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THE ABC PROGRAM AND ITS EFFECTS ON PASTURE DEGRADATION AND DEFORESTATION IN THE LEGAL AMAZON

O PROGRAMA ABC E SEUS EFEITOS NA DEGRADAÇÃO DE PASTAGENS E NO DESMATAMENTO NA AMAZÔNIA LEGAL

EL PROGRAMA ABC Y SUS EFECTOS EN LA DEGRADACIÓN DE LOS PASTOS Y LA DEFORESTACIÓN EN LA AMAZONÍA LEGAL

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Walberti Saith[1], **Ânderson Pereira Rocha**[2]

ABSTRACT

The study shows that credit from the ABC pasture recovery program has a direct and indirect impact on reducing pasture degradation in the Legal Amazon but does not significantly influence deforestation. Spatial analysis reveals that the credit has positive effects that spread to neighboring municipalities, suggesting that policies incentivizing pasture recovery can generate beneficial regional externalities. On the other hand, pasture degradation is strongly associated with increased deforestation, indicating that the loss of productivity leads to the expansion of the agricultural frontier into forested areas. Thus, access to rural credit for sustainable agriculture should be strengthened and expanded, especially in regions with high levels of degradation, as this can be an effective strategy to indirectly curb deforestation. However, the limited effect of the program on deforestation reinforces the need for complementary actions, such as increased enforcement. Furthermore, the spatial concentration of impacts indicates that coordinated regional policies are essential to mitigate the diffuse effects of extensive livestock farming and promote an effective transition to sustainable agricultural practices.

Keywords: Sustainable Intensification. Public Policies. Livestock Farming. Spatial Analysis.

RESUMO

O estudo demonstra que o crédito do programa de recuperação de pastagens ABC tem um impacto direto e indireto na redução da degradação de pastagens na Amazônia Legal, mas não influencia significativamente o desmatamento. A análise espacial revela que o crédito tem efeitos positivos que se estendem aos municípios vizinhos, sugerindo que políticas de incentivo à recuperação de pastagens podem gerar externalidades regionais benéficas. Por outro lado, a degradação de pastagens está fortemente associada ao aumento do desmatamento, indicando que a perda de produtividade leva à expansão da fronteira agrícola para áreas florestais. Assim, o acesso ao crédito rural para a agricultura sustentável deve ser fortalecido e ampliado, especialmente em regiões com altos níveis de degradação, pois essa pode ser uma estratégia eficaz para conter indiretamente o desmatamento. Contudo, o efeito limitado do programa sobre o desmatamento reforça a necessidade de

[1] PhD in Applied Economics. Federal University of Rondônia (UNIR). E-mail: walberti@unir.br
Orcid: https://orcid.org/0000-0001-8407-4223
[2] MBA/Specialist in Public Institution Management. State Institute for the Development of Professional Education of Rondônia (IDEPRO). E-mail: andersonpvh12@gmail.com
Orcid: https://orcid.org/0000-0001-5616-263X

ações complementares, como o aumento da fiscalização. Além disso, a concentração espacial dos impactos indica que políticas regionais coordenadas são essenciais para mitigar os efeitos difusos da pecuária extensiva e promover uma transição efetiva para práticas agrícolas sustentáveis.

Palavras-chave: Intensificação Sustentável. Políticas Públicas. Pecuária. Análise Espacial.

RESUMEN
El estudio muestra que el crédito del programa de recuperación de pasturas del ABC tiene un impacto directo e indirecto en la reducción de la degradación de pasturas en la Amazonía Legal, pero no influye significativamente en la deforestación. El análisis espacial revela que el crédito tiene efectos positivos que se extienden a los municipios vecinos, lo que sugiere que las políticas que incentivan la recuperación de pasturas pueden generar externalidades regionales beneficiosas. Por otro lado, la degradación de pasturas está fuertemente asociada con el aumento de la deforestación, lo que indica que la pérdida de productividad conduce a la expansión de la frontera agrícola en áreas forestadas. Por lo tanto, el acceso al crédito rural para la agricultura sostenible debe fortalecerse y ampliarse, especialmente en regiones con altos niveles de degradación, ya que esta puede ser una estrategia eficaz para frenar indirectamente la deforestación. Sin embargo, el efecto limitado del programa sobre la deforestación refuerza la necesidad de acciones complementarias, como una mayor aplicación de la ley. Además, la concentración espacial de los impactos indica que las políticas regionales coordinadas son esenciales para mitigar los efectos difusos de la ganadería extensiva y promover una transición efectiva a prácticas agrícolas sostenibles.

Palabras clave: Intensificación Sostenible. Políticas Públicas. Ganadería. Análisis Espacial.

1 INTRODUCTION

Most cattle farming in Brazil is based on pasture-based feeding systems, providing sustenance for cattle in a more economical way. With the increase in international demand for meat, there has been an expansion of the Brazilian herd, which jumped from 185.3 million head in 2002 to 238.6 million head in 2023 (IBGEa, 2025). E. This increase was accompanied by the expansion of pasture areas, which jumped from 172 million hectares (ha) to 179 million (ha) in the same period (LAPIG, 2025). Much of this growth occurred in the Legal Amazon, where the herd jumped from 57.1 million head (30.8% of the national total) to 106.6 million head, equivalent to 44.7% of the national total.

One of the major obstacles in the cattle and beef production chain is its low productivity, largely due to pasture degradation. Dias-Filho (2017) highlights that one of the main causes of pasture degradation in Brazil is the inadequate management of pasture areas, particularly overgrazing. Other consequences of excessive livestock density include soil compaction, decreased soil organic matter, increased soil erosion, and deterioration of the soil's physical and hydrological attributes (Galdino *et al*., 2016; Moratelli *et al*., 2023). From an environmental perspective, pasture degradation causes the release of carbon stored in the soil. Dias-Filho (2017) argues that this phenomenon reduces the capacity of pastures to retain carbon, releasing large quantities of CO2 into the atmosphere, which exacerbates climate change.

Pasture degradation, in addition to reducing livestock productivity, indirectly contributes to deforestation by increasing the demand for new areas to maintain production levels (Garcia *et al*., 2017; Silveira *et al*., 2022). In this context, pasture recovery emerges as a key strategy to mitigate environmental impacts and improve land use efficiency. Among public policies aimed at agricultural sustainability, the Low Carbon Agriculture Program (ABC) stands out, which aims to promote the adoption of sustainable technologies through rural credit, focusing on the recovery of degraded areas, crop-livestock-forestry integration, and reduction of greenhouse gas emissions. These strategies contribute to increasing soil carbon sequestration and reducing the intensity of pasture emissions (Silva *et al.*, 2017; Feltran-Barbieri; Féres, 2021).

According to LAPIG (2025), in 2023 Brazil had 115.4 million hectares of pastureland with some level of degradation, with 43.6 million hectares located in the Legal Amazon (37.8% of the total). Despite the implementation of public policies aimed at sustainable agriculture, such as the ABC Program, the effectiveness of these actions in reducing environmental

pressure remains uncertain. In this context, the need arises to understand the determinants of pasture degradation and deforestation, as well as the spatial effects associated with these dynamics. Thus, this study seeks to answer: what is the relationship between pasture degradation, ABC Program credit, cattle farming, and deforestation in the municipalities of the Legal Amazon, and how do these variables interact spatially over time?

Thus, the overall objective of this study is to analyze the spatial determinants of pasture degradation and deforestation in municipalities of the Legal Amazon between 2010 and 2023, evaluating the role of rural credit from the ABC Program, cattle production, and municipal income, through the application of spatial panel models. Specifically, it aims to investigate the association between ABC Program credit and the area of degraded pastures, considering local and spatial effects among municipalities. Furthermore, it seeks to assess the impact of pasture degradation on deforestation dynamics, focusing on direct and regional effects.

2 THE ABC PROGRAM IN BRAZIL

Pasture degradation represents one of the main obstacles to the sustainability of cattle farming and is also a significant factor in greenhouse gas (GHG) emissions. Degraded pastures lose their ability to efficiently capture and store carbon in the soil, becoming a source of CO2 emissions (Galdino *et al*., 2016; Dias-Filho, 2017). This dynamic amplifies the effects of climate change and contributes to the expansion of the agricultural frontier over forest areas, especially in the Legal Amazon (Garcia *et al*., 2017; Silva *et al*., 2017).

In this context, the federal government created the Sectoral Plan for Mitigation and Adaptation to Climate Change for the Consolidation of a Low-Carbon Economy in Agriculture - the ABC Plan. Established in 2010 as an instrument for implementing the National Policy on Climate Change (Law No. 12.187/2009)[3], it emerges as one of the main strategies for mitigating and adapting to climate change in the Brazilian agricultural sector. Its practical operation is carried out through the ABC program, which consists of specific rural credit lines aimed at financing sustainable and low-carbon technologies.

The ABC Program provides financing for six main practices: (i) no-tillage farming systems; (ii) recovery of degraded pastures (RDP); (iii) crop–livestock–forest integration (CLFI); (iv) biological nitrogen fixation (BNF); (v) planted forests; and (vi) animal waste management. These practices aim not only to reduce emissions but also to increase

[3] Its institutionalization occurred through Decree No. 7.390/2010

productivity and enhance the climate resilience of national agriculture (Feltran-Barbieri; Féres, 2021).

The degraded pasture recovery subprogram, in particular, seeks to restore low-productivity pasture areas through techniques such as the establishment of suitable forage species, corrective soil fertilization, weed control, and pasture rotation. In addition to promoting carbon sequestration in the soil, restored pastures exhibit higher livestock carrying capacity, reducing the need to open new areas to increase production and thus indirectly acting as a control on deforestation (Silva *et al*., 2017).

During the first phase of the program (2010–2020), the established target was to restore an area of 15 million hectares (ha) (Agroicone, 2020; Gianetti; Ferreira-Filho, 2021). It is estimated that approximately 10.44 million hectares of degraded pastures were effectively restored, contributing to the mitigation of 39.57 to 57.52 million tonnes of CO2 equivalent (Agroicone, 2020). The ABC Program credit line, linked to the national agricultural policy, financed a total of R$ 19.6 billion during this period, with the recovery of degraded pastures (RDP) being one of the practices that absorbed the largest share of resources.

The ABC Plan (2010–2020) was an important instrument for Brazil to achieve its climate change mitigation targets. With the end of the initial period, the government launched a new version in 2020, the ABC+ Plan (2020–2030) (Decree No. 10,431/2020). With a broader and more robust approach than its predecessor, the ABC+ Plan set a target of restoring 30 million hectares of degraded pastures by 2030 (Matias; Albuquerque, 2024; MAPA, 2025).

Recent evidence indicates that the ABC Program, especially the RPD credit line, can play a central role in the sustainable intensification of cattle production. Bragança *et al*. (2022), for example, show that the rural extension services provided by the program were essential in expanding the adoption of good management practices and the restoration of pastures on farms with different production profiles.

However, there are still important challenges to be considered. Piao *et al*. (2021) d highlight that the effectiveness of the plan may be limited by the lack of adequate technical training, difficulties in accessing credit, and weak coordination with local institutions. In addition, the regional distribution of credit is uneven: states with greater infrastructure and productive organization, such as Mato Grosso, have a higher capacity to absorb funds, while regions such as the North show low levels of access to resources (Gianetti; Ferreira-Filho, 2021; Telles *et al*., 2024).

According to Cardoso *et al*. (2024), the main challenges in accessing credit under the ABC Program are faced by family farmers, who encounter bureaucratic hurdles—especially those imposed by the credit lines—and a lack of specialized technical assistance for preparing project proposals. For Conceição (2025), low uptake of the credit lines is also due to limited awareness of these instruments among both producers and bank employees, particularly when compared to other programs, such as the National Program for Strengthening Family Farming (Pronaf).

Another recurring challenge concerns the measurement of the program's actual impacts on environmental variables. While some studies identify positive effects on pasture recovery and cattle productivity (Oliveira; Souza; Assunção, 2024), the direct impact on curbing deforestation remains uncertain, often being indirect or conditional on other territorial and institutional factors.

Even so, the literature converges on the assessment that policies such as the ABC Program are fundamental to promoting the sustainable intensification of agriculture and cattle production, reducing the negative environmental impacts of the activity, and increasing the resilience of productive systems to climate change. When combined with territorial strategies and environmental governance instruments, these initiatives can represent an important pathway for reconciling cattle production with environmental conservation, especially in sensitive biomes such as the Amazon and the Cerrado.

3 EMPIRICAL STRATEGY

Considering the data structure, with variation over time (years) and space (municipalities), a panel data model was chosen, as it allows controlling for unobserved heterogeneity across spatial units (fixed or random effects specific to each municipality) and for common shocks or trends over time (time fixed effects). This approach makes it possible to obtain robust estimates. Mathematically, the panel data model can be defined as:

$$Y_{¿} = X_{¿}\beta + \alpha_i + \gamma_t + \varepsilon_{¿} \quad (1)$$

where $Y_{¿}$ is the dependent variable; $X_{¿}$ is the vector of independent variables; β is the vector of coefficients to be estimated; α_i is the unit-specific fixed effect for unit i; γ_t is the time fixed effect, capturing variations common to all units in period t; and $\varepsilon_{¿}$ is the random error associated with observation (i,t), which assumes a variance–covariance structure. The panel data models will be estimated in R using the *plm* package (Croissant; Millo, 2008), which

allows the implementation of fixed-effects and random-effects models.Based on Equation (1), two fixed-effects models will be estimated. The first considers degradation as the dependent variable, with the main objective of verifying whether credit from the ABC Program effectively impacts pasture recovery. In the second model, deforestation is treated as the dependent variable and degradation as the explanatory variable, in order to test the hypothesis that an increase in degraded pastures affects deforestation. In other words, degradation may act as a mediating variable between ABC Program credit and deforestation. In both models, control variables will be included, as presented in Table 1.Both dependent variables analyzed (degradation and deforestation) represent changes in land use and therefore may exhibit spatial dependence effects. To verify the existence of spatial autocorrelation, Moran's *I* is estimated, a statistical technique used to assess whether the values of a variable across different geographic regions display any spatial pattern, such as clustering or dispersion.

Although Moran's *I* provides a global statistic of spatial autocorrelation, it does not offer information on the existence of spatial *clusters* or spatial *outliers*. For this purpose, Anselin (1995) proposed the *Local Indicators of Spatial Association* (*LISA*), which make it possible to identify local spatial patterns. *LISA* quantifies spatial autocorrelation for each spatial unit, allowing the identification of local clusters of High–High (HH) and Low–Low (LL) values, as well as spatial outliers such as High–Low (HL) and Low–High (LH) patterns. Moran's *I* and *LISA* will be estimated using the *rgeoda* package a (Li; Anselin, 2025).

To capture spatial interdependence among municipalities, the panel data model can be extended to incorporate spatial effects. Specifically, spatial lags of both the dependent variable and the independent variables can be included, in addition to municipality-specific and year-specific fixed effects. In addition, spatial autocorrelation in the error term was incorporated, as represented in the system of equations (2).

$$y_{¿} = \rho W y_{¿} + X_{¿}\beta + \alpha_i + \mu_t + \epsilon_{¿} \quad (2)$$

where $y_{¿}$ is the dependent variable; ρ is the spatial dependence coefficient, that is, how the value of $y_{¿}$ in one unit is influenced by the values of the dependent variable in neighboring units; W is the spatial weights matrix, which describes the spatial relationships among units[4]; $X_{¿}$ is the vector of explanatory variables (e.g., ABC credit, GDP *per capita*, cattle herd; β is the coefficient that measures the impact of the explanatory variables on the dependent variable;

[4] The choice of the matrix type is made empirically through the estimation of Moran's *I*.

α_i is the fixed-effect term or individual effect; μ_t is the time effect term or time fixed effect, which controls for temporal variation; and $\epsilon_{¿}$ is the random error or disturbance term.

Two specifications will be estimated in a manner similar to Equation (1): first, with degradation as the dependent variable as a function of ABC Program credit; and second, with deforestation as the dependent variable and degradation as the explanatory variable. The estimations will be performed using the *splm* package (Millo; Piras, 2012).

3.1 DATA

The study area is the Legal Amazon, composed of nine states: Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins. The Legal Amazon occupies approximately 59% of the national territory. This area has 772 municipalities and encompasses most of the Amazon Rainforest, making it a focus of studies on the balance between agricultural growth and environmental preservation.

Data on the volume of credit from the ABC program aimed at pasture recovery were obtained from o BACEN (2025). The information released pertains to contracts per rural producer; this data was grouped at the municipal level for the entire Legal Amazon region for the years 2013 to 2023 (the available period).

The variable measuring degraded pasture areas was obtained from the Image Processing and Geoprocessing Laboratory (LAPIG, 2025), which provides information on pasture vigor for all municipalities in Brazil, from 2013 to 2023. Pasture vigor is measured using the Normalized Difference Vegetation Index (NDVI), which is obtained from satellite imagery. Degradation levels are divided into absent, moderate, and severe. In this study, we summed the areas of moderate and severe levels into a single class called pasture degradation.

We also used historical data on cattle herds collected through the Municipal Livestock Survey (PPM), obtained from the Brazilian Institute of Geography and Statistics (IBGEa, 2025) for the period from 2013 to 2023, for all municipalities belonging to the Legal Amazon.

The deforested area is sourced from Mapbiomas (2025) based on land use and land cover monitoring data. The platform uses satellite imagery and remote sensing technology to map and analyze changes in Brazilian territory over time. The data presented are annual statistics on deforested areas, covering the period from 2013 to 2023 for all municipalities in the Legal Amazon.

For the calculation of Gross Domestic Product (GDP) *per capita* we used data from the Gross Domestic Product of Municipalities Survey (PIB-Munic) (IBGEb, 2025) and the Population Estimates Survey (EstimaPop) (IBGEc, 2025), both surveys are annual for all Brazilian municipalities and the years 2013 to 2023 were selected for compatibility with the other variables.

Table 1 presents all the variables used in the study, their respective descriptions, data sources, and units of measurement.

Table 1

Variables used in the study

Variable	Description	Source	Unit
ABC	ABC Program Credit	BACEN	BRL (R$)
Degradation	Degraded pasture areas	LAPIG	hectare
Deforestation	Deforested area	Mapbiomas	hectare
Herd	Cattle herd	IBGE	number of heads
GDP	Gross Domestic Product	IBGE	BRL (R$)
Population	Estimated population	IBGE	number of people

Source: own elaboration.
Notes:GDP per capita is calculated by dividing GDP by Population, both from IBGE (Brazilian Institute of Geography and Statistics).

There are many municipalities that did not receive resources from the ABC program and therefore show a value of zero. For this reason, the inverse hyperbolic transformation (*IHS*), or hyperbolic logarithm, was applied[5]. This transformation was applied to all variables used in the estimations of the models presented in the next section.

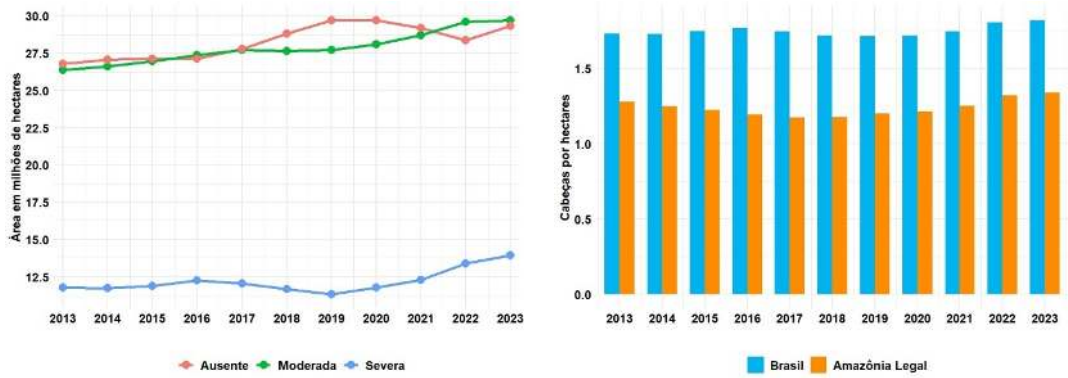
4 PASTURE DEGRADATION AND DEFORESTATION

The cattle herd has been expanding at an accelerated pace in the Legal Amazon, increasing from 80.3 million head in 2013 to 106.7 million in 2023. To support the increase in the herd, there has also been growth in pasture areas, which increased from 64.9 million hectares (ha) in 2013 to 72.9 million hectares (ha) in 2023. As a consequence of the growth in cattle farming, degraded pasture areas have also increased; Figure 1 shows the evolution of pasture areas according to the level of degradation (absent, moderate, and severe) in the Legal Amazon between 2013 and 2023, in addition to comparing cattle stocking rates, with the annual average number of cattle per hectare, between Brazil and the Legal Amazon during the same period.

[5] Defined mathematically as: $IHS(x) = \ln\left(x + \sqrt{x^2+1}\right)$.

Figure 1

Evolution of pasture areas by level of degradation and animal stocking rate in the Amazon Legal data from 2013 to 2023



Source: own elaboration.

The Legal Amazon region consistently presents a lower stocking rate than the national average (Figure 1), with values ranging between 1.2 and 1.3 head per hectare, while Brazil maintains rates close to or above 1.7. This difference indicates that the region still predominantly adopts an extensive cattle farming model, with inefficient land use. This pattern is directly associated with large areas of degraded pastures (Figure 1).

An intensification of pasture degradation has been observed in the Legal Amazon (Figure 1). Even though areas without degradation remain relatively stable, the continuous growth of areas with moderate and, especially, severe degradation shows failures in pasture recovery processes, particularly in more recent years.

Moderately degraded pastures show consistent growth over time, increasing from 26 million hectares in 2013 to 29 million hectares in 2023. As a result, from 2021 onwards, this level surpassed the area of pastures without degradation, suggesting a predominance of moderate degradation in the region. Severely degraded pastures, although representing the smallest area among the three categories, after initial stability, show significant growth from 2020 onwards, with a more pronounced increase between 2021 and 2023, reaching almost 14 million hectares in 2023.

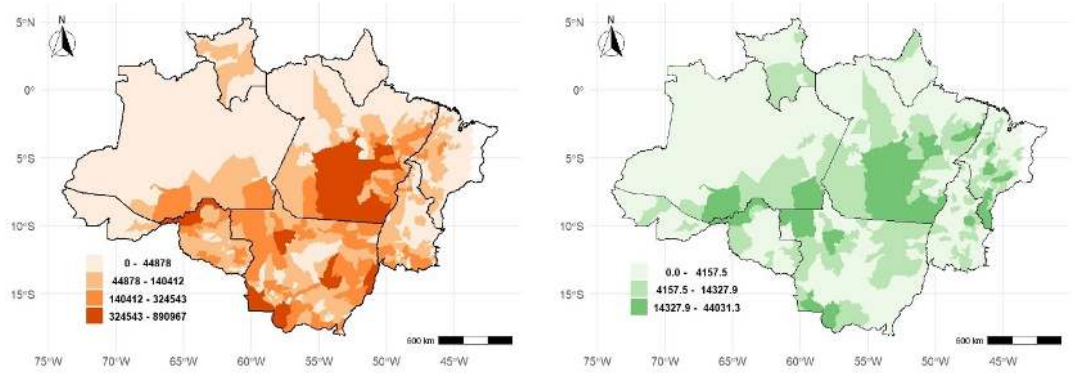
Degradation is quite heterogeneous among the states, mainly concentrated in Mato Grosso, Pará, Rondônia, and Tocantins; together these states account for 86.3% of the degraded pastures (severe and moderate) in the Legal Amazon in 2023. This concentration seems to be associated with the spatial distribution of livestock farming, which is heavily concentrated in the states of Mato Grosso, Pará, Rondônia, and Tocantins, which together hold about 83% of the herd in the region. On the other hand, deforestation does not seem to

follow the same spatial pattern, concentrating in 2023 in Pará (24.8%), Mato Grosso (23.4%), Maranhão (21.3%), and Tocantins (13.8%).

Figure 2 shows the distribution of degraded pasture areas at the municipal level in 2023. The increase in pasture degradation can have significant indirect impacts on the forest, with pressure for new pasture areas due to loss of productivity. Figure 2 also shows the distribution of deforested areas in the municipalities of the Legal Amazon in 2023.

Figure 2

Distribution of degraded pasture areas and deforestation in hectares in municipalities in the Legal Amazon in 2023



Source: own elaboration.

The largest concentrations of degraded areas are located mainly in southern Pará, northern and eastern Mato Grosso, southeastern Amazonas, and northern Rondônia and Tocantins. A strong pattern of degradation is observed on the edges of the Amazon biome (arc of deforestation), where the expansion of agriculture and cattle farming and the conversion of forests into pastures are most pronounced.

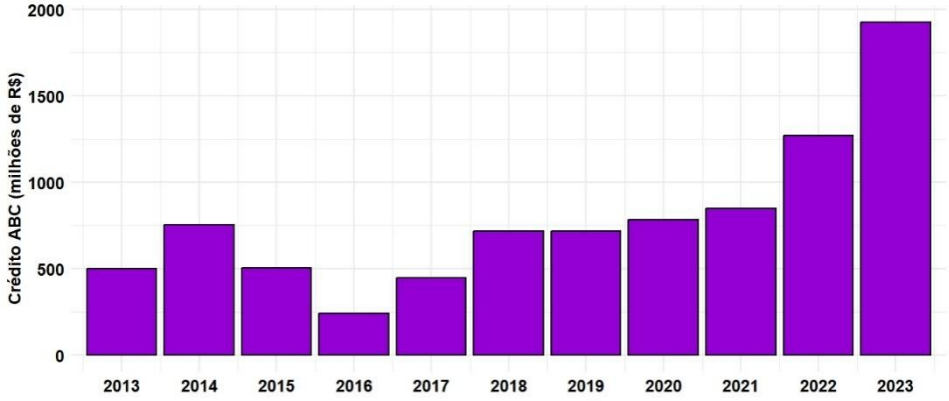
We can observe in Figure 2 a concentration of deforested areas in the states of Mato Grosso, Pará, and Rondônia, mainly in regions along the agricultural frontier known as the Arc of Deforestation. In the state of Amazonas, deforestation is more dispersed, but there are central and southern municipalities with significant values, evidencing the recent inland spread of forest loss. Tocantins and Maranhão, located in the eastern portion of the Legal Amazon, also have municipalities with high levels of deforestation.

Figure 3 shows the evolution of rural credit granted through the ABC program, aimed at pasture recovery in municipalities of the Legal Amazon, from 2013 to 2023. Between 2013 and 2016, credit showed a downward trend, reaching its lowest value in 2016 (close to R$ 250

million). From 2017 onwards, a continuous growth trend is observed, especially in 2022 and 2023, when the values exceeded R$ 1.2 billion and R$ 1.9 billion, respectively.

Figure 3

Amount of credit from the ABC program for Legal Amazon



Source: own elaboration.

This upward trend is particularly driven by the state of Mato Grosso (MT), which receives the largest volume of credit. The states of Tocantins, Pará, and Rondônia also stand out, showing gradual increases in credit volume. The availability of this resource seems to be linked to degradation, as these are also the states with the highest concentration of degraded pastures. States like Amapá, Amazonas, and Roraima, on the other hand, maintain low levels of credit uptake throughout the period, which can be explained by the small cattle herds and, consequently, smaller pasture areas.

4.1 IMPACTS ON MUNICIPALITIES

Table 2 shows the factors associated with pasture degradation in municipalities of the Legal Amazon. From an economic point of view, the results highlight three central dimensions: the role of incentives via rural credit, the intensity of land use by cattle farming, and the effects of local income.

Table 2

Panel data models for degraded pasture areas

Variables	(1)	(2)	(3)	(4)
ABC	-0.0014***	-0.0015***	-0.0014***	-0.0009**
	(0.0004)	(0.0004)	(0.0004)	(0.0004)
Herd		0.1357***	0.1031***	0.0802***
		(0.0301)	(0.0303)	(0.0300)

GDP per capita			0.8933***	-0.3288
			(0.1681)	(0.2027)
Time fixed effects				Yes
Observations	8,492	8,492	8,492	8,492
R^2	0.0011	0.0233	0.0408	0.0835
AIC	-1803.36	-1992.16	-2143.58	-2510.73

Source: own elaboration.
Notes: Four progressive models were estimated, incorporating different control variables. All models include municipality fixed effects; Model 4 also includes time fixed effects (not reported in the table). Levels of statistical significance are as follows: *** p-value less than 0.01; ** p-value less than 0.05; * p-value less than 0.1. Robust standard errors are reported in parentheses.

The estimated coefficients indicate that the ABC Program credit is negatively associated with degraded pasture areas in all models. Although the coefficient value is small, the consistent negative sign suggests that the program may have contributed to mitigating degradation. Similar results were presented by Oliveira; Souza; Assunção (2024), who showed that the effects of the ABC Pasture Recovery credit are very small in the Cerrado. On the other hand, Telles *et al*., (2024) shows that in Brazil, 10% of the reduction in degraded pasture areas between 2016 and 2021 can be partly attributed to the ABC Program.

The cattle herd shows a positive and statistically significant relationship with degraded pasture areas. This behavior reflects the increasing pressure on pasture areas in the region, which can result in productivity losses. Furthermore, this relationship shows production characterized by the extensive expansion of cattle farming. In the absence of good management practices, the growth of the cattle sector continues to generate increasing environmental pressures, mainly in relation to forest areas.

The relationship between GDP *per capita* and degraded pastures, however, is not so clear. Although the coefficient is positive in some models, it loses significance as other structural variables are controlled. This suggests that the level of municipal income, in isolation, does not determine degradation, and that other factors such as access to technology, local institutions, and productive structure may be more relevant.

Table 3 shows how rural credit from the ABC program impacts deforestation in municipalities within the Legal Amazon. The main finding is that, unlike the effect observed on pasture degradation (Table 2), credit from the ABC program does not show a statistically significant relationship with deforestation in any of the models. This indicates that, although the program has an impact on pasture recovery, it does not directly impact deforestation.

Table 3

Estimated panel data models for deforested areas

Variables	(1)	(2)	(3)	(4)	(5)
ABC	-0.0013	-0.0008	-0.0008	-0.0008	0.0004
	(0.0010)	(0.0010)	(0.0010)	(0.0010)	(0.0010)
Degradation		0.3474***	0.3369***	0.3430***	0.3157***
		(0.0479)	(0.0485)	(0.0481)	(0.0525)
Herd			0.4087	0.4983*	-0.2302
			(0.2851)	(0.3023)	(0.4641)
GDP per capita				-0.0514	-0.0732*
				(0.0394)	(0.0428)
Time fixed effects					Yes
Observations	8,492	8,492	8,492	8,492	8,492
R^2	0.0001	0.0195	0.0201	0.0206	0.0655
AIC	13727.02	13562.84	13559.51	13557.43	13178.99

Source: own elaboration.
Notes: Five progressive models were estimated, incorporating different control variables. All models include fixed effects per municipality; model 5 also includes time effects (not reported in the table). Levels of statistical significance: * p-value less than 0.01; * p-value less than 0.05; * p-value less than 0.1. Robust standard errors in parentheses.

Table 3 also shows that degraded pasture areas are positively associated with deforestation. As existing pastures lose productivity, the need to maintain or expand livestock farming increases the pressure to open new areas. This result corroborates the argument that the reduction of degraded pasture areas has an indirect and important effect on containing deforestation.

The relationship between cattle herds and deforestation is not robust when controlling for different specifications, showing a positive association in only one of the estimated models. This result suggests that herd growth, by itself, is not a direct determinant of the expansion of the agricultural frontier. What is observed, then, is that the loss of productivity in pasture areas due to degradation generates pressure for increased deforestation.

GDP *per capita* shows a negative relationship with deforestation, suggesting that municipalities with higher income levels tend to exert less pressure on forest areas. This may reflect greater economic diversification, greater access to information, or a stronger institutional presence. However, the effect is sensitive to the specificity of the model.

4.2 SPATIAL IMPACTS

The existence of spatial autocorrelation in degraded pasture areas and deforested areas is verified in Table 4. In all specifications, both types of areas show positive and statistically significant spatial autocorrelation. Municipalities with greater degradation or greater deforestation tend to be close to other municipalities with similar patterns, revealing spatial concentration in land use.

Table 4

Moran's I estimated for different matrices

Variable	Queen	Rook	5 neighbors	6 neighbors
Degradation	0.5118***	0.5146***	0.4080***	0.4115***
	(23.61)	(23.46)	(19.43)	(21.45)
Deforestation	0.3549***	0.3595***	0.2911***	0.2873***
	(16.39)	(16.41)	(13.88)	(15.00)

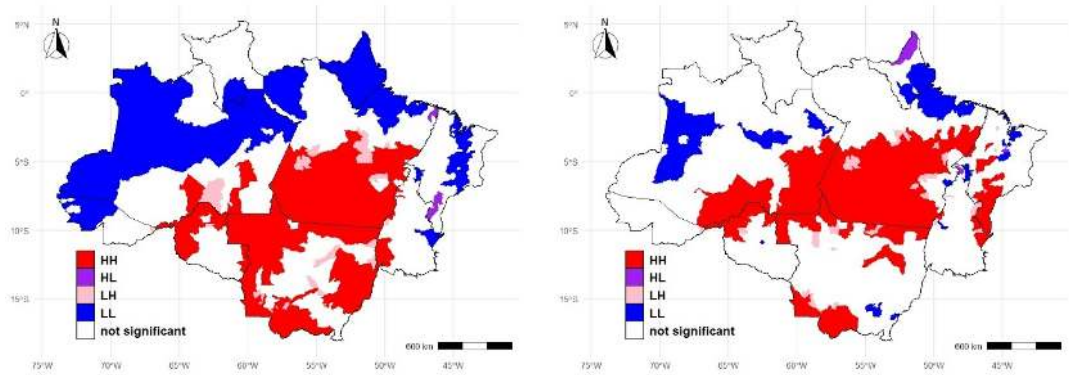
Source: own elaboration.
Notes: Autocorrelations were estimated considering different types of matrices: Queen, Rook, 5 nearest neighbors, and 6 nearest neighbors. Statistical significance levels: *** p-value less than 0.01; ** p-value less than 0.05; * p-value less than 0.1. Standard errors in parentheses are estimated with 999 random permutations.

The robustness of the results across different matrices reinforces the existence of spatial dependence. This result indicates that pasture degradation and deforestation processes do not occur in isolation or randomly, but follow dynamics of geographic interdependence, likely influenced by common factors such as infrastructure and logistics. Therefore, there is a significant diffusion effect for both processes.

The spatial clusters identified by the LISA index for the municipalities of the Legal Amazon in 2023 are presented in Figure 4. It is possible to observe the presence of significant concentrations of hotspots. These patterns indicate that the processes of pasture degradation and deforestation are not randomly distributed in space but rather organized into geographic clusters with common land use dynamics.

Figure 4

Local Indicators of Spatial Association (LISA) in 2023



Source: own elaboration.

There is a large number of HH and LL type clusters, as we can see in Figure 4, which reinforces the hypothesis that the effects of degradation spread between neighboring

municipalities (slipover effect). The AA clusters are concentrated mainly in the south and east of the state of Mato Grosso, north of Rondônia, and parts of the southwest of Pará. This result indicates regions where pasture degradation may be a chronic problem.

The LL clusters appear in much of Amazonas, Acre, and Amapá, as well as in areas of northern Maranhão and western Pará. These are areas with low degradation, surrounded by other regions with similarly low levels. These regions suffer less agricultural pressure or a more intense presence of forest, as well as a greater number of conservation units. The HL and LH clusters are more dispersed and occur in zones where degradation is changing its pattern, suggesting areas where degradation may be expanding (HL) or receding (LH).

Figure 4 (right side) shows that the HH clusters are heavily concentrated in the east and south of the state of Pará, north of Mato Grosso, north of Tocantins, and west of Maranhão. This indicates a slipover effect of deforestation, which coincides with the known agricultural expansion zone where the agricultural frontier advances over forested areas. On the other hand, the LL clusters are concentrated in the north of Amazonas, Acre, and Roraima, as well as some areas in the northeast of Pará and south of Maranhão. These regions have a greater presence of indigenous lands, conservation units, or low population density, which tends to reduce deforestation.

The spatial effects of the determinants of pasture degradation are presented in Table 5. While Table 2 shows local (intra-municipal) impacts, Table 5 shows that impacts can also propagate spatially. Credit from the ABC program has positive externalities, while herd growth generates negative externalities.

Table 5

Spatial model for degraded pastures

Variables	(1)	(2)	(3)	(4)
ABC	-0.0005*	-0.0005*	-0.0005*	-0.0004
	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Herd		0.0378***	0.0334***	0.0314***
		(0.0056)	(0.0059)	(0.0060)
GDP per capita			0.0837**	-0.1042
			(0.0370)	(0.0665)
Time fixed effects				Yes
λ	0.8830***	0.8764***	0.8735***	0.8647***
	(0.0076)	(0.0079)	(0.0081)	(0.0086)
ρ	-0.4960**	-0.4910***	-0.4839***	-0.4708***
	(0.0271)	(0.0272)	(0.0275)	(0.0281)
Observations	8,492	8,492	8,492	8,492
AIC	-7973.70	-7984.87	-7983.61	-7962.50

Source: own elaboration.

Notes: Four progressive models were estimated, incorporating different control variables. All models include fixed effects per municipality; model 4 also includes time effects (not reported in the table). All models were

estimated considering a tower matrix. Statistical significance levels: *** p-value less than 0.01; ** p-value less than 0.05; * p-value less than 0.1.
Note: Four progressive models were estimated, incorporating different control variables. All models include fixed effects per municipality; model 4 also includes time effects (not reported in the table). All models were estimated considering a tower matrix. Statistical significance levels: *** p-value less than 0.01; ** p-value less than 0.05; * p-value less than 0.1.

The ABC program credits show a negative and statistically significant impact, suggesting that financing aimed at pasture recovery reduces degradation within the municipality itself. The spatial effect, incorporated into the analysis, reinforces the findings observed in Table 2, suggesting that the impact of the credit extends beyond the municipality that directly receives the resource. The interdependence among municipalities may amplify the effects of the public policy in neighboring regions.

The cattle herd maintains its positive and significant impact on degraded pastures. In addition to the direct impact already observed (Table 2), there is also a positive indirect effect, suggesting that the growth of cattle farming also affects neighboring municipalities. This effect can be interpreted as a reflection of the expansion of extensive cattle farming, where the increase in activity in one municipality pressures its neighbors to adopt similar production patterns, often without adequate management. The impact of GDP per capita loses significance when the effect of time is incorporated, indicating that the level of local income, in isolation, does not have a systematic effect on pasture degradation.

The spatial effects proved to be robust, independent of the control variables considered. Thus, the process of pasture degradation cannot be considered a local or isolated phenomenon. The contagion effect (λ) shows that unobserved factors affecting several municipalities simultaneously, such as climate shocks, state policies, or logistical structures, have a positive impact on pasture degradation. While the direct contagion effect (ρ) shows that pasture degradation in one municipality is correlated with the degradation observed in neighboring municipalities; that is, there is a diffusion effect.

The determinants of deforestation with spatial effects are presented in Table 6. Credit from the ABC program has no significant effect on deforestation, either directly or indirectly. This suggests that, although the program has a positive impact on pasture recovery (as shown in Table 3 and Table 5), it has not been able to contain the expansion of the agricultural frontier into forest areas.

Table 6

Spatial model for deforestation

Variables	(1)	(2)	(3)	(4)	(5)
ABC	0.0010	0.0003	0.0003	0.0003	0.0006
	(0.0008)	(0.0008)	(0.0008)	(0.0008)	(0.0008)
Degradation		0.0846***	0.0843***	0.0860***	0.0887***
		(0.0149)	(0.0152)	(0.0153)	(0.0159)
Herd			0.0095	0.0331	0.0555
			(0.0914)	(0.0966)	(0.1758)
GDP per capita			0.0095	(0.0156)	-0.0152
			(0.0914)		(0.0159)
Time fixed effects					Yes
λ	-0.482***	0.8713***	0.8713***	0.8711***	0.8595***
	(0.0275)	(0.0082)	(0.0082)	(0.0083)	(0.0090)
ρ	0.8777***	-0.4740***	-0.4739***	-0.4739***	-0.4550***
	(0.0080)	(0.0277)	(0.0277)	(0.0277)	(0.0285)
Observations	8,492	8,492	8,492	8,492	8,492
AIC	17681.99	8366.841	8368.853	8371.151	8394.608

Source: own elaboration.
Notes: Five progressive models were estimated, incorporating different control variables. All models include fixed effects per municipality; model 5 also includes time effects (not reported in the table). All models were estimated considering a tower matrix; model 5 also includes the effects of years. Statistical significance levels: *** p-value less than 0.01; ** p-value less than 0.05; * p-value less than 0.1.

Even considering spatial effects, municipalities with a higher proportion of degraded pastures tend to have higher rates of deforestation. This effect also extends to neighboring areas (indirect effect), suggesting that degradation acts as a geographical precursor to the expansion of the agricultural frontier: degraded areas cease to be productive, putting pressure on the advance into forest areas for the opening of new pastures.

GDP per capita and cattle herd size cease to be statistically significant, suggesting that, once spatial dependence among municipalities is incorporated, these factors alone do not robustly explain the variation in deforestation. This indicates that the advance of the agricultural frontier is not directly associated with the level of local income or the size of the cattle herd in a single municipality, but rather with regional dynamics represented in clusters.

Similar to degraded pastures, deforestation is a spatially dependent phenomenon. Unobserved spatial effects (λ) positively and simultaneously impact deforestation. However, spatial dependence in deforestation has proven to be negative (ρ), indicating that municipalities with large, deforested areas would be associated with small areas in neighboring municipalities, a pattern of territorial compensation or dispersion. This could occur, for example, if protected or highly monitored areas prevented the expansion of unsustainable practices in adjacent municipalities, or if there was a land-use substitution between nearby regions.

4.3 MARGINAL EFFECTS

The direct, indirect (spatial) and total marginal effects are presented in Table 7. This information allows us to verify the effects on deforestation and pasture degradation. Causal relationships operate differently in the two environmental processes: the ABC program credit directly affects pasture degradation, but not deforestation; while degradation, in turn, has a direct and indirect impact on deforestation.

Table 7

Marginal effects of spatial models

Variables	Degradation			Deforestation		
	Direct	Indirect	Total	Direct	Indirect	Total
ABC	-0.0007*	-0.0035*	-0.0042*	0.0004	0.0020	0.0024
	(0.0004)	(0.0019)	(0.0023)	(0.0009)	(0.0043)	(0.0052)
Herd	0.0452***	0.2148***	0.2600***	-0.0157	-0.0733	-0.0889
	(0.0082)	(0.0420)	(0.0499)	(0.0208)	(0.0982)	(0.1189)
GDP per capita	0.1129**	0.5367**	0.6497**	0.0445	0.2080	0.2525
	(0.0472)	(0.2242)	(0.2709)	(0.1312)	(0.6181)	(0.7492)
Degradation				0.1157***	0.5410***	0.6566***
				(0.0201)	(0.1021)	(0.1214)

Source: own elaboration.
Notes: Marginal effects are derived from model 3 in Table 5 and model 4 in Table 6. Statistical significance levels: * p-value less than 0.01; * p-value less than 0.05; * p-value less than 0.1.

An increase in credit from the ABC Program is associated with a reduction in pasture degradation, both in the municipality receiving the credit (direct effect) and in its neighbors (indirect effect), with the effect being greater in the latter. The credit favors sustainable practices that recover or preserve the productive capacity of the soil, with potential regional demonstration effects, leading neighboring municipalities to adopt similar practices.

The cattle herd also presents statistically significant direct and indirect effects, suggesting that an increase in the number of heads is strongly associated with greater pasture degradation, both locally and in neighboring municipalities. Extensive cattle farming increases pressure on pasture areas, resulting in overgrazing and degradation. Indirect effects may reflect the spread of unsustainable practices or the expansion of activity to nearby areas.

The growth of GDP per capita is associated with increased pasture degradation, with significant local and regional effects. Possibly, wealthier municipalities may be in more advanced stages of land use, with greater use of previously underutilized areas.

Deforested areas are impacted only by degraded pasture areas, both within the municipality and in neighboring municipalities. When pastures become unproductive, there is greater pressure to open new areas, usually in forested areas, to maintain or expand cattle production. Indirect effects suggest a regionalized and more intense pattern. There is a dynamic of territorial substitution: degraded pastures lose productive value, generating deforestation in neighboring regions for the expansion of pasture areas.

5 FINAL CONSIDERATIONS

This study analyzed the spatial determinants of pasture degradation and deforestation in the Legal Amazon between 2013 and 2023, focusing on the effects of credit from the ABC program and its impacts on land use dynamics. The results indicate that the rural credit granted has a significant effect on reducing pasture degradation, both in the municipality receiving the resources and in neighboring municipalities, revealing an important spatial diffusion effect. This demonstrates the program's potential as a public policy instrument to promote sustainable land use practices and the recovery of degraded productive areas.On the other hand, the study found no evidence that credit from the ABC program has a direct or indirect impact on reducing deforestation. The main variable associated with increased deforestation was pasture degradation, suggesting that the loss of productivity in these areas intensifies the pressure for new areas, often at the expense of forest cover. This finding reinforces the idea that policies focused solely on recovery, without integration with control mechanisms, tend to be insufficient to contain the advance of deforestation in the region.

Spatial analysis revealed clear patterns of concentration of degradation and deforestation processes, with hotspots located especially on the edges of the Amazon rainforest, in the states of Mato Grosso, Pará, Rondônia, and Tocantins. Therefore, the ABC program credit presents significant potential to improve the sustainability of cattle farming. However, to maximize its environmental impact and curb deforestation, it is necessary to expand its integration with other public policies, such as environmental enforcement. The expansion of the ABC+ Program, with more ambitious targets for 2030, represents a strategic opportunity to consolidate low-carbon agriculture in the Legal Amazon.

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