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Original article

Evaluating the spillover effects of rural credit and policies on land use change in the Mato Grosso Amazon Biome, Brasil

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ABSTRACT

This study evaluated the effectiveness of policies aimed at curbing deforestation in the Amazon biome, specifically focusing on how these policies changed agricultural land-use patterns in the state of Mato Grosso, Brazil, throughout the 21st century. Utilizing land use and land cover (LULC) maps, we analyzed the transformation of natural forests into agricultural lands over time by comparing pre- and post-policy implementation with a Spatial Durbin Model, recognizing potential spillover effects on neighbouring municipalities. Our research indicates that disincentives such as environmental penalties and land use planning decreased deforestation rates when accompanied by intense monitoring efforts. Brazilian rural credit incentives stimulate farmers to adopt environmental compliance, which has an important role in slowing down deforestation, although the Central-West Constitutional Fund (FCO) resources have limited regional impact. We observed in LULC maps that the major growth of cropland occurs in pasture areas, which in turn is displaced to the Amazon biome frontier and causes new deforestation spots, although this process lost strength after 2008 owing to new institutional path. Ultimately, the research highlights the ongoing challenges of achieving long-term sustainability amidst economic pressures, especially commodity prices, emphasizing the need for innovative policies to promote sustainable agricultural practices.

KEY WORDS: cattle ranching, deforestation, environmental fines, soybean, spatial econometrics

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1. Introduction

Deforestation of the Brazilian Amazon reached its highest annual rate in the first years of the 21st century, especially in most agriculturally developed areas. Mato Grosso state is a prominent agricultural producer in Brazil, in 2021 the state produced 3.99 million tons of cotton, accounting for 70.0% of the national total, 35.33 million tons of soybeans (26.2% of the national yield), and 32.05 million tons of maize (36.3% of the national total). The state also has the largest cattle herd in Brazil, with a total of 32.42 million heads in 2021, comprising 14.4% of the national herd (IBGE, 2024). This large agricultural production has expanded over the last three decades, mainly over the Cerrado and Amazon biomes, raising concerns about the environmental impacts of such activities.

The state of Mato Grosso, Brazil, has the second largest accumulated deforested area in the Amazon biome, and most deforestation has been caused by the expansion of the agricultural frontier, especially cattle ranching and temporary crops (SKIDMORE ET AL., 2021; SONG ET AL., 2021). The drastic environmental problems raised in the Amazon urged the government to act and develop a set of policies to curb such rates to protect the biome, despite the current scenario of relaxed enforcement actions (Nunes et al., 2024).

The Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) was the initial policy to combat deforestation and adopted a set of integrated actions and cooperation between government agencies, civil society entities, and the private sector (Bragança & Dahis, 2022; West & Fearnside, 2021). In 2008, the Federal Decree number 6.514 focused on creating disincentive mechanisms for environmental crimes, such as fines, embargoes, suspension of activities and product commercialization (Brancalion et al., 2016; Albuquerque Sant'Anna & Costa, 2021). Disincentives, such as environmental fines, have limited reach, because administrative and judicial appeals, as well as deregulation, tend to lengthen the process, even leading to the prescription and consequent non-punishment of individuals (Vale et al., 2021).

Complementary mechanisms have been developed to address the economic and environmental externalities associated with disincentive policies. In hybrid frameworks, policies designed to incentivize the adoption of sustainable practices are implemented alongside the private sector's responsibility to ensure that economic agents throughout the supply chain comply with environmental regulations. This strategy offers incentives to those who comply with the established standards, ensuring that the benefits of mitigating environmental impacts exceed the gains of non-compliance, such as the REDD+ initiatives (Bidone, 2022). Here, we highlight the Brazilian rural credit policy, which is responsible for influencing the behaviour of individuals within the agricultural sector and therefore may influence deforestation rates. This policy was designed to provide financial resources to farmers at subsidized rates, incentivizing an increase in agricultural output (Nascimento et al., 2023). The Brazilian Central Bank modified the institutional framework with the resolution number 3545 in 2008, establishing that farmers should observe environmental compliance on their activities. Assunção et al. (2020) found significant effects of the resolution on reducing deforestation in Brazilian Amazon municipalities since 2008.

Rural credit sources include credit bills, bank deposits, and rural savings accounts, which collectively contribute a significant portion of the available resources each year. Complementary, government sources augment these resources, often targeting the mitigation of regional disparities following the general principles of environmental compliance. Constitutional fund resources originate from federal taxes and are dedicated exclusively to less-developed regions in Brazil (Oliveira et al., 2019; Ribeiro et al., 2020). The Central-West Constitutional Fund (*Fundo Constitucional do Centro-Oeste* – FCO) in Mato Grosso provides financial resources for activities to reduce intra-regional income disparities and that promote environmental preservation.

Several studies have investigated deforestation in the Brazilian Amazon, including the analysis of the role of government policies (Bragança & Dahis, 2022; West & Fearnside, 2021), the impact of economic and social variables (Santos et al., 2021), the institutional framework of rural credit (Assunção et al., 2020) and testing the hypothesis of the Environmental Kuznets Curve (EKC) in a relationship between income and deforestation (Danish et al., 2019; Faria & Almeida, 2016). Here, we aimed to evaluate the effectiveness of government and hybrid policies implemented to curb deforestation in the Amazon biome throughout the 21st century, and to assess whether they affected agricultural land use patterns in the state of Mato Grosso.

2. Materials and methods

2.1. Land use and land cover assessment

The Amazon biome is an ecological spatial delimitation that covers several municipalities in Brazilian territory. This study selected 76 municipalities where the Amazon biome is classified as predominant in Mato Grosso state – in Brazil's Midwest region, covering the period between 2001 and 2021. The state has the largest soybean area and cattle heads in Brazil; however, these activities are frequently highlighted as being threatening to the environment through forest clearance for crop and pasture areas.

To assess land use change in the Mato Grosso Amazon biome, we used the land use and land cover (LULC) transition maps from MapBiomas collection 8 (MapBiomas, 2024), which are based on pixel-by-pixel (at 30 × 30 m spatial resolution) classifications of Landsat images carried out by a machine learning algorithm implemented on the Google Earth Engine (Souza et al., 2020). Transition maps were used to distinguish land cover changes that occurred from 2001 to 2021. Forest loss due to agricultural use (*FLoss*) was used as a proxy for deforestation in this study and was calculated from LULC transition maps as the sum of all transitions of forest formation to farming use. Additionally, the coverage areas for pasture and soybean were calculated annually for each municipality.

The Environmental Rural Registry (*Cadastro Ambiental Rural* – CAR) has the record of farms in Brazilian territory (Brazil, 2024). We cross-referenced data from CAR, MapBiomas LULC forest loss due to agricultural activities, and the records of rural credit contracts to verify whether there were properties that obtained rural credit resources with deforested areas after 2008. However, given the recent requirement of CAR registry in rural credit contracts, there is only data from 2018 onwards.

2.2. Econometric approach

When assessing the efficacy of mechanisms designed to mitigate deforestation, it is expected that there will be spatial spillover effects of local variables, meaning that the expansion of agricultural frontiers in municipalities causes forest cover loss and pressures its neighbours, while policies, enforcement actions, and market variables influence the behaviours of economic agents at a regional scale. To address this hypothesis, we estimated the Spatial Durbin model (SDM) with a balanced panel data, which incorporates the spatially lagged dependent and independent variables influencing the municipality and its neighbourhood (Eq. 1) in the time series. Considering that municipalities have different available area and temporal dynamics that cause heteroscedasticity in panel data, we estimated robust standard errors to fit the model. Our approach focused on estimating the influence of government and hybrid policies on private agents' decisions to convert forests into agricultural areas. All variables were logarithmically transformed to represent coefficients as elasticities.

$$Y_{ti} = \eta\tau + \rho W Y_{ti} + X\gamma + WX\theta + D + \epsilon_{it} \qquad \text{(Eq. 1)}$$

Where $i\,(i = 1, 2, \ldots, 76)$ is the Mato Grosso municipalities located in the Amazon biome, t ($t = 2001, 2002, \ldots, 2021$) is the time series, Y is the dependent variable (annual forest loss due to agricultural activities, in km^2); η is the constant parameter and τ is a vector of ones; W is a N x N matrix of spatial weights, which was computed using the queen criterion, where municipalities that share some intersection receive a value of 1. ρ and θ are the spatial autoregressive coefficient and the spatial coefficient associated with independent variables, respectively; and ϵ is the disturbance term.

The matrix of independent variables is represented by X and its γ coefficients respectively. We tested the effects of rural credit sources, splitting the resources into the Constitutional Funding (FCO) and all the other sources (CREDIT). The demand for rural credit is dependent on the agricultural area of each municipality, and to avoid issues concerning endogeneity, these variables were expressed in Brazilian currency (R$) per hectare, as the ratio between the credit value and the agricultural area. The municipal mean income and its squared value test the hypothesis of the EKC. Additionally, we included an index of cattle and crop prices to represent the market incentives to agricultural expansion.

To check the effectiveness of government actions, we included three main variables. The first variable is the basic punitive mechanism of applying monetary fines to individuals who violate environmental legislation. Given that there is a time lag between the environmental impact and the administrative sanctions, we assume the environmental fines intensity (*FINES*) as the ratio between the value of fines in year t and the lagged (t-1) forest loss (*FLoss*) area. To check the temporal effects of command-and-control operations and policies in Amazon territory, we assumed a dichotomous variable (D) that takes a value of 1 between 2008 and 2019, as proxy and time control for the period that government actions were more intense in the region (de Andreazzi et al., 2020; Dutra da Silva & Fearnside, 2022; Vale et al., 2021), as well as the interaction between the D variable and environmental fines to check whether fines have more effects when accompanied by such enforcement actions. Protected areas and cross-effect with the dichotomous variable were also included as part of the Brazilian policies to restrict the advancement of deforestation. The Eq. 2 provides the computation of the partial derivative in spatial econometrics, where the estimated coefficients represent the direct (diagonal), indirect –spillover– (off-diagonal), and total (sum of the direct and indirect) effects (Elhorst, 2014; LeSage & Pace, 2009).

$$\frac{\partial y}{\partial x} = (I - \rho W)^{-1}(\gamma + W\theta) \qquad \text{(Eq. 2)}$$

2.3. Econometric data

To estimate the econometric models, we gathered municipal level data from several Brazilian sources. Total rural credit (cost funding, investment, marketing, and industrialization) was obtained from the Brazilian Central Bank and split into Central-West Constitutional Fund resources (*FCO*) and all other sources of funding (*CREDIT*). Gross Domestic Product per capita (*GDPpc*) of each municipality was acquired from the Brazilian Statistical Office to represent the mean income. The fines applied against flora crimes (environmental fines) were gathered from the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA). We summed the area of Conservation Units and Indigenous Land, obtained from the Ministry of Environment and Climate Change (MME) and National Indigenous Peoples Foundation (*Fundação Nacional dos Povos Indígenas* – FUNAI), respectively, to characterize the extent of governmental protected areas (*PROT*).

The index for crop prices (*Pcrop*) was derived using data from agricultural crops (k = 1, 2, ..., 69) available from the Brazilian Agricultural Production Research of the Brazilian Statistical Office (IBGE, 2024). First, for each crop k in municipality i in year t, the local crop price was calculated as the ratio between the total value of production (*APV*) in Brazilian Currency and the total produced quantity (Q) in tons. Considering that some activities have relatively higher prices and lower production, we built the index, based on HARDING ET AL. (2021)as the weighted sum of each crop price by the relative share of area in Mato Grosso's total cultivated area (Eq. 3). To estimate the cattle price index (*Pcattle*), we followed ASSUNÇÃO ET AL. (2015), using the Paraná state price series of cattle (*PP*), and weighted with the share of cattle herd for each municipality (*CH*) in the total of Mato Grosso livestock (Eq. 4). Data on cattle herds were obtained from the Brazilian Statistical Office (IBGE, 2024). All variables in the Brazilian currency were updated to 2021 prices using the IGP-DI from the Getúlio Vargas Foundation (Table 1).

$$Pcrop_{it} = \sum_{k=1}^{69} \frac{APV_{ikt}}{Q_{ikt}} AREA_{ikt} \qquad \text{(Eq. 3)}$$

$$Pcattle_{it} = PP_t CH_{it} \qquad \text{(Eq. 4)}$$

Table 1. Summary statistics

Variable	Unit	Mean	S.D.	Source
FLoss	km²	50.53	79.94	(MapBiomas, 2024)
FCO	R$/hectare	12.33	28.07	(BCB, 2023)
Credit		193.94	291.03	
GDPpc	R$/habitant	42.58	32.12	(IBGE, 2024)
FINES	R$/km² (ratio of total environmental fines by deforested area in previous year)	522634.51	4915034.11	(IBAMA, 2024)
PROT	km²	14.81	33.93	(FUNAI, 2024; MMA, 2024)
Pcrop	Weighted index	8.11	14.41	(IBGE, 2024)
Pcattle		2.27	2.06	(IBGE, 2024; Paraná, 2024)

3. Results

3.1. Deforestation and policies

The Mato Grosso state had the highest deforestation rates in the Brazilian legal Amazon between 2000 and 2004 and has the second largest accumulated deforested area in the 21st century (INPE, 2024). From 2001 to 2021, Based on the MapBiomas LULC transition maps, we estimated 80,638 km² of new pasture areas originating from forested areas in the municipalities of Mato Grosso in the Amazon biome; 69.18% of this conversion occurred between 2001 and 2008, especially concentrated in the northern region (Fig. 1). A huge increase in pasture areas was noticed in the northwest region until 2010, the latter becoming crop areas. The municipalities of Colniza, Nova Ubiratã, and Confresa led the ranking of new pasture areas, while 16 (of 76) municipalities accounted for 50.69% of this deforestation.

The soybeans and other temporary crops accounted for approximately 2,399 km² of new crop areas owing to the conversion of forested areas to agriculture, with 69.35% of this area occurring between 2001 and 2008. Interestingly, the expansion of most agricultural commodities is due to a pasture shift to soybean and other temporary crops (approximately 47,547 km^2), mainly in the eastern Mato Grosso region. Querência, São Félix do Araguaia, and Tabaporã are the municipalities with the largest area shift from pasture to crop, while 12 municipalities concentrate 50.71% of total converted area.

Rural credit plays an important role in boosting agricultural production in Mato Grosso, Brazil. In 2001, the 76 municipalities with predominance of the Amazon biome in Mato Grosso secured 362.38 million (Brazilian currency) in rural credit (27.72% of state total), increasing to 16.28 billion in 2021, representing almost half of Mato Grosso rural credit (48.53%). Since 2010, credit destined for crop production has been relatively dominant over animal production credit, thereby solidifying the region's status as a significant producer of agricultural commodities (Fig. 2). The FCO resources, despite the importance on regional development, represented only 6.4% of rural credit in the municipalities between 2001 and 2021, and is heavily concentrated, with 8 municipalities summing up 52.8% of FCO sources.

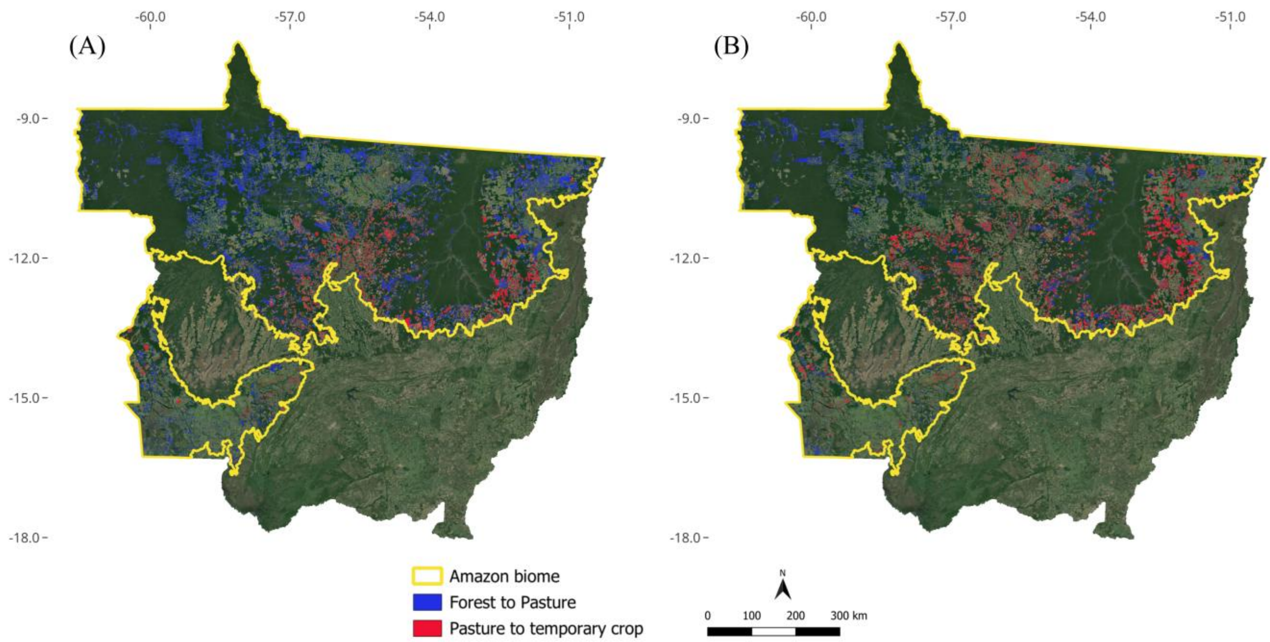

Fig. 1. Transition patterns in the Mato Grosso Amazon biome: (A) 2000–2010; (B) 2010–2020. Note: Temporary crops include soybean area. Map lines delineate study areas and do not necessarily depict accepted national boundaries

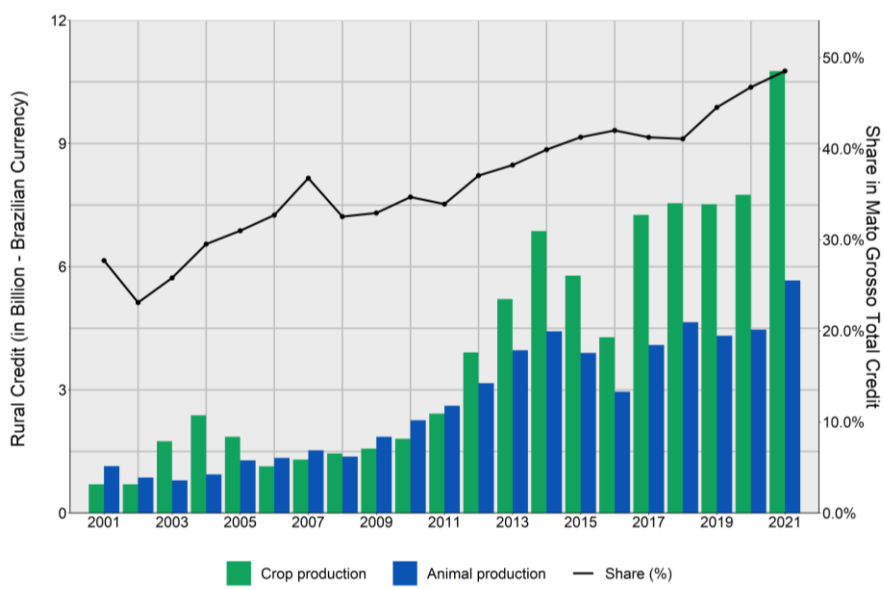

Fig. 2. Rural credit obtained by Amazon biome municipalities and its share of the total in Mato Grosso state

Despite the importance of increasing agricultural output, rural credit may indirectly or directly incentivize deforestation. To address this issue, since 2008, rural credit has required environmental compliance checks for farmers seeking loans. We compared the data from the Brazilian Central Bank and CAR registry to identify farms that obtained rural credit and presented the conversion of forest areas to agricultural uses (Table 2). Although environmental compliance is essential, there is still a notable lack of CAR registry data on rural credit. The first identification of CAR registry in credit contracts began in 2018, and the data revealed that only 10.32% of rural credit in the Mato Grosso Amazon biome was acquired by farms with CAR registry in that year, improving in the following year (55.03% of contracts had CAR registry). Comparing the data with MapBiomas LULC transition maps we identified 263.32 km^2 of natural forest conversion to agricultural use in farms with active credit contracts between 2018 and 2021, representing only 3% of total deforestation, most of these farms (95.97%) obtained resources to pasture. However, it is essential to note that this forest loss represents a small proportion of annual deforestation and may not necessarily be illegal according to the Brazilian Forest Code.

Table 2. Rural credit and forest conversion in farms with CAR identification

Year	CAR count	Rural Credit (with CAR identification, billion – Brazilian currency)	Forest conversion (km^2)	
			To pasture	To temporary crops
2018	1,977	1.258	42.99	0.52
2019	8,702	6.516	120.28	8.91
2020	4,316	2.783	66.64	0.39
2021	3,649	2.457	22.79	0.80
Total		13.014	252.70	10.62

3.2. Econometric results

To investigate the consequences of policies, rural credit, and prices on deforestation, we estimated a Spatial Durbin Model panel data (SDM). We tested goodness of fit of the SDM by removing the rural credit variables from the model. The Log-Likelihood (-965.742, p-value <0.05) confirmed the full model (Table 3) as best predictor.

Deforestation in the Amazon biome's agricultural frontier is not confined to municipal boundaries, therefore, local actions are expected to exert pressure on increasing or decreasing deforestation rates in neighbouring municipalities, and vice-versa. Our study found that rural credit directly influences the local forest conversion to agricultural areas. A 1% increase in *FCO* would result in a 0.017% decrease in forest loss in the municipality. The rural credit, except for *FCO* resources, showed impacts in the municipality (0.067%) as well as in the neighbourhood with spillover effects.

We included *GDPpc* as a proxy for mean income in each municipality to test the EKC hypothesis on deforestation. Our findings indicate that as income rises, the conversion of forest areas to agriculture tends to decrease (elasticity of -3.355%), and there is a significant negative spillover effect on neighbours. However, the results also show that each increase in income has a lower impact, as indicated by the significant and positive sign of the squared *GDPpc* variable.

Brazilian policies have evolved over the 21st century to develop a set of mechanisms to combat deforestation. In our analysis, we added the intensity of environmental fines (*FINES*) for illegal actions to determine whether monetary penalties had an impact on current forest loss. The coefficient for this variable was significant and positive and did not confirm that environmental fines were effective in reducing deforestation when acting independently.

To assess the impact of enforcement actions, we have also included a dichotomous variable *D* that takes a value of one after 2008 as temporal proxy to test the period when government actions to monitoring, control, and punishment of illegal deforestation were intensified due to the new institutional environment (PPCDAm policy, the Federal Decree number 6.514/2008, and Brazilian Central Bank resolution 3545/2008). The cross-effect between *FINES* and *D* variable (significant and negative coefficient, elasticity of-0.029 %) indicates that the set of policies, when implemented simultaneously, can reduce deforestation rates. The demarcation of protected areas (*PROT*), particularly conservation units and indigenous areas had larger efficiency during periods of intense monitoring. The total protected area increased from 808 km^2 in 2008 to 1241.3 km^2 in 2021. Additionally, this policy had a spillover effect on neighbouring municipalities, reducing contiguous deforestation.

Table 3. Spatial Durbin panel data model (SDM) estimates for 76 municipalities between 2001 and 2021. Robust standard error in parenthesis

Variable	Coefficient	Effects		
		Direct	Indirect	Total
Constant	8.991* (0.584)	-	-	-
FCO	-0.017* (0.009)	-0.018 (0.010)	-0.001 (0.012)	-0.018 (0.017)
Credit	-0.067* (0.016)	-0.071* (0.017)	-0.107 (0.125)	-0.178 (0.131)
GDPpc	-3.355* (0.246)	-3.401* (0.256)	-0.790* (0.147)	-4.191* (0.346)
$GDPpc^2$	0.351* (0.034)	0.353* (0.036)	0.024 (0.038)	0.377* (0.060)
FINES	0.077* (0.008)	0.078* (0.008)	0.018* (0.004)	0.097* (0.010)
PROT	0.010* (0.001)	0.010* (0.001)	0.002* (0.001)	0.012* (0.002)
Pcrop	0.680* (0.024)	0.687* (0.025)	0.160* (0.028)	0.846* (0.043)
Pcattle	0.454* (0.035)	0.458* (0.034)	0.107* (0.020)	0.565* (0.047)
D	-0.082 (0.104)	-0.082 (0.102)	-0.019 (0.024)	-0.101 (0.126)
D x FINES	-0.029* (0.011)	-0.030* (0.011)	-0.007* (0.003)	-0.037* (0.014)
D x PROT	-0.005* (0.002)	-0.005* (0.002)	-0.001* (0.001)	-0.006* (0.002)
W x FCO	-0.001 (0.017)	-	-	-
W x Credit	-0.049* (0.029)	-	-	-
W x GDPpc	-0.071 (0.106)	-	-	-
W x FINES	0.003 (0.010)	-	-	-
ρ	0.196* (0.027)			

Although government policies act to limit deforestation in the Amazon biome, market forces drive agricultural expansion, encouraging the opening of new areas through forest conversion. To assess the intensity of these pressures, we included *Pcrop* and *Pcattle* index in our model, and the coefficients for these variables were significant, with elasticities of 0.68% and 0.45%, respectively. The model confirmed the expectations, with prices demonstrating a spillover – indirect – effect on neighbouring municipalities.

4. Discussion

4.1. Disincentive policies

To reduce deforestation rates in the Amazon biome, the Brazilian government tightened its control of illegal deforestation in the 21st century. The PPCDAm policy first broke government inertia in punishing agents who illegally deforested the biome, followed by Federal Decree number 6.514 in 2008, which introduced more severe punishment for environmental crimes. Therefore, a series of command-and-control operations occurred throughout most of the Amazon to reduce deforestation in the Amazon biome through disincentive policies. We explored the effects of such policies in Mato Grosso state, which has experienced large growth in pasture and crop land in recent decades and may pressure the surrounding Amazon preserved forest through spillover effects.

To check the effect of intensive deforestation control policies, the dichotomous variable D was used as temporal proxy in our econometric approach to cover the period from 2008 to 2019. The findings revealed that the enforcement mechanisms implemented by the Brazilian government contributed to a reduction in deforestation during the selected period of intense monitoring and land-use planning. Environmental fines, as an independent mechanism, were ineffective at curbing deforestation in Mato Grosso. Our results expand the study of BENEVIT ET AL. (2024), which has already demonstrated the effects of the PPCDAm policy before 2008.

However, the interaction between environmental fines and the dichotomous variable showed that the set of enforcement policies (e.g., fines, embargoes, and asset seizures) may increase the risk of illegal activities regionally, as evidenced by the spillover effect, ultimately reducing deforestation rates. The priority list of municipalities (CREPIN, 2024), which includes municipalities in Mato Grosso, illustrates a successful monitoring and control policy at the regional level.

The establishment of protected areas near the agricultural frontier to prevent its expansion into forested areas was one of the key objectives of the PPCDAm policy (WEST & FEARNSIDE, 2021). According to the SDM results, the implementation of protected areas had a significant impact on reducing deforestation during the period of intense monitoring. The expansion of agriculture is geographically contiguous, and this policy has significant implications for land use in the Amazon region preventing deforestation through a break in the spatial contiguity.

4.2. Incentive policy: rural credit

Although enforcement has produced short-term results, the use of disincentive policies has limited influence on the economic agent's behaviour. In 2008, rural credit contracts in municipalities within the Amazon biome were subject to regulations by the Brazilian Central Bank, which required, through resolution number 3545 in 2008, that farms present environmental compliance. The rural credit coefficients of the SDM showed the expected effect, meaning that they have a significant influence on the slowdown of deforestation caused by agricultural land use. Our decomposition of rural credit resources demonstrates that the FCO policy did not exhibit spillover effects, limiting its influence on farmers at the municipal level. This outcome may be attributed to two main factors: i) the concentration of these resources in some municipalities of the state, limiting its effectiveness and ii) the lower relative share of these resources when compared to other sources of rural credit.

The subsidized rates of rural credit resources are fundamental to Mato Grosso's agricultural development; therefore, farmers were incentivized to achieve environmental compliance to be eligible for this policy. Additionally, new credit programs have been developed to provide funding for environmentally friendly activities such as low-carbon agriculture (STABILE ET AL., 2020). Increasing the resources available for sustainable systems, especially cattle ranching intensification, can improve the effectiveness of rural credit, especially FCO resources, through the diffusion of this source to new farmers who have not yet access to FCO (CARRER ET AL., 2020; MÜLLER-HANSEN ET AL., 2019).

In 2020, resolution number 4883 of the National Monetary Council made mandatory the presentation of CAR in credit operations. Our analysis of credit contracts with the CAR registry started in 2018 and the data show that only 3% of deforestation occurred within farms with the registry and obtained rural credit, demonstrating that rural credit policy was able to reduce deforestation on farms. While CAR was not mandatory to rural credit contracts before 2020 (and therefore increases data variability), the available information indicate that deforestation predominantly occurred on cattle ranching farms. The limited available registry for rural credit hinders the effective regulation of farms potentially involved in illegal deforestation. However, it is expected that with the mandatory CAR registration and increasing available data, considering the cross-referencing between rural credit contracts, CAR registry, and LULC data will provide better identification of environmental compliance at the individual level.

4.3. Economic influence on deforestation and land use change

After examining the annual LULC transitions from MapBiomas, it became evident that the major cause of forest loss is its conversion to pasture lands. This study indicates that a total of 80,638 square kilometres of forested land in the Mato Grosso Amazon biome municipalities were converted to pasture between the years 2001 and 2021. Although this trend experienced a considerable decrease following the implementation of enforcement policies in 2008 yet remain concentrated close to the borders of Mato Grosso state.

Agricultural commodities require a minimum level of infrastructure to advance their frontiers. Once these requirements are met, cattle ranching is partially displaced, allowing temporary crops to be cultivated in such areas in the state of Mato Grosso (VIEIRA ET AL., 2022). Our results confirm and extend the findings of previous studies, highlighting that the most significant growth in croplands occurs over pasture areas that were once forests. Already deforested areas significantly increase land values in Mato Grosso due to their use for agricultural crops (Lourençoni et al., 2021), while cattle ranching is pushed into new areas where infrastructure is inadequate for major agricultural commodities and forested areas predominate. This displacement of cattle ranching to new areas, as a spatial reallocation of the activity, results in further deforestation required to establish the pasture (Barbosa et al., 2023; Fearnside, 2001). These findings align with the current literature, which identifies cattle ranching as the primary cause of deforestation in the Brazilian Legal Amazon owing to its extensive management model (Colman De Azevedo Junior et al., 2022; Skidmore et al., 2021).

The EKC hypothesis suggests that higher levels of environmental degradation are typically associated with the early stages of economic growth. However, as per capita income rises, the relationship between economic growth and environmental improvement becomes evident. Our results demonstrate that the income increase in Mato Grosso lead to reduced deforestation rates. This is more evident when comparing municipalities where the livestock farming is predominant, being an activity characterized by low use of capital and labour in extensive models (Müller-Hansen et al., 2019; Pedrosa et al., 2021), consequently, it has a low impact on income and has higher deforestation rates, since this activity drives deforestation to new areas. However, when it shifts to agricultural crops, there is a substantial rise in income and due to land use policies and use of already cleared land, deforestation rates are low (Pereira & Brisola, 2022).

Agricultural prices create incentives for farmers to expand their operations and total output, which in turn cause new deforestation to expand crop and pasture areas. Meanwhile, enforcement policies act as a counterbalance, reducing the expected returns for those involved in illegal deforestation. Previous studies, using different approaches, demonstrated that agricultural commodities prices exert pressures in forested areas (Assunção et al., 2015; Harding et al., 2021).

Our analysis used an index of agricultural crop prices by weighting each crop price by its area for each municipality and cattle by the share of the herd in the municipality, relativizing the impact of each activity. The results confirm that prices are an important component of deforestation process in the Brazilian Amazon, since agricultural activities are the major cause of forest loss. However, agricultural commodities, such as soybean, maize, cotton, frequently expand substituting pasture areas by crop area, therefore, their direct impact on forested areas are minor, and as argued, while cattle prices are attractive, this activity is displaced to new areas in the Amazon. We suggest that future studies explore how relative prices between agricultural crops and cattle impact temporal decisions to convert land use.

5. Conclusions

This study assessed the effects of policies to curb Amazon deforestation on land-use change in Mato Grosso. This process slowed down in the 21st century, particularly after the measures were developed since 2008. The findings indicate that the Brazilian government's efforts to reduce deforestation through disincentives, such as environmental fines, command and control operations, and land-use planning, have yielded significant results. However, that institutional environment has been weakened in recent years, with reduction of monitoring and law enforcement, slowdown of establishment of new protected areas, and loosening of rules for environmental licensing, the deforestation rates have increased, demanding new strategies (as hybrid policies) to maintain control over forested areas.

For analysing the incentive policies, the spatial model included rural credit as a variable distinguished FCO from other credit sources. This financial policy acted as an incentive mechanism to reduce forest area loss, requiring farmers to seek environmental compliance for subsidized resources and to constrain illegal deforestation. However, the results show that economic incentives, especially prices, encouraged land-use changes that expanded the agricultural frontier by converting natural forests to pasture and subsequent succession to arable lands.

Long-term sustainability remains challenging as economic pressure drives land conversion. This study confirms the influence of agricultural prices within the Amazon frontier, incentivizing pasture-to-arable land shifts and pasture displacement to forest areas, causing new deforestation. Deforestation containment policies and economic incentives for arable land have produced spillover effects, with the process expanding deeper into the Amazon year on year owing to proximity to the agricultural frontier. To address this spatial effect, the government should consider incentivizing new mechanisms to control deforestation, such as market agreements with a greater capacity to enforce compliance.

Additionally, expanding and developing new rural credit programs to fund sustainable activities, particularly cattle production and low-carbon programs, is recommended as positive effects have been observed at municipal and regional scales.

Data Statement

The data that support the findings of this study are openly available in: Rodrigues, Marcos (2024), "Data: Evaluating the Spillover Effects of Deforestation Policies on Land Use Change in the Mato Grosso Amazon biome", Mendeley Data, V1, doi: 10.17632/wp2v8gddwn.1

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