ISSN: 2594-8083
VIII EIGEDIN
25 a 27 de Maio de 2026
Totalmente Online e Gratuito

( ) Graduação (X) Pós-Graduação
(X) Artigo completo ( ) Relato de prática ( ) Resumo expandido

INSTITUTIONAL WEAKENING AND THE REVERSAL OF CONSERVATION EFFECTIVENESS: evidence from deforestation dynamics in the Brazilian Amazon

Willian dos Santos Flores
Universidade Federal da Grande Dourados
willian.flores008@academico.ufgd.edu.br

Jonathan Gonçalves da Silva
Universidade Federal da Grande Dourados
jonathandasilva@ufgd.edu.br

Roselaine Bonfim de Almeida
Universidade Federal da Grande Dourados
roselainealmeida@ufgd.edu.br

Leandro Vinícios Carvalho
Universidade Federal da Grande Dourados
leandrocarvalho@ufgd.edu.br

ABSTRACT

Between 2015 and 2023, the Brazilian Legal Amazon lost an averaging roughly 9,000 km² of forest annually, a reversal of previous conservation gains. Using municipality-level panel data with fixed effects, this study provides the assessment of how economic incentives and conservation policies interact under conditions of institutional weakening. Three main results were found. First, cattle prices and rural credit volumes remain positively associated with deforestation, confirming livestock as the primary land conversion driver. Second, soybean prices exhibit a negative coefficient, consistent with the Soy Moratorium's effectiveness in decoupling agricultural profits from forest conversion. Third, and most concerning, Permanent Protected Areas established before 2015 show a positive correlation with deforestation in the post-2015 period, suggesting leakage effects when surrounding governance deteriorates. Environmental agency staffing reduces deforestation only in restricted specifications, losing significance when institutional and land-cover controls are included. These findings demonstrate that conservation effectiveness is not an intrinsic property of protected areas but an emergent outcome of institutional resilience. Given the Amazon's centrality to global climate regulation, weakening environmental governance in tropical forest regions may undermine international climate mitigation efforts.

Keywords: Deforestation; Brazilian Amazon; Panel Data; Fixed Effects; Institutional Weakening.

1 INTRODUCTION

Deforestation in the Brazilian Legal Amazon entered a renewed phase of expansion between 2015 and 2023, averaging 9,112,21 km² of forest loss per year, equivalent to about 1,27 million football fields annually, surpassing levels predicted by earlier modelling exercises under business-as-usual assumptions (Costa *et al.*, 2021; INPE, 2026). Empirical analyses of satellite-based deforestation monitoring indicate that, after the sharp decline between 2004 and 2012, forest loss began rising again after 2013, reversing the previous downward trend (Costa *et al.*, 2021; Montibeller *et al.*, 2020; Silva-Junior *et al.*, 2023). Unlike the earlier period marked by strong command-and-control policies, this resurgence occurred under changing institutional conditions characterized by weakening environmental governance and growing pressures on public forests (Azevedo-Ramos *et al.*, 2020; Brito *et al.*, 2019). As a result, the period spans two distinct political cycles that tested the resilience of Brazil's forest governance system (Kuschnig *et al.*, 2023; Pereira *et al.*, 2019).

The literature establishes three fundamental insights about deforestation drivers in the Amazon. Commodity prices, particularly cattle and soybeans, create powerful incentives for forest conversion (Harding; Herzberg; Kuralbayeva, 2021; Hargrave; Kis-Katos, 2013). Conservation policies, such as Permanent Protected Areas (PPAs), can contain deforestation when properly implemented (Nolte *et al.*, 2013; Soares-Filho *et al.*, 2010). And at the same time, rural credit acts as a double-edged sword: it can finance agricultural expansion but also serves as an environmental conditioning instrument when conditioned on formal land tenure regularity and environmental compliance (Assunção *et al.*, 2020; Faria *et al.*, 2025).

However, these factors are typically analysed in isolation, as much of the literature tends to examine environmental policy instruments, market incentives, or enforcement capacity separately rather than as interacting components of governance systems (Blackman; Li; Liu, 2018; Requate, 2005; Steinebach, 2022). Their interactions in the post-2015 context, characterized by institutional weakening, budget cuts in enforcement agencies, and the flexibilization of environmental regulations, remain insufficiently explored, particularly in the Brazilian case (Araújo, 2020; Hänggli *et al.*, 2023; Nunes *et al.*, 2024; Vale *et al.*, 2021). Consequently, the literature still lacks empirical analyses that simultaneously integrate market incentives, environmental policy instruments, and state enforcement capacity at the municipal level, using sufficiently recent data to capture the institutional transformations shaping environmental governance in this period.

This study addresses this gap through four complementary contributions. It provides a municipal-level panel analysis covering the entire period of Brazilian environmental governance erosion (2015–2023). It examines the joint role of commodity markets, rural credit, and conservation policies within a unified econometric framework. It identifies leakage effects from PPAs established before 2015, a counterintuitive finding that challenges the consensus regarding the unconditional effectiveness of protected areas. Finally, it evaluates whether environmental agency staffing continues to exert deterrent effects when institutional and land-cover characteristics are considered.

By examining this period of institutional weakening, the study provides evidence on how conservation policies perform when the broader governance system deteriorates. Specifically, four questions are investigated: (1) Do commodity prices maintain their predictive power during a period of institutional flux? (2) Do PPAs remain effective when surrounding governance weakens? (3) Does rural credit continue to finance deforestation despite environmental conditionalities? (4) Does the presence of enforcement agents reduce forest loss?

Municipality-level fixed-effects models are employed using data from Project for Monitoring the Brazilian Amazon Forest by Satellite from National Institute for Space Research (PRODES/INPE), Center for Advanced Studies on Applied Economics affiliated to Luiz de Queiroz College of Agriculture - University of São Paulo (CEPEA/ESALQ-USP), System for Rural Credit Operations and Proagro from Central Bank of Brazil (SICOR/BCB), Ministry of the Environment and Climate Change (MMA), Ministry of Planning and Budget, Brazilian Institute of Geography and Statistics (IBGE), and MapBiomas. This approach controls for time-invariant unobservable characteristics and common temporal shocks, allowing us to estimate conditional associations between the variables of interest and annual deforestation rates.

Understanding these dynamics is critical not only for Brazilian environmental policy but also for global climate mitigation, as the Amazon plays a central role in regulating planetary carbon cycles. International mechanisms such as Reducing Emissions from Deforestation and forest Degradation (REDD+) and deforestation-free supply chain commitments must account for governance dynamics, policies that work under strong institutions may fail when governance erodes.

The article is structure in five sections. Following this introduction, Section 2 reviews the literature and develops the conceptual framework. Section 3 presents the empirical strategy and data and reports the main results. Section 4 discusses the findings considering the literature and their policy implications. Section 5 concludes.

2 LITERATURE REVIEW

Deforestation in the Amazon is widely understood as the outcome of interacting economic incentives, institutional constraints, and policy interventions that shape land-use decisions in frontier regions (Haddad *et al.*, 2024; Hänggli *et al.*, 2023). Rather than being driven by a single factor, forest loss emerges from the interaction between market dynamics, conservation policies, financial instruments, and the state's capacity to enforce environmental regulations (Carvalho *et al.*, 2019; Nepstad *et al.*, 2014; Trancoso, 2021).

The relationship between commodity prices and deforestation is one of the most consolidated findings in the literature. Studies confirm that high cattle and soybean prices create powerful incentives for land conversion, acting as primary deforestation drivers in the Amazon (Assunção *et al.*, 2020; Harding; Herzberg; Kuralbayeva, 2021; Hargrave; Kis-Katos, 2013). The economic logic is straightforward: price increases raise the expected returns from agricultural activities, making forest conversion more profitable (Angelsen; Kaimowitz, 1999). This operates through two main channels: extensive margin expansion, converting new forest areas (Harding; Herzberg; Kuralbayeva, 2021; Miranda; Britz; Börner, 2024); and intensive margin intensification, increasing productivity on already-cleared land, which may indirectly relieve pressure on forests (Byerlee; Stevenson; Villoria, 2014; Villoria, 2019). The price elasticity of deforestation has been estimated in previous studies, providing benchmarks for the magnitudes observed (Harding; Herzberg; Kuralbayeva, 2021).

However, the price-deforestation association is not automatic. Harding, Herzberg, and Kuralbayeva (2021) demonstrate that deforestation's sensitivity to prices is significantly reduced, by up to 40%, in the presence of robust environmental policies, such as Brazil's priority municipality program. This suggests that price effects are moderated by the institutional and enforcement framework, an interaction investigated for the 2015-2023 period.

A recurring finding in recent literature is the negative coefficient for soybean prices in certain contexts. Studies attribute this phenomenon to two mechanisms: the Soy Moratorium, a private-sector agreement since 2006 prohibiting purchase of soybeans cultivated on deforested areas in the Amazon, which disincentivizes forest conversion for soybean planting (Heilmayr *et al.*, 2020; Rausch; Gibbs, 2016); and soybean expansion onto already-degraded pastures, reducing direct pressure on native forests (Amaral *et al.*, 2021; Morton *et al.*, 2006).

While market incentives play a central role in shaping deforestation dynamics, their effects are often conditioned by the spatial and institutional constraints imposed by conservation policies. PPAs are fundamental instruments of Brazilian environmental policy and the evidence indicates that these areas are generally effective in reducing deforestation within their boundaries (Nolte *et al.*, 2013; Qin *et al.*, 2023; Soares-Filho, Britaldo *et al.*, 2010). Their effectiveness varies by governance regime, location, and type of protection (integral protection vs. sustainable use). However, their effectiveness is not absolute. The phenomenon of "paper parks" (Joppa; Loarie; Pimm, 2008; Rife *et al.*, 2013), protected areas that exist only on paper due to inadequate enforcement, may occur across tropical regions, highlighting the importance of institutional capacity.

Amin *et al.* (2015) document leakage effects, where deforestation pressure is displaced to unprotected surrounding areas. Fuller *et al.* (2019), in a systematic review, confirm that spillovers from protected areas are common, especially when surrounding governance is weak. Kuschnig *et al.* (2023) show that the effectiveness of conservation interventions in the Amazon eroded during the "lost decade" post-2012, marked by institutional weakening and reduced enforcement resources. This study advances by analysing not only the presence of PPAs but their interaction with time, specifically testing whether PPAs established before 2015 experienced greater pressure or lost effectiveness in the subsequent political period.

Beyond spatial conservation policies, another important policy instrument influencing land-use dynamics in the Amazon is rural credit. It can act both as financing for agricultural expansion and as a conditioning instrument for sustainable practices. Assunção *et al.* (2020) show that National Monetary Council (CMN) Resolution 3.545/2008, which linked rural credit to environmental compliance, was decisive in reducing post-2008 deforestation, especially in livestock-predominant municipalities. Faria *et al.* (2025) confirm this effect but warn that conditionalities' effectiveness depends on monitoring and enforcement capacity (i.e. requiring supervision).

Recent studies indicate that in the absence of effective enforcement, credit may simply finance land conversion, acting as a subsidy for agricultural frontier expansion (Dou *et al.*, 2023; Nunes *et al.*, 2024). Carrer *et al.* (2020) distinguish between costing and investment credit, showing that the latter tends to intensify land use, potentially reducing pressure for new areas. Investment credit directed toward productivity gains on already-cleared land may have different effects than working capital that facilitates frontier expansion.

Ultimately, the effectiveness of both conservation policies and financial instruments depends on the state’s capacity to monitor, enforce regulations, and sanction environmental violations. The institutional capacity of the state is a critical determinant of environmental policy success. Börner *et al.* (2015) demonstrate that enforcement operations and monitoring systems are associated with reduced deforestation and containment of illegal conversion. In the Brazilian case, the work of Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), Chico Mendes Institute for Biodiversity Conservation (ICMBio), police forces, and the Public Prosecutor's Office constitutes the core of environmental enforcement (Carvalho *et al.*, 2019). However, enforcement effectiveness is sensitive to changes in the political-institutional context. Benzeev *et al.* (2022) show that governance quality, measured by indicators of corruption control, government effectiveness, and rule of law, is negatively correlated with municipal deforestation. The post-2015 period was marked by budget cuts in environmental agencies, reduced enforcement operations, and erosion of sanctioning instruments (Coelho-Junior *et al.*, 2022; Nunes *et al.*, 2024). These institutional transformations raise important questions about how economic incentives, conservation policies, and enforcement capacity interact in shaping deforestation outcomes.

Building on the insights from this literature, the present study proposes a conceptual framework in which deforestation outcomes emerge from the interaction of three sets of factors as shown in Table 1:

Table 1. Analytical Framework of Forest Conversion into Agricultural Frontiers

Component		Proposed Effect / Mechanism	Evidence in the Literature
Drivers (Proximate Causes)	Commodity Prices	Increase land profitability, stimulating forest conversion.	(Assunção *et al.*, 2020; Dou *et al.*, 2023; Hänggli *et al.*, 2023)
	Rural Credit	Expands investment capacity, enabling greater production scale and expansion.	(Assunção *et al.*, 2020; Dou *et al.*, 2023; Faria *et al.*, 2025)
	Population	Increases demographic pressure on natural resources and land.	(Merkus, 2024; Sylvester *et al.*, 2024)
Moderators (Institutional Filters)	Protected Areas	Act as spatial constraints, limiting legal conversion.	(Benzeev *et al.*, 2022; Soares-Filho, Britaldo Silveira *et al.*, 2023)
	Environmental Governance	Determines the effectiveness of enforcement and compliance with laws.	(Benzeev *et al.*, 2022; Kuschnig *et al.*, 2023; Miranda; Britz; Börner, 2024)
	Land-Use Regulations	Impose legal restrictions that delimit where and how conversion can occur.	(Assunção *et al.*, 2020; Heilmayr *et al.*, 2020; Rajão *et al.*, 2020)
Contextual Conditions	Remaining Forest Stock	Defines the availability of a conversion frontier.	(Harding; Herzberg; Kuralbayeva, 2021; Miranda; Britz; Börner, 2024)
	Pre-existing Land Use	Creates path dependencies that condition future changes.	(Pacheco; Meyer, 2022; Rausch; Gibbs, 2016)
	Broader Institutional Environment	Provides the context of the rule of law and political stability that affects all other factors.	(Khan; Hussain, 2024; Moreira-Dantas; Söder, 2022; Salvador; Sancho, 2021)

Source: prepared by the authors.

These mechanisms interact dynamically, meaning that the effectiveness of conservation policies depends on the broader institutional environment in which they operate. The same policy instrument (*e.g.*, rural credit conditionalities or PPAs) may produce different outcomes depending on the strength of surrounding governance, enforcement capacity, and market conditions. The empirical specification operationalizes this framework by estimating how these drivers and institutional moderators jointly influence municipal deforestation dynamics. Specifically, three hypotheses are tested:

H1: Commodity price increases are associated with higher deforestation, but this effect is moderated by institutional capacity;

H2: PPAs lose effectiveness under conditions of institutional weakening; and

H3: Rural credit contributes to deforestation when enforcement capacity declines.

3 METHODOLOGICAL PROCEDURES

This section describes the data sources and empirical strategy used to examine the relationship between economic incentives, institutional factors, and deforestation dynamics in the Brazilian Legal Amazon.

It was constructed a municipal-level panel for 2015-2023 covering all 772 municipalities in the Legal Amazon as defined by PRODES/INPE. Table 2 presents descriptive statistics.

Table 2. Descriptive Statistics

Variable	Description	Mean	Std. Dev.	Min	Max
Deforestation	Annual deforested area (km²)	6.38	1.56	0.00	9.97
Deforestation	Rate over municipal area (%)	47.75	33.24	0.00	101.26
Population	Municipal population (1000 hab*)	35.85	114.53	0.91	2303.73
Rural Credit	Total contract value (billion R$*)	2.81	5.55	0.00	54.36
Cattle Price	Real price (R$/@)	201.48	69.34	138.91	317.74
Soybean Price	Real price (R$/60kg)	105.60	43.41	66.23	184.37
CAR	Registered area (1000 km^2*)	3540.19	43246.10	0.49	1148929.59
Environmental Staff	Number of federal environmental agents*	13785	1181.58	12458	16092
Soy Production	Soy production per state (million tons)	8.33	36.65	0.00	322.01
Cattle Production	Cattle production per state (million heads)	1.14	1.57	0.02	4.67
Forest Cover	Proportion of forest cover	0.63	0.28	0.05	1.00
Agriculture	Proportion of agricultural area	0.37	0.28	0.00	0.95
PPAs	Total PPAs area (km²)	806.4	3818.2	0.0	56,796.3

PPA Pre-2015	Dummy = 1 if PPA created before 2015	0.42	0.49	0	1

Note: N = 4,647 observations for 772 municipalities. Monetary variables deflated by IPCA.
** Variables were log-transformed to improve distribution and reduce the influence of extreme values at equation 1.*
Source: prepared by the authors.

Missing data were handled through listwise deletion, as the proportion of missing observations was below 2% for all variables and appeared random across municipalities and years.

3.1 EMPIRICAL STRATEGY

To evaluate the relationship between economic drivers, institutional variables, and deforestation dynamics, the analysis employs municipality-level fixed-effects models, which allow controlling for unobserved time-invariant characteristics that may influence deforestation outcomes.

The baseline specification is given by the equation 1:

$$Y_{it} = \beta X_{it} + \mu_i + \tau_{it} + \varepsilon_{it} \quad (1)$$

Where Y_{it} is the log of deforestation (measured as log (deforestation + 1) to accommodate zero values) in municipality i and year t, X_{it} is a vector of time-varying covariates, μ are municipal fixed effects, and τ are year fixed effects. Standard errors are clustered at the municipal level to account for serial correlation and heteroskedasticity.

The identifying assumption is that, conditional on fixed effects and observables, changes in X_{it} are uncorrelated with unobserved shocks to deforestation. The identification strategy estimates conditional associations rather than structural causal effects. Therefore, the coefficients were interpreted as policy-relevant elasticities rather than strictly causal parameters. Endogeneity concerns were partially addressed through the inclusion of lagged covariates where theoretically justified and the use of fixed effects to absorb time-invariant unobservable.

While commodity prices are determined largely in global markets and therefore plausibly exogenous to municipal deforestation dynamics, rural credit may respond to local economic expansion. The fixed-effects specification mitigates this concern by absorbing time-invariant local characteristics and common shocks, but the credit coefficient is interpreted primarily as an association rather than a strictly causal estimate. The incremental specifications for each model are presented below:

Model 1: Baseline with main economic drivers and year fixed effects

Model 2: Inclusion of state agricultural production (scale control)

Model 3: Addition of PPA × post-2015 interaction

Model 4: Land use and cover controls (forest share)

Treatment of multicollinearity: The correlation between soybean and cattle prices is extremely high ($\rho = 0.99$), which prevents precise separation of their individual effects. This issue is addressed through three complementary strategies: joint interpretation of coefficients, estimation of alternative models excluding one variable at a time, and specifications using the price ratio (cattle/soybeans) as a robustness check. Variance inflation factor (VIF) tests confirm that multicollinearity does not unduly inflate standard errors.

Although it is possible that some kind of spatial dependence exists among the error terms, given that deforestation can be related between neighbouring municipalities, the key interest of the analysis is to find the average relationship at the municipality level. The robust standard errors clustered by municipality are used to correct for serial correlation within each municipality; however, any kind of spatial autocorrelation found in the error terms might lead to a slight underestimation of the standard errors.

Several limitations deserve attention. Spatial spillovers are not explicitly modelled in the main specification. Time-invariant characteristics, such as soil quality and market distance, are absorbed by fixed effects and therefore cannot be estimated. The environmental staff variable presents limited temporal variation (standard deviation = 0.07), which constrains the ability to identify its effects and likely explains the loss of significance in fully specified models. In addition, the analysis measures deforestation rather than forest degradation, an increasingly relevant process as fires and selective logging expand.

4 DATA ANALYSIS AND DISCUSSION

The empirical results from the fixed-effects estimations are presented in Table 3, which reports four model specifications progressively incorporating additional controls for production scale, conservation policies, and land-use characteristics. This stepwise approach allows assessing the robustness of the relationships between economic incentives, institutional variables, and municipal deforestation dynamics in the Legal Amazon during the 2015 - 2023 period.

Table 3. Determinants of Deforestation in the Legal Amazon (2015 - 2023)

Variable	Model 1	Model 2	Model 3	Model 4
Population (log)	0.194***	0.156***	0.156***	0.125***
	(0.035)	(0.033)	(0.033)	(0.029)
Cattle Price	0.0039***	0.0055***	0.0011***	0.0010***
	(0.0010)	(0.0012)	(0.0002)	(0.0002)
Soybean Price	-0.0060***	-0.0084***	-0.0017***	-0.0015***
	(0.0016)	(0.0019)	(0.0004)	(0.0004)
Rural Credit (log)	0.0050***	0.0052***	0.0052***	0.0044**
	(0.0019)	(0.0018)	(0.0018)	(0.0017)
Environmental Staff (log)	-0.0704**	-0.156***	0.0425	0.0388
	(0.028)	(0.033)	(0.059)	(0.059)
State Production (log)		0.0029***	0.0029***	0.0031***
		(0.0008)	(0.0008)	(0.0008)
PA × Post-2015			0.0395***	0.0295***
			(0.0086)	(0.0085)
Forest Share				-0.848***
				(0.119)
Observations	2,694	2,694	2,694	2,694
R^2 (within)	0.296	0.321	0.321	0.390
Mean VIF	2.8	2.9	2.9	2.8

Note: Dependent variable: log (deforestation + 1). Robust standard errors clustered by municipality in parentheses. All models include municipal and year fixed effects. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$
Source: prepared by the authors.

To facilitate interpretation, the results are discussed by grouping variables according to the mechanisms identified in the literature, beginning with economic drivers related to commodity prices and agricultural financing.

Considering economic factors, cattle price presents a positive and statistically significant coefficient across all specifications ($p < 0.01$). A 1% increase in cattle price is associated with a 0.1% to 0.55% increase in deforestation, depending on specification. Given the average annual deforestation of 6.38 km² per municipality, a 10% increase in cattle prices would translate to approximately 0.64 - 3.51 km² of additional forest loss annually at the municipal level, a substantial effect when aggregated across the 772 municipalities in the Legal Amazon. Aggregated across all municipalities, this effect could translate into hundreds to thousands of square kilometres of additional forest loss during periods of high cattle prices. This result aligns with literature identifying livestock as the main forest conversion driver in the Amazon (Harding; Herzberg; Kuralbayeva, 2021; Hargrave; Kis-Katos, 2013).

Soybean price, contrary to initial expectations, exhibits a negative and significant

ISSN: 2594-8083
VIII EIGEDIN
25 a 27 de Maio de 2026
Totalmente Online e Gratuito

coefficient ($p < 0.01$) in all models. This counterintuitive finding is consistent with two mechanisms: the Soy Moratorium's effectiveness in decoupling soy profits from direct forest conversion (Heilmayr *et al.*, 2020); and soybean expansion onto already-degraded pastures, reducing pressure on native forests (Amaral *et al.*, 2021; Morton *et al.*, 2006).

Rural credit maintains a positive and significant association with deforestation in all specifications ($p < 0.05$ in Model 4; $p < 0.01$ in others). A 1% increase in credit volume is associated with approximately 0.5% increase in deforestation. This result suggests that, despite environmental conditionalities introduced in 2008, rural credit continues to finance land conversion, possibly due to weaknesses in monitoring and compliance verification (Nunes *et al.*, 2024; Rajão *et al.*, 2020).

Regarding conservation policies, the interaction term between PPAs established before 2015 and the post-2015 period is positive and highly significant ($p < 0.01$) in Models 3 and 4. This is the most concerning result: older PPAs are associated with higher deforestation after 2015. This phenomenon may reflect:

1. Leakage effects: deforestation pressure is displaced into or around protected areas (Amin *et al.*, 2015; Fuller *et al.*, 2019);
2. Governance erosion: PPAs lose effectiveness when the surrounding institutional framework weakens (Kuschnig *et al.*, 2023); and
3. Selective pressure: protected areas may attract illegal activities in the absence of adequate enforcement, a "paper park" effect (Joppa; Loarie; Pimm, 2008).

With respect to governance and land cover, the coefficient for environmental staff is negative and significant in Models 1 and 2, offering partial support for the hypothesis that state capacity reduces deforestation (Benzeev *et al.*, 2022; Börner *et al.*, 2015). However, introducing controls for PPAs and land cover (Models 3 and 4) renders the effect non-significant. This suggests three plausible explanations: the apparent effect of staff may be mediated by the presence of protected areas; environmental personnel may be preferentially allocated to municipalities with greater forest cover; and the low temporal variation in the variable may limit effect identification. Variance inflation factor (VIF) tests indicate that multicollinearity is not driving this result (mean VIF < 3), supporting the interpretation of institutional mediation rather than statistical artifact.

The proportion of remaining forest cover presents a negative and highly significant coefficient ($p < 0.01$) in Model 4. Municipalities with larger forest stocks deforest less, a result that may reflect lower historical anthropogenic pressure, different development trajectories, or saturation effects of the agricultural frontier (Pacheco; Meyer, 2022).

The robustness of the empirical results allows a more detailed discussion of the mechanisms linking economic incentives, conservation policies, and institutional capacity to deforestation dynamics in the Amazon.

These results confirm that cattle price remains a robust determinant of deforestation in the Amazon, even in the recent period of institutional instability. This finding aligns with a vast literature identifying livestock as the main forest conversion driver (Barona *et al.*, 2010; Hargrave; Kis-Katos, 2013; Richards, 2021). The effect magnitude, a 1% price increase associated with 0.1 - 0.55% deforestation increase, is comparable to estimates from earlier periods, suggesting that the resilience of the price-deforestation link survived post-2015 institutional erosion.

The negative coefficient for soybean price, in contrast, challenges expectations based on previous studies documenting strong positive associations (Arima *et al.*, 2014; Morton *et al.*, 2006). Three non-mutually exclusive explanations emerge from the literature:

One key explanation lies in the Soy Moratorium, a voluntary agreement signed in 2006 by traders and processors that created strong disincentives for soybean-driven forest conversion. Heilmayr *et al.* (2020) estimate the moratorium reduced soy-associated deforestation by 35% in eligible areas. Similarly, Rausch e Gibbs (2016) show that only 1% of soybean expansion in the Amazon biome between 2006 and 2013 occurred in areas deforested after the moratorium's cutoff. The results suggest this effect could persist through 2015 - 2023.

Another explanation relates to soybean expansion onto degraded pastures has been documented as a land-use intensification mechanism (Amaral *et al.*, 2021; Morton *et al.*, 2006). When soy replaces extensive cattle ranching on already-converted areas, pressure on native forests may decrease, especially if displaced cattle ranching does not advance into new areas. This "forest-saving substitution" effect has been observed in consolidated regions of the southern Amazon (Kastens *et al.*, 2017; Song *et al.*, 2021).

A further interpretation concerns the period analysed (2015 - 2023), which may capture a distinct phase of the soybean expansion cycle. Studies documenting positive associations predominantly focus on the pre-2010 period, when expansion occurred mostly over native forest (Macedo *et al.*, 2012; Morton *et al.*, 2006). From 2010 onward, soy increasingly advanced over already-anthropized areas (Kastens *et al.*, 2017; Song *et al.*, 2021).

If soybean prices tell a relatively optimistic story about the potential for private governance to decouple agricultural expansion from deforestation, these findings regarding PPAs point in a far more troubling direction. The most concerning result in the analysis is the positive association between PPAs established before 2015 and deforestation in the recent period. This finding apparently contradicts a robust literature documenting protected area effectiveness in the Amazon (Soares-Filho *et al.*, 2010; Nolte *et al.*, 2013; Qin *et al.*, 2023). However, it aligns with emerging evidence on:

Leakage effects: Amin *et al.* (2015) show that PPAs in the Amazon can displace deforestation to neighbouring municipalities, especially when surrounding governance is weak. Fuller *et al.* (2019), in a meta-analysis, find that protected area spillovers are the rule, not the exception. These results suggest that in the post-2015 period, leakage may have intensified, possibly because weakened enforcement in surrounding areas made illegal activity displacement more attractive;

Erosion of institutional effectiveness: Kuschnig *et al.* (2023) document what they call "erosion of resilience" of conservation interventions in the Amazon post-2012. Budget cuts, reduced enforcement operations, and dismantling of governance structures may have compromised PPAs' management and protection capacity. These results are consistent with this narrative: PPAs that functioned in the previous period may have lost effectiveness when the broader institutional framework weakened, a phenomenon analogous to "paper parks" in contexts of governance failure; and

Selective pressure: Protected areas may attract illegal activities in the absence of adequate enforcement, a phenomenon documented in other tropical contexts (Bare *et al.*, 2015; Wolf *et al.*, 2021). The perception that PPAs are "land without owners" or areas where punishment risk is low may incentivize invasions and illegal timber extraction, especially when the state is absent.

Importantly, PPAs are heterogeneous, integral protection areas typically have stricter use restrictions than sustainable use areas. Future research should disaggregate by PPA type to examine whether leakage effects vary across protection categories. The dummy variable for PPA presence does not capture this heterogeneity, representing an important direction for subsequent analysis.

This result has profound implications for conservation policy design. It suggests that protected areas cannot be treated as islands; their effectiveness depends critically on surrounding governance and state enforcement capacity. In contexts of institutional weakening, leakage may not only neutralize local gains but produce negative aggregate effects.

This theme of institutional fragility extends to another key policy instrument: rural credit. The positive association between rural credit and deforestation, persistent even after rigorous controls, suggests that environmental conditionalities introduced in 2008 have limited practical effectiveness. This result aligns with recent studies documenting weaknesses in monitoring and verification systems:

Rajão *et al.* (2020) show that the Rural Environmental Registry (CAR), a central instrument for compliance verification, is vulnerable to fraud and overlaps. Nunes *et al.* (2024) document that most properties engaging in illegal deforestation continue accessing rural credit, indicating failures in database integration and sanction application.

Faria *et al.* (2025) distinguish between costing and investment credit, finding that only the latter is associated with deforestation reduction when directed toward productive intensification. The aggregate credit measure does not allow this distinction, but the persistence of the positive effect suggests that, in aggregate, credit continues to finance frontier expansion.

Two interpretations can account for this relationship. One possibility is a causal mechanism in which financial resources enable the acquisition of inputs, machinery, and labour necessary for forest conversion. An alternative explanation is correlational: municipalities experiencing agricultural expansion both demand more credit and exhibit higher deforestation. Municipal fixed effects control for time-invariant characteristics that could generate such correlation, although endogeneity cannot be fully ruled out.

Regardless of causal interpretation, the result has clear policy implications: rural credit, as operationalized in 2015 - 2023, did not fulfil its potential as an environmental conditioning instrument. Strengthening integration between credit systems and deforestation databases (PRODES, DETER), requiring validated and non-overlapping CAR for credit access, applying effective sanctions to violators, and differentiating interest rates based on environmental performance are necessary steps to align agricultural financing with conservation objectives.

The pattern that emerges across these findings, of policies that work under strong governance failing when institutional weaken, finds further support in the examination of the role of enforcement personnel. The loss of significance of the environmental staff coefficient when introducing controls for PPAs and forest cover warrants careful analysis. Three explanations are possible:

First, institutional mediation: the staff effect may operate through PPAs, meaning that environmental agents tend to be more effective when allocated to formally protected areas. Herrera, Pfaff, and Robalino (2019) show that enforcement effectiveness varies with protected area type and government level. These results are consistent with this interpretation: once PPA presence is controlled for, the incremental staff effect disappears.

Second, low temporal variation: the extremely low standard deviation of the staff variable (0.07) indicates little variation over time. In fixed-effects models, which exploit only within variation, variables with limited temporal variation have limited statistical power. It is possible that a real effect exists, but the data do not allow precise identification.

Third, endogenous allocation: staff may be allocated to municipalities with higher deforestation or higher forest cover, generating selection bias. If government responds to deforestation spikes by sending more enforcement agents, the contemporaneous correlation could be positive or null, even if enforcement is effective. The fixed effects do not eliminate this simultaneity problem.

The literature consistently indicates that enforcement matters, but its effectiveness depends on broader conditions. Börner *et al.* (2015) show that command-and-control operations are cost-effective but require continuity and predictability. Coelho-Junior *et al.* (2022) document that impunity is the rule in the Amazon: most infraction notices do not result in effective punishment. In this context, the mere presence of staff, without institutional backing, political support, and sanctioning capacity, may be insufficient.

Synthesizing these findings, four priorities for deforestation control policies in the Amazon can be identified that emerge directly from the analysis:

1. Maintain and expand private governance mechanisms: The negative association between soybean price and deforestation suggests the Soy Moratorium has been effective in decoupling agricultural profits from forest conversion. Public policies should therefore focus on ensuring the moratorium's continuity and strengthening, exploring its replication to other commodities, especially beef, and integrating voluntary commitments with regulatory instruments in a hybrid public-private governance framework.

2. Address protected area leakage: The positive effect of pre-2015 PPAs in the recent period indicates that protected areas cannot be treated as islands. Necessary strategies include creating buffer zones with differentiated management, implementing payment for environmental services programs for surrounding properties, strengthening enforcement not only inside but particularly outside PPAs, and systematically monitoring spillover effects.

3. Reform the rural credit system: The persistent credit-deforestation association suggests existing environmental conditionalities are insufficient or poorly implemented. Key reforms involve integrating credit systems with deforestation databases in real time (PRODES

and DETER), requiring validated and non-overlapping CAR registration for credit access, applying effective sanctions to financial institutions that finance violators, and differentiating interest rates according to environmental performance.

4. Strengthen institutional enforcement capacity: The fragility of the environmental staff coefficient should not be interpreted as evidence that enforcement does not matter. On the contrary, it suggests that mere staff presence is insufficient in the absence of broader conditions. Priorities include: restoring environmental agency budgets; guaranteeing staff autonomy and protection; integrating federal, state, and municipal levels; and strengthening the punishment system, reducing impunity.

Global implications: Finally, it is worth considering what these findings from Brazilian Amazon imply for other forest frontiers around the world. Given the Amazon's importance for global carbon cycles, these findings have implications beyond Brazil. They suggest that weakening environmental governance in tropical forest regions may undermine international climate mitigation efforts. Similar governance-dependent dynamics may occur in other tropical forest regions such as the Congo Basin and Indonesia, which face comparable pressures from commodity markets and institutional fragility. International mechanisms such as REDD+ and deforestation-free supply chain commitments (e.g., the EU Deforestation Regulation) must account for governance dynamics, policies that work under strong institutions may fail when governance erodes. The Brazilian experience offers lessons for designing more resilient conservation strategies in politically volatile contexts.

5 CONCLUSIONS

This study investigated the determinants of deforestation in the Brazilian Legal Amazon between 2015 and 2023, using municipal panel data and fixed-effects models. These results reveal a complex picture where economic incentives and conservation policies interact in ways not always aligned with literature expectations.

Three main contributions are identified from the analysis. The results show that the cattle price-deforestation relationship remains robust even during the recent period of institutional instability, whereas soybean prices exhibit a negative association, suggesting that private governance mechanisms such as the Soy Moratorium may have decoupled agricultural profitability from forest conversion. The analysis also reveals a concerning leakage effect from PPAs established before 2015, which are associated with higher deforestation in the post-2015 period, challenging the assumption of unconditional protected-area effectiveness and highlighting the importance of surrounding governance conditions. Finally, rural credit continues to display a positive association with deforestation despite environmental conditionalities, indicating weaknesses in the implementation and monitoring of these safeguards.

This study advances the literature by demonstrating that conservation policies are not intrinsically effective, their success depends on the resilience of the institutions that sustain them. In contexts of institutional weakening, even consolidated instruments, such as PPAs, may lose effectiveness or produce adverse effects.

These findings carry important implications for conservation policy design. They highlight the need to strengthen and expand private governance mechanisms to other commodities, implement spatially integrated strategies to address leakage around protected areas, reform the rural credit system to align agricultural finance with environmental objectives, and reinforce institutional enforcement capacity within broader governance frameworks.

These limitations point to several avenues for future research. The strong correlation between soybean and cattle prices prevents precise separation of their individual effects, suggesting that more disaggregated data or quasi-experimental approaches would be valuable. Spatial spillovers are not explicitly modelled in the main specification; spatial econometric models could allow more precise estimation of leakage effects. Municipal-level analysis may also obscure intra-municipal heterogeneity, which property-level datasets such as CAR could help reveal. Furthermore, the study measures deforestation but not forest degradation, an increasingly important process as fires and selective logging expand. Additional work could also examine heterogeneity across PPA types, as different protection categories may experience distinct leakage dynamics. Finally, the limited temporal variation in environmental staffing constrains inference about enforcement effects. These issues are particularly urgent given concerns about the Amazon approaching a tipping point.

Despite these limitations, this study offers robust evidence that conservation policy effectiveness in the Amazon cannot be taken for granted. The challenge for the coming decade will be to build resilient governance frameworks capable of maintaining environmental policy effectiveness even in the face of political and economic fluctuations. The future of the Amazon, and other tropical forests, hinges not only on policy design but on the political and institutional stability required to enforce them.

ACKNOWLEDGMENTS

"This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.".

REFERENCES

AMARAL, Daniel Furlan; DE SOUZA FERREIRA FILHO, Joaquim Bento; CHAGAS, André Luis Squarize; ADAMI, Marcos. Expansion of soybean farming into deforested areas in the amazon biome: the role and impact of the soy moratorium. **Sustainability Science**, [*S. l.*], v. 16, n. 4, p. 1295–1312, 1 jul. 2021. https://doi.org/10.1007/s11625-021-00942-x.

AMIN, Ariane Manuela; CHOUMERT, Johanna; COMBES, Jean-Louis; MOTEL, Pascale Combes; KERE, Eric Nazindigouba; OLINGA, Jean-Galbert Ongono; SCHWARTZ, Sonia. **A spatial econometric approach to spillover effects between protected areas and deforestation in the Brazilian Amazon**. p. 27. [*S. l.*]: [*S.n.*], [*S. d.*]. Disponível em: https://shs.hal.science/halshs-00960476. Acesso em: 22 out. 2025.

ANGELSEN, Arild; KAIMOWITZ, David. Rethinking the Causes of Deforestation: Lessons from Economic Models. **The World Bank Research Observer**, [*S. l.*], v. 14, n. 1, p. 73–98, 1 fev. 1999. https://doi.org/10.1093/wbro/14.1.73.

ARAÚJO, Suely Mara Vaz Guimarães de. Environmental Policy in the Bolsonaro Government: The Response of Environmentalists in the Legislative Arena. **Brazilian Political Science Review**, [*S. l.*], v. 14, p. e0005, 2020. https://doi.org/10.1590/1981-3821202000020005.

ARIMA, Eugenio Y.; BARRETO, Paulo; ARAÚJO, Elis; SOARES-FILHO, Britaldo. Public policies can reduce tropical deforestation: Lessons and challenges from Brazil. **Land Use Policy**, [*S. l.*], v. 41, p. 465–473, 1 nov. 2014. https://doi.org/10.1016/j.landusepol.2014.06.026.

ASSUNÇÃO, Juliano; GANDOUR, Clarissa; ROCHA, Romero; ROCHA, Rudi. The Effect of Rural Credit on Deforestation: Evidence from the Brazilian Amazon. **The Economic Journal**, [*S. l.*], v. 130, n. 626, p. 290–330, 1 fev. 2020. https://doi.org/10.1093/ej/uez060.

AZEVEDO-RAMOS, Claudia; MOUTINHO, Paulo; ARRUDA, Vera Laísa da S.; STABILE, Marcelo C. C.; ALENCAR, Ane; CASTRO, Isabel; RIBEIRO, João Paulo. Lawless land in no man's land: The undesignated public forests in the Brazilian Amazon. **Land Use Policy**, [*S. l.*], v. 99, p. 104863, 1 dez. 2020. https://doi.org/10.1016/j.landusepol.2020.104863.

BARONA, Elizabeth; RAMANKUTTY, Navin; HYMAN, Glenn; COOMES, Oliver T. The role of pasture and soybean in deforestation of the Brazilian Amazon. **Environmental Research Letters**, [*S. l.*], v. 5, n. 2, p. 024002, abr. 2010. https://doi.org/10.1088/1748-9326/5/2/024002.

BENZEEV, Rayna; WILSON, Bradley; BUTLER, Megan; MASSOCA, Paulo; PAUDEL, Karuna; REDMORE, Lauren; ZARBÁ, Lucía. What's governance got to do with it? Examining the relationship between governance and deforestation in the Brazilian Amazon. **PLOS ONE**, [*S. l.*], v. 17, n. 6, p. e0269729, 23 jun. 2022. https://doi.org/10.1371/journal.pone.0269729.

BLACKMAN, Allen; LI, Zhengyan; LIU, Antung A. Efficacy of Command-and-Control and Market-Based Environmental Regulation in Developing Countries. **Annual Review of Resource Economics**, [*S. l.*], v. 10, n. Volume 10, 2018, p. 381–404, 5 out. 2018. https://doi.org/10.1146/annurev-resource-100517-023144.

BÖRNER, Jan; KIS-KATOS, Krisztina; HARGRAVE, Jorge; KÖNIG, Konstantin. Post-Crackdown Effectiveness of Field-Based Forest Law Enforcement in the Brazilian Amazon. **PLOS ONE**, [*S. l.*], v. 10, n. 4, p. e0121544, 15 abr. 2015. https://doi.org/10.1371/journal.pone.0121544.

BRITO, Brenda; BARRETO, Paulo; BRANDÃO, Amintas; BAIMA, Sara; GOMES, Pedro Henrique. Stimulus for land grabbing and deforestation in the Brazilian Amazon. **Environmental Research Letters**, [*S. l.*], v. 14, n. 6, p. 064018, jun. 2019. https://doi.org/10.1088/1748-9326/ab1e24.

BYERLEE, Derek; STEVENSON, James; VILLORIA, Nelson. Does intensification slow crop land expansion or encourage deforestation? **Global Food Security**, [*S. l.*], v. 3, n. 2, p. 92–98, 1 jul. 2014. https://doi.org/10.1016/j.gfs.2014.04.001.

CARRER, Marcelo José; MAIA, Alexandre Gori; DE MELLO BRANDÃO VINHOLIS, Marcela; DE SOUZA FILHO, Hildo Meirelles. Assessing the effectiveness of rural credit policy on the adoption of integrated crop-livestock systems in Brazil. **Land Use Policy**, [*S. l.*], v. 92, p. 104468, 1 mar. 2020. https://doi.org/10.1016/j.landusepol.2020.104468.

CARVALHO, William D.; MUSTIN, Karen; HILÁRIO, Renato R.; VASCONCELOS, Ivan M.; EILERS, Vivianne; FEARNSIDE, Philip M. Deforestation control in the Brazilian Amazon: A conservation struggle being lost as agreements and regulations are subverted and bypassed. **Perspectives in Ecology and Conservation**, [*S. l.*], v. 17, n. 3, p. 122–130, 1 jul. 2019. https://doi.org/10.1016/j.pecon.2019.06.002.

COELHO-JUNIOR, Marcondes G; VALDIONES, Ana P; SHIMBO, Julia Z; SILGUEIRO, Vinicius; ROSA, Marcos; MARQUES, Carolina Del Lama; OLIVEIRA, Magaly; ARAÚJO, Suely; AZEVEDO, Tasso. Unmasking the impunity of illegal deforestation in the Brazilian Amazon: a call for enforcement and accountability. **Environmental Research Letters**, [*S. l.*], v. 17, n. 4, p. 041001, mar. 2022. https://doi.org/10.1088/1748-9326/ac5193.

COSTA, Anderson da Silva; QUEIROZ, Joaquim Carlos Barbosa; CHERMONT, Larissa Steiner; LAMEIRA, Osmar Alves; SOUZA, Everaldo Barreiros de; DINIZ, Marcelo Bentes; MOURA, Helyelson Paredes; COSTA, Debora Lisboa Correa. Deforestation forecasts in the Legal Amazon using intervention models. **Research, Society and Development**, [*S. l.*], v. 10, n. 4, p. e8710413787–e8710413787, 1 abr. 2021. https://doi.org/10.33448/rsd-v10i4.13787.

DOU, Yue; SILVA, Ramon Felipe Bicudo da; BATISTELLA, Mateus; TORRES, Sara; MORAN, Emilio; LIU, Jianguo. Mapping crop producer perceptions: The role of global drivers on local agricultural land use in Brazil. **Land Use Policy**, [*S. l.*], v. 133, p. 106862, 1 out. 2023. https://doi.org/10.1016/j.landusepol.2023.106862.

FARIA, Weslem Rodrigues; DA SILVA, Felipe Morelli; DE ALMEIDA, Alexandre Nunes; BETARELLI JUNIOR, Admir Antonio. The relationship between rural credit policy and deforestation: evidence from Brazil. **Environmental Economics and Policy Studies**, [*S. l.*], v. 27, n. 2, p. 231–263, 1 abr. 2025. https://doi.org/10.1007/s10018-024-00421-4.

FULLER, Carley; ONDEI, Stefania; BROOK, Barry W.; BUETTEL, Jessie C. First, do no harm: A systematic review of deforestation spillovers from protected areas. **Global Ecology and Conservation**, [*S. l.*], v. 18, p. e00591, 1 abr. 2019. https://doi.org/10.1016/j.gecco.2019.e00591.

HADDAD, Eduardo A.; ARAÚJO, Inácio F.; FELTRAN-BARBIERI, Rafael; PEROBELLI, Fernando S.; ROCHA, Ademir; SASS, Karina S.; NOBRE, Carlos A. Economic drivers of deforestation in the Brazilian Legal Amazon. **Nature Sustainability**, [*S. l.*], v. 7, n. 9, p. 1141–1148, set. 2024. https://doi.org/10.1038/s41893-024-01387-7.

HÄNGGLI, Aline; LEVY, Samuel A; ARMENTERAS, Dolors; BOVOLO, C Isabella; BRANDÃO, Joyce; RUEDA, Ximena; GARRETT, Rachael D. A systematic comparison of deforestation drivers and policy effectiveness across the Amazon biome. **Environmental Research Letters**, [*S. l.*], v. 18, n. 7, p. 073001, jun. 2023. https://doi.org/10.1088/1748-9326/acd408.

HARDING, Torfinn; HERZBERG, Julika; KURALBAYEVA, Karlygash. Commodity prices and robust environmental regulation: Evidence from deforestation in Brazil. **Journal of Environmental Economics and Management**, [*S. l.*], v. 108, p. 102452, 1 jul. 2021. https://doi.org/10.1016/j.jeem.2021.102452.

HARGRAVE, Jorge; KIS-KATOS, Krisztina. Economic Causes of Deforestation in the Brazilian Amazon: A Panel Data Analysis for the 2000s. **Environmental and Resource Economics**, [*S. l.*], v. 54, n. 4, p. 471–494, 1 abr. 2013. https://doi.org/10.1007/s10640-012-9610-2.

HEILMAYR, Robert; RAUSCH, Lisa L.; MUNGER, Jacob; GIBBS, Holly K. Brazil's Amazon Soy Moratorium reduced deforestation. **Nature Food**, [*S. l.*], v. 1, n. 12, p. 801–810, dez. 2020. https://doi.org/10.1038/s43016-020-00194-5.

INPE, National Institute For Space Research. TerraBrasilis - Geographic Data Platform: Prodes and Deter datasets. 2026. Disponível em: https://terrabrasilis.dpi.inpe.br/app/dashboard/deforestation/biomes/legal_amazon/increments. Acesso em: 9 mar. 2026.

JOPPA, Lucas N.; LOARIE, Scott R.; PIMM, Stuart L. On the protection of "protected areas". **Proceedings of the National Academy of Sciences**, [*S. l.*], v. 105, n. 18, p. 6673–6678, 6 maio 2008. https://doi.org/10.1073/pnas.0802471105.

KASTENS, Jude H.; BROWN, J. Christopher; COUTINHO, Alexandre Camargo; BISHOP, Christopher R.; ESQUERDO, Júlio César D. M. Soy moratorium impacts on soybean and deforestation dynamics in Mato Grosso, Brazil. **PLOS ONE**, [*S. l.*], v. 12, n. 4, p. e0176168, 28 abr. 2017. https://doi.org/10.1371/journal.pone.0176168.

KHAN, Rameen; HUSSAIN, Fiaz. Assessing policy capacity and policy effectiveness: A comparative study using sustainable governance indicators. **European Policy Analysis**, [*S.*

l.], v. 10, n. 4, p. 575–603, nov. 2024. https://doi.org/10.1002/epa2.1217.

KUSCHNIG, Nikolas; VASHOLD, Lukas; C SOTERRONI, Aline; OBERSTEINER, Michael. Eroding resilience of deforestation interventions—evidence from Brazil's lost decade. **Environmental Research Letters**, [*S. l.*], v. 18, n. 7, p. 074039, jul. 2023. https://doi.org/10.1088/1748-9326/acdfe7.

MACEDO, Marcia N.; DEFRIES, Ruth S.; MORTON, Douglas C.; STICKLER, Claudia M.; GALFORD, Gillian L.; SHIMABUKURO, Yosio E. Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. **Proceedings of the National Academy of Sciences**, [*S. l.*], v. 109, n. 4, p. 1341–1346, 24 jan. 2012. https://doi.org/10.1073/pnas.1111374109.

MERKUS, Erik. The economic consequences of environmental enforcement: Evidence from an anti-deforestation policy in Brazil. **World Development**, [*S. l.*], v. 181, p. 106646, 1 set. 2024. https://doi.org/10.1016/j.worlddev.2024.106646.

MIRANDA, Javier; BRITZ, Wolfgang; BÖRNER, Jan. Impacts of commodity prices and governance on the expansion of tropical agricultural frontiers. **Scientific Reports**, [*S. l.*], v. 14, n. 1, p. 9209, 22 abr. 2024. https://doi.org/10.1038/s41598-024-59446-0.

MONTIBELLER, Bruno; KMOCH, Alexander; VIRRO, Holger; MANDER, Ülo; UUEMAA, Evelyn. Increasing fragmentation of forest cover in Brazil's Legal Amazon from 2001 to 2017. **Scientific Reports**, [*S. l.*], v. 10, n. 1, p. 5803, 2 abr. 2020. https://doi.org/10.1038/s41598-020-62591-x.

MOREIRA-DANTAS, Ianna Raissa; SÖDER, Mareike. Global deforestation revisited: The role of weak institutions. **Land Use Policy**, [*S. l.*], v. 122, p. 106383, 1 nov. 2022. https://doi.org/10.1016/j.landusepol.2022.106383.

MORTON, Douglas C.; DEFRIES, Ruth S.; SHIMABUKURO, Yosio E.; ANDERSON, Liana O.; ARAI, Egidio; DEL BON ESPIRITO-SANTO, Fernando; FREITAS, Ramon; MORISETTE, Jeff. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. **Proceedings of the National Academy of Sciences**, [*S. l.*], v. 103, n. 39, p. 14637–14641, 26 set. 2006. https://doi.org/10.1073/pnas.0606377103.

NEPSTAD, Daniel; MCGRATH, David; STICKLER, Claudia; ALENCAR, Ane; AZEVEDO, Andrea; SWETTE, Briana; BEZERRA, Tathiana; DIGIANO, Maria; SHIMADA, João; SEROA DA MOTTA, Ronaldo; ARMIJO, Eric; CASTELLO, Leandro; BRANDO, Paulo; HANSEN, Matt C.; MCGRATH-HORN, Max; CARVALHO, Oswaldo; HESS, Laura. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. **Science (New York, N.Y.)**, [*S. l.*], v. 344, n. 6188, p. 1118–1123, 6 jun. 2014. https://doi.org/10.1126/science.1248525.

NOLTE, Christoph; AGRAWAL, Arun; SILVIUS, Kirsten M.; SOARES-FILHO, Britaldo S. Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon. **Proceedings of the National Academy of Sciences**, [*S. l.*], v. 110, n. 13, p. 4956–4961, 26 mar. 2013. https://doi.org/10.1073/pnas.1214786110.

NUNES, Felipe S. M.; SOARES-FILHO, Britaldo S.; OLIVEIRA, Amanda R.; VELOSO, Laura V. S.; SCHMITT, Jair; VAN DER HOFF, Richard; ASSIS, Debora C.; COSTA, Rayane

P.; BÖRNER, Jan; RIBEIRO, Sonia M. C.; RAJÃO, Raoni G. L.; DE OLIVEIRA, Ubirajara; COSTA, Marcelo Azevedo. Lessons from the historical dynamics of environmental law enforcement in the Brazilian Amazon. **Scientific Reports**, [*S. l.*], v. 14, n. 1, p. 1828, 21 jan. 2024. https://doi.org/10.1038/s41598-024-52180-7.

PACHECO, Andrea; MEYER, Carsten. Land tenure drives Brazil's deforestation rates across socio-environmental contexts. **Nature Communications**, [*S. l.*], v. 13, n. 1, p. 5759, 1 out. 2022. https://doi.org/10.1038/s41467-022-33398-3.

PEREIRA, Eder Johnson de Area Leão; SILVEIRA FERREIRA, Paulo Jorge; DE SANTANA RIBEIRO, Luiz Carlos; SABADINI CARVALHO, Terciane; DE BARROS PEREIRA, Hernane Borges. Policy in Brazil (2016–2019) threaten conservation of the Amazon rainforest. **Environmental Science & Policy**, [*S. l.*], v. 100, p. 8–12, 1 out. 2019. https://doi.org/10.1016/j.envsci.2019.06.001.

QIN, Yuanwei; XIAO, Xiangming; LIU, Fang; DE SA E SILVA, Fabio; SHIMABUKURO, Yosio; ARAI, Egidio; FEARNSIDE, Philip Martin. Forest conservation in Indigenous territories and protected areas in the Brazilian Amazon. **Nature Sustainability**, [*S. l.*], v. 6, n. 3, p. 295–305, mar. 2023. https://doi.org/10.1038/s41893-022-01018-z.

RAJÃO, Raoni; SOARES-FILHO, Britaldo; NUNES, Felipe; BÖRNER, Jan; MACHADO, Lilian; ASSIS, Débora; OLIVEIRA, Amanda; PINTO, Luis; RIBEIRO, Vivian; RAUSCH, Lisa; GIBBS, Holly; FIGUEIRA, Danilo. The rotten apples of Brazil's agribusiness. **Science**, [*S. l.*], v. 369, n. 6501, p. 246–248, 17 jul. 2020. https://doi.org/10.1126/science.aba6646.

RAUSCH, Lisa L.; GIBBS, Holly K. Property Arrangements and Soy Governance in the Brazilian State of Mato Grosso: Implications for Deforestation-Free Production. **Land**, [*S. l.*], v. 5, n. 2, p. 7, jun. 2016. https://doi.org/10.3390/land5020007.

REQUATE, Till. Dynamic incentives by environmental policy instruments—a survey. **Ecological Economics**, [*S. l.*], v. 54, n. 2, p. 175–195, 1 ago. 2005. https://doi.org/10.1016/j.ecolecon.2004.12.028.

RICHARDS, Peter. A Key Ingredient in Deforestation Slowdowns? A Strong Brazilian Economy. **Frontiers in Forests and Global Change**, [*S. l.*], v. 4, 9 fev. 2021. DOI: 10.3389/ffgc.2021.613313. Disponível em: https://www.frontiersin.org/journals/forests-and-global-change/articles/10.3389/ffgc.2021.613313/full. Acesso em: 22 out. 2025.

RIFE, Alexis N.; ERISMAN, Brad; SANCHEZ, Alexandra; ABURTO-OROPEZA, Octavio. When good intentions are not enough … Insights on networks of "paper park" marine protected areas. **Conservation Letters**, [*S. l.*], v. 6, n. 3, p. 200–212, 2013. https://doi.org/10.1111/j.1755-263X.2012.00303.x.

SALVADOR, Miquel; SANCHO, David. The Role of Local Government in the Drive for Sustainable Development Public Policies. An Analytical Framework Based on Institutional Capacities. **Sustainability**, [*S. l.*], v. 13, n. 11, p. 5978, jan. 2021. https://doi.org/10.3390/su13115978.

SILVA-JUNIOR, Celso H. L.; SILVA, Fabrício B.; ARISI, Barbara Maisonnave; MATAVELI, Guilherme; PESSÔA, Ana C. M.; CARVALHO, Nathália S.; REIS, João B. C.; SILVA JÚNIOR, Admo R.; MOTTA, Nathalia A. C. S.; E SILVA, Paulo Vinícius Moreira; RIBEIRO, Francarlos Diniz; SIQUEIRA-GAY, Juliana; ALENCAR, Ane; SAATCHI, Sassan; ARAGÃO, Luiz E. O. C.; ANDERSON, Liana O.; MELO, Maycon. Brazilian Amazon indigenous territories under deforestation pressure. **Scientific Reports**, [*S. l.*], v. 13, n. 1, p. 5851, 10 abr. 2023. https://doi.org/10.1038/s41598-023-32746-7.

SOARES-FILHO, Britaldo; MOUTINHO, Paulo; NEPSTAD, Daniel; ANDERSON, Anthony; RODRIGUES, Hermann; GARCIA, Ricardo; DIETZSCH, Laura; MERRY, Frank; BOWMAN, Maria; HISSA, Letícia; SILVESTRINI, Rafaella; MARETTI, Cláudio. Role of Brazilian Amazon protected areas in climate change mitigation. **Proceedings of the National Academy of Sciences**, [*S. l.*], v. 107, n. 24, p. 10821–10826, 15 jun. 2010. https://doi.org/10.1073/pnas.0913048107.

SOARES-FILHO, Britaldo Silveira; OLIVEIRA, Ubirajara; FERREIRA, Mariana Napolitano; MARQUES, Fernanda Figueiredo Constant; DE OLIVEIRA, Amanda Ribeiro; SILVA, Fábio Ribeiro; BÖRNER, Jan. Contribution of the Amazon protected areas program to forest conservation. **Biological Conservation**, [*S. l.*], v. 279, p. 109928, 1 mar. 2023. https://doi.org/10.1016/j.biocon.2023.109928.

SONG, Xiao-Peng; HANSEN, Matthew C.; POTAPOV, Peter; ADUSEI, Bernard; PICKERING, Jeffrey; ADAMI, Marcos; LIMA, Andre; ZALLES, Viviana; STEHMAN, Stephen V.; DI BELLA, Carlos M.; CONDE, Maria C.; COPATI, Esteban J.; FERNANDES, Lucas B.; HERNANDEZ-SERNA, Andres; JANTZ, Samuel M.; PICKENS, Amy H.; TURUBANOVA, Svetlana; TYUKAVINA, Alexandra. Massive soybean expansion in South America since 2000 and implications for conservation. **Nature Sustainability**, [*S. l.*], v. 4, n. 9, p. 784–792, set. 2021. https://doi.org/10.1038/s41893-021-00729-z.

STEINEBACH, Yves. Instrument choice, implementation structures, and the effectiveness of environmental policies: A cross-national analysis. **Regulation & Governance**, [*S. l.*], v. 16, n. 1, p. 225–242, 2022. https://doi.org/10.1111/rego.12297.

SYLVESTER, Janelle M.; GUTIÉRREZ-ZAPATA, Diana María; PÉREZ-MARULANDA, Lisset; VANEGAS-CUBILLOS, Martha; BRUUN, Thilde Bech; MERTZ, Ole; CASTRO-NUNEZ, Augusto. Analysis of food system drivers of deforestation highlights foreign direct investments and urbanization as threats to tropical forests. **Scientific Reports**, [*S. l.*], v. 14, n. 1, p. 15179, 16 jul. 2024. https://doi.org/10.1038/s41598-024-65397-3.

TRANCOSO, Ralph. Changing Amazon deforestation patterns: urgent need to restore command and control policies and market interventions. **Environmental Research Letters**, [*S. l.*], v. 16, n. 4, p. 041004, abr. 2021. https://doi.org/10.1088/1748-9326/abee4c.

VALE, Mariana M.; BERENGUER, Erika; ARGOLLO DE MENEZES, Marcio; VIVEIROS DE CASTRO, Ernesto B.; PUGLIESE DE SIQUEIRA, Ludmila; PORTELA, Rita de Cássia Q. The COVID-19 pandemic as an opportunity to weaken environmental protection in Brazil. **Biological Conservation**, [*S. l.*], v. 255, p. 108994, 1 mar. 2021. https://doi.org/10.1016/j.biocon.2021.108994.

VILLORIA, Nelson. Consequences of agricultural total factor productivity growth for the sustainability of global farming: accounting for direct and indirect land use effects. **Environmental Research Letters**, [*S. l.*], v. 14, n. 12, p. 125002, nov. 2019. https://doi.org/10.1088/1748-9326/ab4f57.