indicated that, in the absence of this instrument and its affiliated programs, deforestation would be 10% higher.

Martinez and Melo Júnior (2019) analyzed the environmental perception of using agroforestry systems for the recovery of legal reserves among farmers in the municipality of Cametá (PA). They found that a lack of knowledge about environmental laws and insufficient financial resources could lead to non-compliance with the CAR, potentially contributing to vegetation loss.

According to Maciel and Maciel (2022), the development of a tool that promotes biodiversity conservation is important for future planning. In their study, the authors observed a positive evolution in the number of rural properties and hectares registered each year. They noted that the North and Central-West regions have the highest number of registered hectares.

Souza *et al*. (2022) found that the CAR had a significant impact on reducing deforestation on rural properties. The instrument led to a marked and lasting decrease in deforestation on small properties in the Cerrado starting from the second year of implementation. However, the impact estimates for large properties indicated an opposite trend. Finally, they observed a negative relationship between the level of deforestation and the level of adherence to the CAR.

The second part of the ex-post evaluation report, prepared by the Ministry of Agriculture (2023), conducted an analysis of results to observe the expected outcome and impact indicators. Specifically, the analysis focused on the impact of the CAR on reducing the loss of native vegetation on rural properties, highlighting a decreasing trend in deforestation in most of the years examined. Since 2008, the trajectory of deforestation has shown a decline, reaching its peak in 2013, a year before the CAR's implementation. Subsequently, between 2016 and 2018, the country recorded the lowest deforestation rates; however, an increase was observed in the years 2019 and 2020 (MAPA, 2022).

METHODOLOGICAL ASPECTS

In this section, the transmission mechanisms of the CAR for achieving the objective of reducing deforestation in rural properties will be addressed. The databases used in the analysis, the construction of the two environmental indicators, and the application of the Difference-in- Differences methodology proposed by Callaway and Sant'Anna (2021) will be presented.

TRANSMISSION MECHANISMS

Registration in the CAR plays a crucial role by integrating detailed information about rural properties, forming a database for control, monitoring, environmental and economic planning, and combating deforestation. Additionally, the registration of rural properties constitutes the first step toward environmental regularization through the Environmental Regularization Program (PRA).

In this way, the loss of native vegetation is understood as the central issue to be mitigated by the CAR. It is important to note that a problem tree was constructed to identify this issue, and among the described causes is the conversion of native areas for planting, pastures, etc., carried out by rural producers. Therefore, with continuous monitoring by the CAR, such actions are discouraged due to the risk of sanctions (MAPA, 2022).

The mechanism for achieving the goal of reducing deforestation within rural properties can be understood through the logical model proposed by the MAPA evaluation team in the first volume of the Ex-Post Evaluation Final Report of CAR (2022). This model is a detailed and structured design of a program that aims to show how inputs and actions generate products, results, and their respective impacts (Brasil, 2018).

Regarding CAR, the inputs used include information technology (IT) infrastructure, integration among federal agencies and technical personnel, federal, state, and municipal budgets, international financial and technical cooperation, technical assistance, rural producers, and their representative entities. The use of these inputs enables the reception of registrations and integration of state data into SICAR, facilitating the analysis process.

Such actions result in products including the number of CAR registrations for rural producers and publicly accessible SICAR data (excluding personal data). Thus, a dataset is available for analysis on various themes, including environmental preservation. In this sense, the mechanism of registering rural properties in CAR can have a causal effect on the deforestation indicator.

DATABASE

To meet the objectives of this study, geospatial data from SICAR, IBGE, and the National Institute for Space Research (PRODES/INPE) were used. Table 1 presents the variables used to assess the effect of CAR implementation on deforestation, while Table 2 lists the variables used to measure the environmental compliance of rural properties. The treatment group consisted of rural properties registered between 2014 and 2021 in the Central-West agricultural frontier. The control group consisted of properties in the region that had not yet been registered. A rural property was considered treated from the moment of its CAR registration. For both groups, annual deforestation records covered the period from 2008 to 2023.

Table 1 | Description of the variables used in the analysis of CAR's Impact on Deforestation.

Variable	Description
Log Deforestation area	Logarithm of the deforested area (in hectares) within the property
Year of Deforestation	Year in which deforestation occurred
CAR Year	Year in which the property was first registered in the CAR system
GO	State dummy. Takes the value 1 if the rural property is located in Goiás, and 0 otherwise
MS	State dummy. Takes the value 1 if the rural property is located in Mato Grosso, and 0 otherwise
MT	State dummy. Takes the value 1 if the rural property is located in Mato Grosso do Sul, and 0 otherwise
Bioma	Biome dummy. Takes the value 1 if the rural property is located in the Cerrado biome, and 0 otherwise

Source: Prepared by the authors.

Table 2 | Description of variables used in the CAR analysis of Environmental Compliance.

Variable	Description
Area of property	Area of the rural property in hectares
Legal Reserve Area	Area of legal reserve in hectares
Deforestation in Legal Reserve	Area deforested within the legal reserve, in hectares
Native Vegetation in Legal Reserve	Difference between the legal reserve area and deforestation in the legal reserve
Proportion of Legal Reserve	Percentage of area to be reserved within rural properties, according to the Forest Code
Dummy for Forest Code Compliance Index (ICCF)	Takes the value 0 if the ICCF is less than one and 1 otherwise
Year of Deforestation	Year in which deforestation occurred
CAR Year	Year in which the property was first registered in the CAR system
GO	State dummy. Takes the value 1 if the rural property is in Goiás and 0 otherwise
MS	State dummy. Takes the value 1 if the rural property is in Mato Grosso and 0 otherwise
MT	State dummy. Takes the value 1 if the rural property is in Mato Grosso do Sul and 0 otherwise
Biome	Biome dummy. Takes the value 1 if the rural property is in the Cerrado and 0 otherwise

Source: Prepared by the authors.

In this study, the analyses will be conducted considering the size of the rural properties. This is justified by the fact that deforestation on a small property or a large estate has proportionally distinct impacts. Similarly, the effects of the CAR on deforestation may vary considerably depending on the size of the property. Adopting this strategy will allow for a more precise and contextualized understanding of this impact.

Law No. 8,629/1993, updated by Law No. 13,465/2017, classifies rural properties according to the size of their area as follows:

a. Minifundio**:** a rural property with an area smaller than the Minimum Parceling Fraction (FMP);

b. Small Property**:** a property with an area between the Minimum Parceling Fraction (FMP) and 4 fiscal modules;

c. Medium Property: a rural property with an area greater than 4 and up to 15 fiscal modules;

d. Large Property: a rural property with an area greater than 15 fiscal modules. For the analysis, minifundio and small property will be considered together.

DATA PROCESSING

In this subsection, the procedures necessary for constructing the database to be used in the analyses will be addressed, as well as the presentation of the key indicators to meet the research proposal.

INDICATOR 1: EVOLUTION OF DEFORESTATION IN RURAL PROPERTIES

The geospatial data were processed using QGIS 3.36.2. Initially, the files were reprojected to the Sirgas 2000 coordinate system (EPSG: 5880), ensuring uniformity and accuracy in the analysis. Topological errors in the geometries of the shapefiles were corrected, maintaining valid geometries and removing duplicates to avoid inflated counts.

The shapefiles of rural properties were associated with the Brazilian Institute of Geography and Statistics (IBGE) municipal mesh through 'intersection,' ensuring the correct location of the properties. Overlapping and non-overlapping areas were separated to avoid overestimation in the analysis, using 'union.'[1] The area of the rural properties was calculated in hectares after reprojection.

1 Although the study attempted to circumvent the issue of overlap between rural properties, it is important to consider that potential biases may persist due to this limitation.

The intersection between the shapefiles of the properties and the deforestation data from INPE allowed for the extraction of deforestation areas within the rural properties. The final database was processed with Python 3.11.1 and analyzed in RStudio 4.4.0, considering only properties with active or pending status and excluding those with suspended or canceled status. The study sample comprised 229,386 rural properties.

INDICATOR 2: ENVIRONMENTAL COMPLIANCE OF MUNICIPALITIES

After constructing the first indicator, the evolution of deforestation within rural properties is observed, and if there is an increase, it is necessary to assess legality. Therefore, the environmental compliance indicator aims to determine whether rural properties are adhering to the minimum percentage of native vegetation that must be maintained as Legal Reserve (RL). According to CFB (2012), the RL is an area within a rural property, one of whose functions is to promote the conservation of biodiversity.

The period analyzed in this study (2008 to 2023) included two forest codes (1965 and 2012); however, the percentage of Legal Reserve (RL) stipulated remained the same in both, varying only with respect to the location of the rural property. Thus, the percentage to be reserved is 80% for forest areas and 35% for Cerrado areas in rural properties located within the Legal Amazon, and 20% in other regions of the country (Brazil, 2012).

The indicator used will follow the model proposed by MAPA (2022):

$$ICCF = \frac{d}{b * c} \qquad (1)$$

where *ICCF* is the Forest Code Compliance Index; *b* is the area of the rural properties; *c* is the proportion of the rural property area that should be RL; *d* is the area of native vegetation within the RL of the rural property.

In constructing the database necessary for calculating this indicator, shapefiles of Legal Reserve from SICAR and annual deforestation increment shapefiles for the Amazon and Cerrado provided by INPE were used. The data processing was similar to that performed previously for Indicator 1. Finally, this analysis considered 106,436 rural properties, as not all contained corresponding Legal Reserve areas.

DIFFERENCES-IN-DIFFERENCES (DID) WITH MULTIPLE TIME PERIODS

To assess the impact of adherence to the Rural Environmental Registry (CAR), the Difference-in-Differences (DiD) method proposed by Callaway and Sant'Anna (2021) for multiple time periods was used. This method allows for the analysis of the intervention over time, dealing with variations in treatment timing and assuming parallel trends between treatment and control groups after controlling for observed covariates.

The analytical approach is divided into three stages: (i) identification of relevant causal parameters, (ii) aggregation of these parameters to obtain summary measures, and (iii) estimation and inference on different target parameters. Callaway and Sant'Anna (2021) propose various estimators for causal parameters, including outcome regression (OR), inverse probability weighting (IPW), and doubly robust (DR) estimators.

DR estimators combine OR and IPW, offering robustness against specification errors in regression and treatment probability models, which improves the accuracy of the estimates. Inverse probability weighting adjusts the weights of observations based on the probability of treatment, correcting for selection bias and assigning more weight to less represented units in the treatment group.

Mathematically, inverse probability weighting is given by the following equation:

$$P_g X = P(G_g = 1 | X, G_g + (1 - D_t)(1 - G_g) = 1) \quad (2)$$

where, G_g is defined as a binary variable that takes the value 1 if the unit is treated in period g; X is a vector of observable variables; and $[(1 - D_t)(1 - G_g) = 1]$ also denotes a binary variable that takes the value 1 if the unit belongs to the control group "Not-Yet-Treated."

In this analysis, once treated, rural properties remain treated in subsequent periods. Thus, the estimation of the Average Treatment Effect on the Treated (ATT) is calculated for a group "g" at a time "t", allowing for variations according to observed covariates, the treatment period, and the temporal evolution of the effects.

To organize the analysis, the properties were grouped according to the registration year, with groups defined as: g = 2014, 2015, 2016, ..., 2021. The semi-parametric approach to ATT is used to capture complex patterns in the data, and estimation is possible even in the presence of a "never treated" or "not yet treated" control group.

In this study, the estimation will be conducted considering rural properties that are not yet treated as the control group. Thus, the estimator is identified by:

$$ATT_{dr}^{ny}(g,t) = E\left[\left(\frac{G_g}{E[G_g]} - \frac{\frac{p_{g,t}(X)(1-D_t)(1-G_g)}{1-p_{g,t}(X)}}{E\left[\frac{p_{g,t}(X)(1-D_t)(1-G_g)}{1-p_{g,t}(X)}\right]}\right)(Y_t - Y_{g-1} - m_{g,t}^{ny}(X))\right] \quad (3)$$

where, $m_{g,t}^{ny}(X) = E[Y_t - Y_{g-1}|X, D_t = 0, G_g = 0]$, and represents the population results for the Not-Yet-Treated group.

The elements $w_g^G = \frac{G_g}{E[G_g]}$ e $w_g^C = \frac{\frac{p_{g,t}(X)(1-D_t)(1-G_g)}{1-p_{g,t}(X)}}{E\left[\frac{p_{g,t}(X)(1-D_t)(1-G_g)}{1-p_{g,t}(X)}\right]}$ correspond to the propensity scores assigned to the treatment and control groups, respectively, allowing both to be properly comparable.

The methodology of Callaway and Sant'Anna (2021) also proposes different schemes for aggregating the treatment effect. One approach is to observe the average effects for each group; that is, instead of analyzing how the treatment affects each group at different time periods, a single average treatment effect is calculated for each group by aggregating the effects over all time periods.

Initially, to obtain the average effect for each group separately, in order to understand the heterogeneity in the effect of participating in the treatment, the following equation is used:

$$\theta_{sel}(\tilde{g}) = \frac{1}{\tau - \tilde{g} - 1} \sum_{t=\tilde{g}}^{\tau} ATT(\tilde{g}, t) \quad (4)$$

ϑ_{sel} $(\tilde{g}\tilde{g})$ corresponds to the average effect of participating in the treatment among units in group $\tilde{g}$, across all its post-treatment periods. Then, the average of these effects is calculated to summarize the overall average treatment effect.

Thus, the average effect of participating in the treatment, experienced by all treatment units, is given by:

$$\theta_{sel}^{O} = \sum_{g \in G} \theta_{sel}(g) P(G = g | G \leq \tau) \quad (5)$$

To highlight the dynamics of how the average treatment effects change over time, according to the duration of exposure to the treatment, the general treatment effect parameters are defined by calculating the average treatment effects across all events, given by:

$$\theta_{es}(e) = \sum_{g \in G} 1\{g + e \leq \tau\} P(G = g | G = e \leq \tau) ATT(g, g + e) \qquad (6)$$

where, $e = t - g$ denotes the time elapsed since the treatment was adopted. Thus, equation (6) represents the average treatment effect after e periods of time since its adoption. In other words, this aggregation method captures the heterogeneity of treatment effects over time.

It is common to use event study regressions and plot β_e at different values of e, interpreting the differences as due to the dynamics of the treatment effect. However, there are some limitations that may include compositional changes that complicate the interpretation of these parameters. To address this issue, an alternative is to "balance" the groups with respect to the time of the event, aggregating the $ATT_{(g,t)}$'s for a fixed set of groups that are exposed to the treatment for at least a specified number of periods, and is defined by:

$$\theta_{es}^{bal}(e;\ e') = \sum_{g \in G} 1\{g = e' \leq \tau\} ATT(g, g + e) P(G = g | G + e' \leq \tau) \qquad (7)$$

ANALYSIS AND DISCUSSION OF RESULTS

In this section, the main results from both the descriptive statistical analysis of the data and the estimation of the CAR effects will be presented.

DESCRIPTIVE DATA ANALYSIS

Table 3 presents the descriptive analysis of the variables used in the estimation, considering the period prior to the implementation of the CAR. Based on the results, it was observed that the agricultural frontier of the Central-West region had 229,386 rural properties that would eventually be registered. Of this total, 54.02% (123,924) were located in the state of Goiás, followed by Mato Grosso with 31.30%. Regarding deforestation in the region, the total area amounted to more than 2.5 million hectares (ha) deforested, with an average of 1.91 ha deforested per property over time.

Analyzing by property size, 67.58% of the total properties are small, meaning they comprise up to four fiscal modules, primarily located in the state of Goiás. The largest total deforested area was observed in Mato Grosso, amounting to 357,248.6 ha, which corresponds to 59.90% of the total deforested area by all small properties.

Regarding medium-sized properties, with areas between four and fifteen fiscal modules, Mato Grosso has half the number of properties compared to Goiás; however, its total deforested area is slightly larger, totaling 291,196.50 ha. The average deforestation per property in the state was 3.94 ha, more than double that observed in Goiás. The observed differences may be associated with the land use dynamics between the two states or the individual size of the properties.

Among properties located in the agricultural frontier, 53.04% of total deforestation occurs on large properties exceeding fifteen fiscal modules, with an average of 8.4 hectares deforested per property. Mato Grosso exhibits the highest deforestation averages (13.90 ha), followed by Goiás (6.27 ha) and Mato Grosso do Sul (5.33 ha). The elevated average in Mato Grosso may be explained by the agricultural pressure the state experiences. According to MAPBIOMAS (2024), between 1985 and 2023, pasture area in the state increased from 6% to 24%, demonstrating agricultural expansion over natural areas.

Table 3 | Descriptive statistics for the variables used, considering the period prior to the implementation of the CAR.

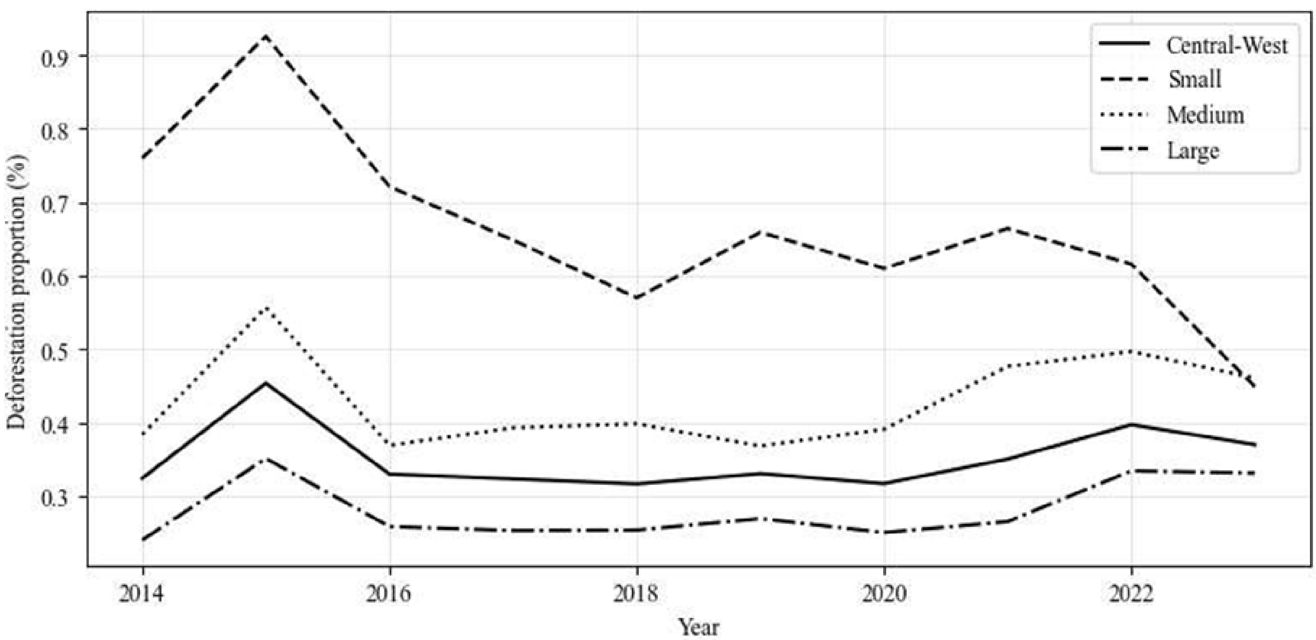
		Deforested area					
Small Properties	**Number of properties**	**Total**	**Min**	**Mean**	**Max**	**Variance**	**Standard deviation**
DF	2,932	727.79	0.00	0.04	16.65	0.10	0.32
GO	88,511	206,671.60	0.00	0.39	139.87	5.43	2.33
MS	13,369	31,712.28	0.00	0.39	224.34	9.22	3.04
MT	50,220	357,248.60	0.00	1.18	351.67	33.81	5.81
Central-West	**155,032**	**596,360.27**	**0.00**	**0.64**	**351.67**	**14.99**	**3.87**
				Medium properties			
DF	676	432.58	0.00	0.11	15.92	0.64	0.80
GO	25,669	283,334.00	0.00	1.84	544.22	80.58	8.98
MS	8,060	81,615.56	0.00	1.65	373.89	88.74	9.42
MT	12,243	291,196.50	0.00	3.94	953.08	470.67	21.69
Central-West	**46,648**	**656,578.64**	**0.00**	**2.33**	**953.08**	**18.42**	**13.73**
				Larges properties			
DF	893	7,970.00	0.00	1.49	394.56	130.31	11.42
GO	9,744	366,506.70	0.00	6.27	5,376.25	1,325.53	36.41
MS	7,733	255,029.40	0.00	5.33	1,537.82	1,039.31	32.24
MT	9,336	786,004.40	0.00	13.90	7,252.05	8,726.27	93.41
Central-West	**27,706**	**1,415,511.50**	**0.00**	**8.41**	**7,252.05**	**3,709.68**	**60.91**
Total	**229,386**	**2,668,450.41**	**0.00**	**1.91**	**7,252.05**	**505.63**	**22.49**

Source: Prepared by the authors.

In the period after the CAR, Figure 1 shows the annual proportion of deforestation in rural property areas, revealing a general trend of decline. It is observed that small properties have the highest proportion of deforested area compared to other sizes, with a peak in 2015 and then a decreasing trend until 2023. The high proportion of deforested area in small properties can be partially attributed to limited productive land availability. These producers often utilize a greater share of their property to maintain subsistence or economic viability, which intensifies pressure on natural resources. This pressure is further compounded by restricted access to technology, credit, and technical assistance. Such constraints frequently result in more intensive land use and, consequently, higher proportional deforestation relative to property size.

Medium-sized properties have a lower proportion of deforestation; however, it is still above the average observed for the entire Central-West frontier and shows a noticeable increase between 2020 and 2022. Finally, large properties have the lowest proportion, although an increasing fluctuation is observed starting in 2021.

Figure 1 | Annual proportion of deforestation relative to rural property area.

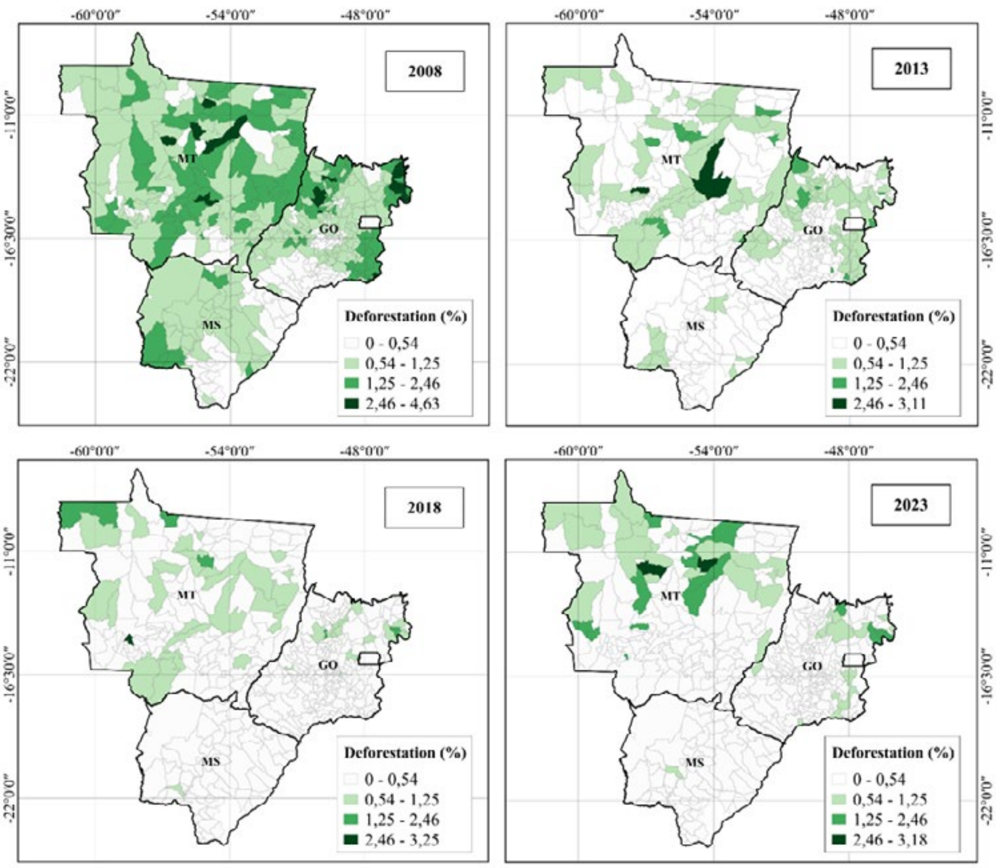


Source: Prepared by the authors.

Figure 2 presents the percentage of deforestation relative to the total area of rural properties in the municipalities. As the analyzed period progresses, the deforestation percentages converge, making the map visualization more homogeneous. In 2008, the highest percentage of native vegetation reduction was 4.62% in properties located in Simolândia (GO). In the year before the CAR (2013), the maximum deforestation percentage decreased to 3.11%, referring to properties in the municipality of Nova Marilândia (MT). In 2018, the deforestation percentage slightly increased to 3.24%, observed in properties in Reserva do Cabaçal (MT). Finally, in 2023, the deforestation percentage reached 3.18% in properties in Poro dos Gaúchos (MT).

This result corroborates the descriptive statistics, which indicated Mato Grosso as the state with the highest deforestation in its rural properties during the period prior to the CAR. This trend is also reflected in later periods, with deforestation percentages being more heterogeneous compared to other states.

Figure 2 | Percentage of deforestation relative to the area of rural properties by municipality in the Central-West agricultural frontier.



Source: Prepared by the authors.

The discussion about the increase in deforestation in rural properties is complex, but some factors that may have contributed include the relaxation of environmental legislation, land use conversion, and the weakening of enforcement by environmental agencies (Costa and Escada, 2023). The descriptive statistics presented are essential for contextualizing the situation before and after the implementation of the CAR; however, it is important to highlight that these results do not establish causality. To measure the impact of the CAR implementation on deforested areas in rural properties in the Central-West agricultural frontier, causal estimations are necessary to isolate and determine the effects of this environmental policy.

EFFECTS[2] ON DEFORESTATION IN RURAL PROPERTIES

Table 4 shows the estimates of the causal impact of the CAR on deforestation in rural properties. This regulatory instrument established a database that allows for the monitoring of properties regarding the reduction of native vegetation, leading to the expectation of a decrease in deforestation.

When analyzing the treatment effects by group for small properties, which is crucial for understanding the deforestation dynamics after rural producers registered their properties in the CAR, different results are observed over the years. For those who registered in 2015, there is a 1.29% reduction in deforestation. For those registered in 2016, the reduction is slightly higher at 1.36%. In contrast, for properties registered in 2021, deforestation increased by 3.72%.

The analysis of the balanced event study reveals important patterns regarding the CAR's impact on deforestation, as it incorporates the duration of exposure to the treatment. For small properties, a positive effect is observed in the year of treatment (e = 0), with a 0.71% increase in deforestation. For groups with at least three years of exposure (i.e., registered in the CAR, e=3), the observed effect was a 1.31% reduction in deforestation starting from the third-year post-treatment. Groups with longer exposure periods (e=4, 5, and 6) showed progressively greater deforestation reductions. These results indicate that while the treatment effect may initially lead to an increase

2 For more information or to access the full details of the parallel trends tests, please contact the authors by email.

in deforestation, it reverses and becomes more pronounced over time, with a more substantial reduction after several years. This pattern suggests that the treatment may have a delayed impact on reducing deforestation, with time allowing the CAR to become more effective in mitigating deforestation.

For medium-sized rural properties, with areas ranging between four and fifteen fiscal modules, the effect of registration in the CAR on deforestation also shows distinct patterns. In 2015, the treatment effect was a 3.07% reduction in deforestation. However, considering the balanced event study, more significant changes are observed over time. For properties with e=4, deforestation decreased by 3.77% in the fourth-year post-treatment. This effect intensified further for groups with e=6, reaching a 7.91% reduction by the sixth year. These results reinforce previous findings that deforestation reductions become more pronounced as the duration of property registration increases.

For large properties (exceeding fifteen fiscal modules), an opposite effect was observed. Groups with at least six years of treatment exposure (e=6) exhibited a 4.30% increase in deforestation at the time of registration. This result suggests a delayed treatment effect and indicates that the CAR's impact may differ for these properties, potentially due to distinct characteristics or variations in policy implementation and monitoring.

Table 4 | Estimates of the CAR's impact on deforestation in rural properties.

Group-Time Effects for Small Properties			
2015	**2016**	**2021**	**ATT**
-0.0129* (0.0038)	-0.0136* (0.0030)	0.0372* (0.0092)	-0.0089 (0.0034)

Period	Event-Study Effects					ATT
***e* = 0** **(2014-2021)**	0 0.0071* (0.0020)					0.0071* (0.0019)
***e* = 3** **(2014-2018)**		3 -0.0131* (0.0028)				-0.0031 (0.0018)
***e* = 4** **(2014-2017)**		3 -0.0131* (0.0025)	4 -0.0145* (0.0030)			-0.0052* (0.0021)
***e* = 5** **(2014-2016)**		3 -0.0129* (0.0028)	4 -0.0145* (0.0034)	5 -0.0222* (0.0043)		-0.0087* (0.0024)
***e* = 6** **(2014-2015)**					6 -0.0229* (0.0064)	-0.0069* (0.0036)

Group-Time Effects for Medium Properties	
2015	**ATT**
-0.0307* (0.0107)	-0.0174* (0.0075)

Period	Event-Study Effects		ATT
***e* = 4** **(2014-2017)**	4 -0.0377* (0.0111)		-0.0113 (0.0066)
***e* = 6** **(2014-2015)**		6 -0.0791* (0.0216)	-0.0251* (0.0095)

Event-Study Effects for Large Properties		
***e* = 6** **(2014-2015)**	0 0.0430* (0.0144)	-0.0024 (0.0175)

Source: Prepared by the authors. Note: * p-value < 0.05.

The observed results corroborate the MAPA (2023) evaluation report, which found a reduction in deforestation for small properties after registration in the CAR, and an increase for large properties, considering the duration of time in the program. The effects found in this study are also similar to those presented by Souza *et al.* (2022), although their strategy for defining property size differs. Overall, a reduction in deforestation was observed for small properties, while for large properties, the authors did not find significant effects, which contrasts with the results presented here.

Finally, the increase in deforestation cannot be directly attributed to registration in the CAR, as deforestation is permitted as long as the percentage of native vegetation preservation on the property is respected. On the other hand, registration in the CAR represents the first step towards environmental regularization, and continuous monitoring of properties is a strategy to prevent illegal deforestation.

ENVIRONMENTAL COMPLIANCE IN RURAL PROPERTIES

To complement the previous analysis, which observed effects of both reduction and increase in deforestation, the effect of CAR registration on environmental compliance was assessed. Specifically, this evaluation focuses on the ability of rural properties to meet the environmental requirements imposed by the Forest Code, such as the designation of the Legal Reserve area.

To achieve this, the Forest Code Compliance Index (ICCF) was calculated, where values less than 1 indicate that the rural property is non-compliant, meaning the area of native vegetation is smaller than the area required by law (Legal Reserve). If the ICCF is greater than 1, the rural property has a greater area of native vegetation than legally defined. The ICCF result was treated as a dummy variable, where the value is 0 if the ICCF is less than 1, and 1 otherwise. The effect estimated using the DiD method proposed by Callaway and Sant'Anna (2021)

shows how the treatment alters the probability of a property being compliant or non-compliant. For small properties (Table 5), the estimate indicated a marginally small increase in the probability of properties registered in 2016 being environmentally compliant. On the other hand, for the 2019 group, a negative effect of 0.81% was observed, suggesting a reduction in compliance. Combined with the analysis presented in the previous section, it is noted that for the group registered in 2016, there was a decrease in deforestation and an increase in environmental compliance.

In the balanced event study for small properties (Table 5), results indicate variations in environmental compliance probability according to CAR exposure time. For the group with at least one year of exposure (e=1), we observed a 0.43% reduction in compliance probability; for e=2, the reduction was 0.39%. In contrast, properties with e=4 showed a 0.55% increase. These results suggest that environmental compliance tends to improve with longer CAR registration duration. The initial-year reductions may reflect the time required for institutional effects to materialize, including cadastral data processing, environmental agencies' responsiveness, and producers' adaptation periods to Forest Code requirements.

Table 5 | Estimates of the CAR's Impact on Environmental Compliance in Rural Properties.

		Group-Time Effects for Small Properties		
		2016	**2019**	**ATT**
		0.0056* (0.0020)	- 0.0081* (0.0027)	0.0005 (0.0012)
Period		**Event-Study Effects**		
***e* = 1** **(2014-2020)**	1 -0.0043* (0.0012)			-0.0025* (0.0009)
***e* = 2** **(2014-2019)**	1 -0.0039* (0.0011)			-0.0015 (0.0009)
***e* = 4** **(2014-2017)**		4 0.0055* (0.0016)		0.0009 (0.0010)
***e* = 5** **(2014-2016)**		4 0.0049* (0.0016)	5 0.0093* (0.0023)	0.0024* (0.0012)
		Group-Time Effect for Medium Properties		
		2020		**ATT**
		-0.0220* (0.0081)		-0.0030 (0.0024)
		Group-Time Effect for Large Properties		
		2021		**ATT**
		-0.0466* (0.0108)		0.0010 (0.0035)

Source: Prepared by the authors. Note: * p-value < 0.05.

For medium-sized properties, the results show a negative effect for the 2020 registration group, indicating a 2.20% decrease in the probability of environmental compliance. For large properties, a negative effect was observed for the 2021 group, with a 4.66% reduction in the probability of compliance. The variation in environmental compliance may be linked to different economic and environmental conditions present in the years of CAR registration, as well as the specific characteristics of each property.

This study demonstrates that the effectiveness of environmental policies like CAR varies significantly by property size in Central-West Brazil's agricultural frontier, a core commodity-producing region. The identified heterogeneous effects provide evidence for tailored policy strategies that balance ecological preservation with regional economic development.

FINAL CONSIDERATIONS

The Brazilian agricultural sector, driven by modernization and technologies such as mechanization and genetic improvement, has expanded into new frontiers, often at the expense of native vegetation conversion. The Cerrado and Amazon have been the most affected biomes, which led to the creation of the Rural Environmental Registry (CAR) in 2014, designed to monitor and promote environmental preservation.

This study evaluated the impact of CAR on deforestation and environmental compliance of rural properties in the Central-West agricultural frontier, employing Callaway and Sant'Anna's (2021) Difference-in-Differences method. Data were obtained from SICAR, IBGE, and INPE.

The heterogeneous effects analysis revealed deforestation reductions of 1.29% and 1.36% for small properties registered in 2015 and 2016, respectively. Medium-sized properties also showed deforestation decreases, most notably the 2015 cohort with a 3.07% reduction. The balanced event study demonstrated a duration-dependent treatment effect: longer exposure to CAR registration correlated with greater deforestation mitigation for both small and medium properties.

Regarding environmental compliance, significant heterogeneous effects were observed only for small properties, with increased compliance probability for the 2015 cohort but decreased probability for the 2019 cohort. Medium and large properties showed reduced compliance probabilities overall. The balanced event study revealed positive effects exclusively among small properties, demonstrating progressively higher compliance probabilities with longer exposure to CAR registration.

The study faced limitations, particularly the lack of property-specific variables such as credit access and adopted technologies. Nevertheless, the results demonstrate CAR's significant influence on both reducing deforestation and improving environmental compliance, underscoring its importance as a public policy instrument for environmental preservation in agricultural frontier regions.

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