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Trade, Enforcement, and Deforestation: Evidence from Brazil

By

Coral Richardson
THESIS

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Approved:

Daniel Y. Kono, Chair

Gabriella Montinola

Mark Lubell

Committee in Charge

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To my dad who gave me leaves to make a crown, branches to make a house, a trunk to make a boat, and a quiet place to sit and rest.

To Josh who has read every paper, listened to every talk, and lifted me up when I wanted to stay down. I wouldn't have done this without you.

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Abstract

Deforestation in the Brazilian Amazon is driven by a multitude of complex factors, including market demand for forest resource intensive goods and national policy decisions. Previous literature has highlighted agricultural production of goods such as soy and beef as a key driver of deforestation in the Amazon, though there remains some disagreement over the relevance of international markets. Literature has also identified punitive measures like fines as potentially influential approaches to reducing illicit forest clearing, although the credibility of enforcement is an underexplored component of our understanding of fine effectiveness that this paper works to address. While these are both important to our understanding of drivers and solutions to deforestation, this paper goes further to begin clarifying how the interaction between exporting agricultural goods and the enforcement of forest management policy influences deforestation outcomes. Utilizing municipality-year panel data from 2000-2020, this study ultimately finds a statistically significant and positive relationship between enforcement and deforestation and a negative but insignificant relationship between exports and deforestation. These results ultimately contradict the expected relationships between these variables and deforestation. The key contribution of this paper, however, is the interaction term which remains positive and statistically significant across model specifications. These results imply that the marginal effect of trade is highest in municipalities with the highest level of enforcement. This unexpected result raises concerns for endogeneity and ultimately highlights areas for key future research.

Introduction

Deforestation remains a key area for improvement in climate change mitigation. Forest loss threatens biodiversity, reduces carbon storage, disrupts water cycles, and can threaten the livelihood of communities who depend on forest resources. Therefore, understanding drivers of deforestation and potential solutions to persistent forest loss can be key in meeting future climate goals. This paper examines international market demand for agricultural products as a key driver of forest loss and the effectiveness of punitive policy measures in deterring illegal forest clearing within the Brazilian Amazon as well as the interaction of these variables. The key question this paper seeks to answer is: How does the exporting of agricultural goods and enforcement of forest management policy interact to influence deforestation outcomes? While answering this question provides valuable insight to the drivers of deforestation, it also improves our understanding of policy enforcement as an effective deterrent.

The current state of the literature has identified agricultural production as a key driver of deforestation, particularly in tropical rainforests like the Amazon Rainforest (Busch and Ferretti-Gallon 2017; Angelsen and Kaimowitz 1999). However, there remains some disagreement on whether domestic or international market demands are more influential in driving forest clearing for agricultural expansion (Ehrlich et al. 2020; Pendrill et al. 2022). Changing international demand for products such as beef and soy has been linked to deforestation in the Brazilian Amazon, though other studies have highlighted the role of growing domestic demand for beef products as the key driver in deforestation (Williams 2003; Seymour and Busch 2016). This paper addresses these gaps by isolating municipality-level production of soy and beef products for the export market to determine whether international trade of these products is correlated with deforestation.

When it comes to understanding the effectiveness of mitigation approaches, there is similarly some disagreement in the literature on the effectiveness of punitive measures, like fines, in deterring illegal forest clearing. One key aspect of forest mitigation policy that has been regarded as a significant determinant of effectiveness is the credibility of enforcement (Sousa 2016; Assunção et al. 2015). The intensity of enforcement and the perceived probability of being punished for illicit behavior can be the strongest determinant of policy effectively reducing deforestation (Sousa 2016). The empirical approach of this paper aims to determine whether enforcing environmental policy by distributing fines for illicit clearing has a clear relationship with deforestation.

To evaluate these relationships, this paper utilizes a municipality-year panel dataset from 2000-2020 covering the Brazilian Legal Amazon (LAM). Fixed-effects models are utilized to examine the relationship between policy enforcement, agricultural exports, and the interaction of these variables on deforestation. The empirical results contradict my hypothesized negative relationship between enforcement and deforestation and the hypothesized positive relationship between exports and deforestation. Furthermore, the estimated coefficients for the interaction of these variables on deforestation also contradict the expected relationship. The positive and statistically significant coefficients indicate that the marginal effects of exports on deforestation are higher in municipalities with higher enforcement.

This paper expands on previous theoretical arguments by providing insight into the relationships between exports, enforcement, and deforestation. The contradictory results of this analysis indicate a need for further research. A key limitation to this study is the limited data available for measuring the probability of being fined for illegal deforestation. Future research would benefit from incorporating this data as it becomes more available. Another limitation to this

study that should be addressed by future research is the potential endogeneity. Future model strategies may be effective at mitigating endogeneity in the model to provide a clearer picture of the relationship between the variables.

Literature Review

This section provides an overview of deforestation in the Brazilian Amazon, the relationships with international trade, and conservation policy enforcement. It first looks at deforestation in Brazil focusing on the historical context of forest degradation before exploring some of the key drivers of deforestation. Then, this section highlights the significance of globalization and international trade on deforestation. It discusses international demand for agricultural commodities and the resource intensity of such markets, as well as less direct effects of globalized trade on deforestation. Finally, this section looks at forest management policy approaches and evidence from the literature on how this enforcement can be an impactful approach to reducing deforestation.

Deforestation and the Brazilian Amazon Rainforest

Forests are significant ecosystems that provide important economic, ecological, and cultural benefits. Healthy forests can store carbon, host biodiversity, and effectively filter water, in addition to being sources of culturally and spiritually significant ecosystems (Busch and Ferretti-Gallon 2017; Pert et al. 2014). Meanwhile, the extraction of forest resources can also be an important economic tool for states rich in forest resources. The clearing of forested areas can increase cropland or pasture area for agricultural production, increase accessibility of mining operations and resources, and increase timber or related products (Busch and Ferretti-Gallon 2017). The conflict between forest conservation and extraction creates a social optimum level of

deforestation, however, the global forest loss has both exceeded this level and continues to grow (Hansen et al. 2013; Busch and Ferretti-Gallon 2017). Concern for global forest resources has driven scholarly attention to both the drivers of deforestation and potential solutions to mitigating rising forest loss.

Home to the largest area of the Amazon Rainforest and some of the most accessible and precise data on deforestation, Brazil has received much scholarly attention since the turn of the century. Brazil is home to approximately 4.2 million km^2 of the Amazon rainforest, however by 2004, the total deforested area in Brazil had totaled over 600,000 km^2 or nearly 15% of the original Amazon forest area (INPE, 2017; Assunção et al. 2019). Most importantly, approximately 90% of this deforestation was illegal and the primary goal of the forest clearing was for non-forest land uses such as agriculture, rather than the extraction of timber (Hosonuma et al. 2012). More specifically, conversion for pasture lands accounted for approximately 63% of cleared forest area and cropland conversion accounted for approximately 6% (Assunção et al. 2019; INPE and Embrapa 2016).

The decision to convert forest land to agriculture, pasture, or mining area is driven by a variety of factors that are often interconnected (Busch and Ferretti-Gallon 2017). For example, physical characteristics of land such as the slope, elevation, and soil fertility can drive deforestation in favor of agriculture (Busch and Ferretti-Gallon 2017). Similarly, the built environment, including the connectivity of roads and proximity to towns are also relevant to the decision making process. Finally, market demand for agricultural and timber products can be influential in forest management approaches. These factors are complex and often interconnected with causal relationships that may go in both directions (Busch and Ferretti-Gallon 2017). While each of these

factors are relevant in deforestation and have been supported by the literature as relevant aspects of the deforestation decision making process, pastureland and crop land remain the largest drivers.

Market Demand and Deforestation

Incentives to clear forest area for agriculture are largely inspired by changes to market demands for agricultural goods at both the domestic and international level. Williams (2003), for example, highlighted that the expansion of agricultural land in the tropics was largely driven by the need to provide food for domestic markets until the late twentieth century. This point in history marked the shift in agriculture from a domestic to international industry with increasing globalization and demand for key commodities such as beef, soybeans, and palm oil (Seymour and Busch, 2016; Ehrlich et al. 2020).

During the 1990's, middle-income countries such as China, experienced an unprecedented period of per-capita income growth which then sparked an increase in per capita consumption of oils and meat in place of previous cereal consumption (Ehrlich et al. 2020). At the turn of the century, many of these middle-income countries joined the World Trade Organization which liberalized trade and made international markets more accessible – and therefore profitable – for producers. Trade liberalization in the 1990's shifted the value of agricultural commodities, making soybeans and beef the first and third most valuable traded agricultural commodities (Ehrlich et al. 2020). Tropical rainforests suffered greatly from this shift in international markets, with the new large-scale commercial farming of soybeans, beef, and palm oil accounting for approximately 40% of forest loss while subsistence farming accounted for only 33% (FAO and UNEP 2016).

Early empirical findings on the drivers of deforestation find that deforestation is likely to occur when forested lands are accessible, prices of agricultural commodities and timber are high,

and when there are opportunities for trade (Allen and Barnes 1985; Angelsen and Kaimowitz 1999; Faria and Almeida 2016). Trade openness is one measure of the opportunity for trade that can provide valuable insight on the relationship between trade and deforestation; however, the literature evaluating this relationship is relatively limited. Faria and Almeida (2016) note that while expected returns from international trade is a significant driver of expanding agricultural land in the Amazon, the effects of trade openness on deforestation can be somewhat ambiguous. For example, if openness leads to an increase in exports, openness can put additional pressure on tropical forests. However, if openness results in increased imports, this can reduce the incentives to deforest (Faria and Almeida 2016). In the case of Brazil, Faria and Almeida (2016) found that as trade in the Amazon increases, so does deforestation and the production of soybeans and beef cattle is a key driver of this deforestation. The Amazon region alone saw an increase in exports from 11% in 2000 to 31% in 2010, while exports for Brazil as a whole stayed at approximately 10% during the same period, helping further illustrate the growing significance of international markets in areas with conditions suitable for agricultural expansion (Faria and Almeida, 2016).

While empirical evidence has highlighted the role of international markets in driving deforestation and agricultural exports, there remains some disagreement in the literature on whether domestic market demands are as consequential or more consequential than international markets. Debany (2024) argues that global demand for soy generates a cycle of increased profits, increased production, and increased deforestation in the Brazilian rainforest but also notes the relevance of changing domestic demand in driving deforestation. While Debany (2024) notes domestic market demand also contributes to agriculture related deforestation, others argue – and find evidence in support of – domestic markets being the main driver of deforestation. Ehrlich et al. (2020), for example, describe the 2008 economic boom in Brazil as a turning point in domestic

consumption patterns in favor of less cereals and more meat, with the authors finding that two-thirds of the demand for Brazilian beef has been domestic (Ehrlich et al. 2020). Utilizing a novel physical trade model, Pendrill et al. (2022) similarly find that only 20-25% of deforestation resulting in agricultural production is linked to exports. However, this average hides variations in countries, regions, and commodities. While soybeans, palm oil, and cash crops such as rubber, coffee or cocoa are largely exported goods, beef and cereals are typically consumed domestically (Pendrill et al. 2022). Therefore, the effects of international and domestic market demand may be difficult to disentangle without accounting for these variations. Haddad et al. (2024) disentangled the roles of domestic and international markets on agriculture related deforestation in the Brazilian Legal Amazon (LAM) and found that 55.1% of trade flows from the LAM to domestic markets. However, they also find that foreign exports have the highest deforestation intensity which highlights the impacts of commodities with relatively lower value added and higher environmental impacts. This paper goes on to focus on the relationship between international exports of key commodities (soybeans and beef) to address the uncertainty remaining in the literature.

Monitoring and Enforcement of Forest Management Policies

While understanding key drivers of deforestation is important for guiding mitigation approaches, it is also necessary to understand what solutions are effective in reducing the rate of forest loss. One such solution that has been supported throughout the literature is the implementation of forest management policy, often in the form of punitive measures for non-compliance. For example, Assunção et al. (2015) determined that conservation policies in Brazil significantly contributed to decreases in deforestation. Sousa (2016) corroborated this finding by determining that fines, embargoes on rural private properties, and confiscation of means of production are all negatively correlated with deforestation. However, the author also found that

each policy approach had varying degrees of enforcement which impacted the effectiveness of the approach.

Such research is made possible by the uniquely accessible monitoring and enforcement data available from the Brazilian government which is the result of key policy decisions at the turn of the century. Assunção et al. (2015) identified three key policy efforts the government took throughout the early 2000's: strengthening monitoring and law enforcement; expanding protected territory; and adopting a conditional rural credit policy. In 2004 the government enacted Brazil's Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) which established innovative approaches to monitoring illicit deforestation events including the DETER satellite monitoring service (Assunção et al. 2019; Assunção et al. 2015). DETER was created to compliment the enforcement efforts of IBAMA and used satellite monitoring to identify deforestation events and send real time alerts to local IBAMA enforcement agents (Assunção et al. 2019; Assunção et al. 2015). Brazilian law gave officers the ability to distribute fines as well as embargoes which impact access to government subsidies and rural credits, as well as the seizure or destruction of products and equipment associated with the clearing (Assunção et al. 2019).

Although the distribution of fines is the most common approach to policy enforcement in Brazil, empirical evidence has found mixed support for the effectiveness of fines depending on the scale of the study and the approach to measuring enforcement. Fines act as a method of decreasing the expected revenue from deforestation by increasing the direct costs of clearing (Hargrave and Kis-Katos 2009). However, expected revenue is only affected by the threat of fines when the enforcement of environmental policies is intense and credible (Arima et al. 2014). While the ratification of policy is a necessary first step in deterring deforestation, the literature indicates that it is the effective enforcement of policy that is truly key for impactful change in the rate of forest

loss. For example, Hargrave and Kis-Katos (2009) conducted a study at the municipality scale from 2002 to 2009 and found that a 1% increase in the fining intensity in a municipality has reduced deforestation by an average of 0.2%. This study measured their enforcement variable as the total fines per deforested area while Borner et al. (2015) similarly explored the relationship between policy enforcement and deforestation, but their independent variable was based on the location environmental offenses and IBAMA inspection points. Their results indicate that field-based enforcement operations were most effective in reducing large-scale deforestation, but differences ultimately exist across states and the scale of deforestation.

Addressing the Gaps

Previous research has established that agricultural expansion drives deforestation in tropical regions and the Brazilian Amazon more specifically. However, there remains some disagreement in the role of international and domestic markets. This paper addresses that uncertainty by isolating municipality-level production of soybeans and beef that are exported which allows for a more precise assessment of global demand and how it relates to deforestation.

Another gap concerns the effectiveness of policy enforcement in the form of fines. Although fines are intended to reduce the expected revenue of illegal clearing, few studies measure enforcement as the value of fines issued. This paper contributes by using the total value of fines issued at the municipality level as a measure of enforcement intensity.

The central contribution of this paper is examining the joint relationship between international trade and policy enforcement. By combining detailed export data and monetary fine values, this paper explored how these factors interact and how this interaction impacts

deforestation. This provides a clearer understanding of how global market pressure and local enforcement intensity can shape the future of deforestation in the Brazilian Amazon.

Hypotheses

Understanding deforestation in the Brazilian Amazon requires examining both the economic pressures that incentivize forest clearing and the policy tools designed to deter it. Deforestation in the Brazilian Amazon is often conducted by landholders who do not have legal title to the land they are clearing (Soares et al. 2026). The choice to deforest is therefore, a cost-benefit decision that relies on the expected benefits of removing forest coverage for agriculture and the expected costs associated with being caught illegally deforesting. This decision making process is illustrated with the following equation:

$$\text{EU} = B - pF$$

Where *EU* is the expected utility of deforesting; *B* is the economic benefit of clearing, including increased production of soy and beef; *p* is the probability of being caught; and *F* is the value of the economic penalty of being detected. Therefore, clearing would occur when:

$$B - pF > 0$$

This paper evaluates how international market demand, forest management policy enforcement, and the interaction between these two variables shape the annual rate of deforestation at the municipality level.

Agricultural expansion is largely recognized as a major driver of deforestation in tropical regions, and in Brazil, the production of soybeans and beef is particularly influential in the rate of deforestation. Municipalities that produce more agricultural products for export have stronger

incentives for deforesting and increasing agricultural output. This would increase the value of *B* in the expected utility of clearing and make clearing more likely. While previous literature has highlighted a relationship between agricultural production and deforestation, this paper focuses on agricultural products that are exported to determine whether production for international markets is driving forest clearing, rather than production for domestic markets. By isolating municipality-level production of soy and beef exported to the international market, this study assesses whether global demand has a significant relationship with deforestation in the Amazon. This leads to the first hypothesis to be tested:

International Market Demand: Municipalities with higher production of soy and beef for export will have higher deforestation.

National legislation has been developed to deter deforestation through a variety of tools. The most prolific approach to mitigating deforestation is the distribution of financial penalties in the form of fines. Fines for illegal clearing increase the expected cost of clearing and reduce the expected benefit of clearing by increasing the *pF* term of the above expected utility equation. Effective enforcement of this legislation increases the probability of being caught illegally deforesting (*p*) and is expected to decrease incentives for clearing. While fines as an enforcement measure have been utilized in previous studies, the results of these studies vary depending on how enforcement intensity is measured. This study measures enforcement as the total value of fines at the municipality level to determine whether there is a relationship between the economic cost imposed by fines and deforestation in the Amazon. This leads to the second hypothesis:

Enforcement: Municipalities with increased enforcement of forest management policy will have lower rates of deforestation.

Finally, as municipalities with greater historical rates of deforestation have been targeted by enforcement efforts, I would anticipate a correlation between exports and the probability of detection (Arima et al. 2013). If municipalities with higher agricultural exports have higher rates of deforestation and municipalities with higher deforestation experience increased enforcement, then exports should also correlate with the probability of detection. Therefore, if monitoring and the enforcement of fines is higher where export-driven clearing occurs, I would expect stronger enforcement reduces the marginal impact of agricultural export production on forest clearing. This leads to the third hypothesis tested in this paper:

Enforcement and Market Demand: In municipalities with higher enforcement and exports, the marginal effect of exports on deforestation will decrease.

While it would be ideal to include a more direct measure for the probability of detection, data limitations make this approach infeasible. Therefore, this interaction term acts as a reduced-form test of two mechanisms: export intensity and the probability of detection.

Data

This paper utilizes a 2000 to 2020 municipality-year panel dataset compiled from publicly available data from the Brazilian government. This sample is limited to Brazilian municipalities within the Legal Amazon[1]. The Legal Amazon (LAM) is subject to regionally specific regulation and is the focus of monitoring and enforcement agencies. For example, Amazon Deforestation Satellite Monitoring Program (PRODES) primarily monitors the Amazon rainforest making data beyond this region less consistent and reliable (Brown University 2016). Furthermore, the LAM

[1] The Legal Amazon (LAM) is a socio-political region including nine Brazilian states: Acre, Amapá, Amazonas, Mato Grasso, Maranhão, Pará, Rondônia and Roraima, and Tocantins. This distinction is used to identify the boundary for laws that specifically address conservation and development in the Amazon.

accounts for over 500 million hectares of Brazilian land including the entirety of the Amazônia biome (420 million hectares of rainforest) and a portion of the Cerrado biome (INPE 2019). Restricting the sample to include only the LAM ensures the most reliable data while focusing on the region most effected by deforestation.

Deforestation

The dependent variable in this study is the total area of deforested land in each municipality annually. This data comes from the PRODES system which uses satellite imagery to detect changes in forest coverage throughout the Brazilian Amazon. The satellite imagery collects images during the dry season to minimize interference from cloud coverage, which means that the data aligns with a "PRODES" year which measures clearing that occurred from August of the year *t*-1 through July of year *t* data aligns with PRODES accounts for areas that were partially or completely cleared in the last year (Assunção et al. 2019). Therefore, the 2020 observed deforestation would include the clearing that occurred from August 1, 2019, to July 31, 2020. The data included a long right tail of extremely high values, so the log of the deforestation value was used to make the distribution more normal.

International Exports

The independent variable *exports* is measured as the log of the total annual value of soy and beef exports from each municipality in USD. Trade data at the municipality level is available from Commodity Exchange Inc. (COMEX) and includes the value of all soy and beef products that were produced in the municipality but exported to the international market. This measure provides valuable insight into the products that are produced in each municipality but are destined for the international market and is also a reasonable proxy for participation in international

markets. The soy and beef products include all soybeans whether or not broken and fresh or frozen beef. Some larger municipalities, such as Sao Paolo, presented as extreme outliers in the dataset so the log of the total value of both soybean and beef products was used for the analysis.

Enforcement

The independent variable *enforcement* is measured as the log of the total value of deforestation-related fines issued by IBAMA in each municipality annually. While there is some discourse around the different approaches to measuring enforcement, this measurement approach demonstrates the imposed costs of non-compliance and a clearer understanding of expected losses from punitive fines. This data is made available by the IBAMA organization and contains highly detailed observations of who committed the infraction, where it occurred, the type of infraction, and the fine amount in Brazilian real. The penalty amount was then adjusted for the average annual exchange rate to get the amount in United States Dollar amounts. For example, the total value of fines issued in Brazilian Real in 2015 was divided by the average exchange rate of real to USD in 2015. The data included a long right tail of extremely high values, so the log of the penalty amount was used to make the distribution more normal.

Although a more valid measure of enforcement would include the probability of detection, the consistently available data on the number of detected clearing events is only available from 2016-2026 meaning there is limited overlap with the time period explored in this paper. The inclusion of this measure would severely limit the number of observations and impact the analysis. Instead, with the assumption that export intensity and the probability of detection are correlated, I include an interaction of the values of fines and export intensity. The results of the interaction term would therefore demonstrate the effect of fines when exports are higher or lower.

Control Variables

The modeling also includes a set of variables that may account for relevant differences between municipalities. First, each model includes a control for the size of the municipality as measured by the area of the municipality in kilometers squared. Larger municipalities generally have more forested area and therefore have more opportunity for clearing. Controlling for the size of the municipalities ensures that any relationship between the independent variables and deforestation reflect export activity and enforcement rather than the variation in municipality size. This data is made available by the PRODES system used for the *deforestation* data.

Second, each model includes control for the gross domestic product (GDP) per capita of each municipality. Higher income levels may influence demand for forest intense resources such as beef which may result in increased clearing. Higher GDP per capita may also correlate with participation in international markets. Participation in international markets may require resources that only those in higher income municipalities may have or income may increase with increased international market participation. Controlling for GDP per capita therefore ensures observed effects on deforestation are explained by the independent variables, rather than income levels. This variable is measured as the GDP per capita in each municipality. The data is made available by Brazilian Institute of Geography and Statistics (IBGE) in the Produto Interno Bruto por Município (PIBMUNIC) dataset, however, these values are only available in Brazilian real. Therefore, these values were adjusted by the same annual exchange rates used in the export value and divided by the annual population of the municipality to produce the GDP per capita in USD.

Third, each model contains a control for the population of each municipality. Similar to GDP per capita, population may influence deforestation through increasing demand or a larger workforce. Municipalities with larger populations are likely to have higher demand for resources

which can inspire further clearing of forest resources. Furthermore, a larger population means there are more individuals to participate in clearing. The population of each municipality was collected from the IBGE. While there is annual data available for each municipality, this includes a combination of estimated populations and actual census counts. For years in which a census occurred (2000, 2007, and 2010) there are observed values for municipality population. For years in which a census did not occur (2001-2006, 2008-2009, and 2011-2020), the annual population of each municipality was estimated.

Variable	Measurement	Mean	Median	SD
Area	Area in square kilometers	1300	336	5160
Deforestation	Log of deforested area in square kilometers	6	6	1
Enforcement	Log of penalty amount in USD	11	11	3
Exports	Log of export value of soy and beef produced in the municipality in USD	16	16	3
GDP per capita	GDP per capita in USD	5669	3772	7062
Population	Population of the municipality	34927	11316	19762

Table 1. Variable names, measurements, and descriptive statistics.

Empirical Application

The goal of this paper is the investigate how policy enforcement and trade affect deforestation in the Brazilian Amazon. This relationship is described by the following model:

$$Deforestation_{it} = \beta_1 \log(penalty_usd_{it}) + \beta_2 \log(export_fob_{it}) + X_{it}\beta + \alpha_i + \gamma_t + \varepsilon_{it}$$

Where *deforestation* is the outcome variable measured as the annual loss of forest coverage in municipality *i* in year *t*; $\beta_1 log(penalty_usd_{it})$ is the enforcement explanatory variable measured as the log of the total value of environmental fines issued in municipality *i* in year *t*; $\beta_2 log(export_fob_{it})$ is the export market explanatory variable measured as the log of the total value of soy and beef exports from municipality *i* in year *t*; $X_{it}\beta$ is the vector of control variables in municipality *i* at time *t*; α_i and γ_t are the municipality and year fixed effects; and ε_{it} is the error term.

Municipality fixed effects are included to account for the characteristics of each municipality that may influence deforestation such as soil quality, climate patterns, or other structural differences across municipalities. By controlling for these variances, the estimated coefficients do not reflect inherent differences across municipalities. Year fixed effects are also included to account for shocks that may affect all municipalities such as macroeconomic changes, national policy changes, or annual weather events. These fixed effects allow for the isolation of effects attributed to the independent variables rather than confounding variables.

The second model expands on the investigation of this relationship by including and interaction term between the two key explanatory variables and is represented by the following model:

$$Deforestation = \beta_1 \log(penalty_usd_{it}) + \beta_2 \log(export_fob_{it}) + \beta 3[\log(penalty_usd_{it}) \times \log(export_fob_{it})] + X_{it}\beta + \alpha_i + \gamma_t + \varepsilon_{it}$$

Where $\beta 3[log(penalty_usd_{it}) \times log(export_fob_{it})]$ represents the interaction between enforcement and the value of exported soy and beef products.

Results

This section presents the model outputs estimating the relationships between deforestation, enforcement, and exports. The outputs consistently indicate relationships contrary to expectations including a positive relationship between deforestation and enforcement and a weaker or negative relationship between deforestation and exports. Additionally, the interaction between the independent variables produces a strong positive marginal effect.

Model Results

To address concerns of multicollinearity, the OLS estimates presented in Table 2 are representative of mean-centered independent and dependent variables. These regression outputs consider two different models to provide insight into each of the suggested hypotheses. The coefficients in Model 1 seem to contradict the hypothesized relationships between the independent and dependent variables. More specifically, the value of environmental fines issued has a positive coefficient of 8.113 with a standard error of 2.546, which indicates when exports are at the mean (0), municipalities with higher fine values also have higher deforestation. The positive coefficient contradicts the *enforcement* hypothesis which posited an increase in enforcement should correlate with a decrease in deforestation. However, because fines are issued after illegal clearing is detected, this coefficient may be indicative of enforcement being reactive to deforestation and may ultimately be why this coefficient defies expectations.

The coefficient for the export variable is negative and not statistically significant at standard level with a coefficient of -2.549 and a standard error of 3.655. Which indicates that when enforcement is at the mean (0), an incremental increase in the value of exported agricultural goods is correlated with a decrease in deforestation, though this coefficient is not significant.

Substantively, this suggests that increases in soy and beef production for the international market does not meaningfully correlate to deforestation. Although the coefficient is not significant, the sign on the coefficient being negative contradicts the expected relationship outlined in the *international market demand* hypothesis.

Among the control variables, only GDP has a statistically significant relationship with the dependent variable with a coefficient of 0.003 and a standard error of 0.002 which indicates a marginal increase in GDP per capita correlates with an increase in deforestation, though this is only significant at the 10% level.

	Dependent variable:	
	deforestation	
	(1)	(2)
penalty_usd	8.113***	5.011**
	(2.546)	(2.552)
export_fob	-2.549	-4.336
	(3.655)	(3.613)
gdp	0.003*	0.003*
	(0.002)	(0.002)
pop	-0.0002	-0.0002
	(0.0002)	(0.0002)
area_km2	0.002	0.002
	(0.002)	(0.002)
export_fob:penalty_usd		6.130***
		(0.918)
Constant	-692.097***	-697.811***
	(111.342)	(109.768)
Municipality FE	Yes	Yes
Year FE	Yes	Yes
Observations	1,681	1,681
R^2	0.995	0.995
Adjusted R^2	0.994	0.994
Residual Std. Error	178.444 (df = 1507)	175.916 (df = 1506)
F Statistic	1,644.034*** (df = 173; 1507)	1,682.166*** (df = 174; 1506)
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 2: OLS Regression: Enforcement and Exports on Deforestation

Model 2 in Table 2 features the same model specifications with the inclusion of the interaction term between export values and fine values. The enforcement coefficient is still statistically significant with a coefficient of 5.011 and a standard error of 2.552. This result indicates that when exports are at the mean, a marginal increase in the value of fines distributed correlates to an increase in deforestation. This result further contradicts the *enforcement* hypothesis. The coefficient for the value of exports is also negative with a value of -4.336 and a standard error of 3.613 which is not significant at standard levels, similar to model 1. This result further indicates that when enforcement is at the mean, a marginal increase in the value of exported soy and beef correlates to a decrease in deforestation though the coefficient is not significant.

The coefficient on the interaction term is also positive and statistically significant at the 1% level with a coefficient of 6.130 and a standard error of 0.918. This indicates that the marginal effect of exports on deforestation increases as enforcement intensity also rises. When enforcement is low, the marginal effect of exports is near zero or slightly negative. Figure 1 illustrates this relationship and shows that as enforcement increases, the marginal effect of exports become more positive. Therefore, rather than reducing export-driven clearing, enforcement appears to coincide with clearing which further highlights the potentially unclear causal direction of enforcement, trade, and deforestation.

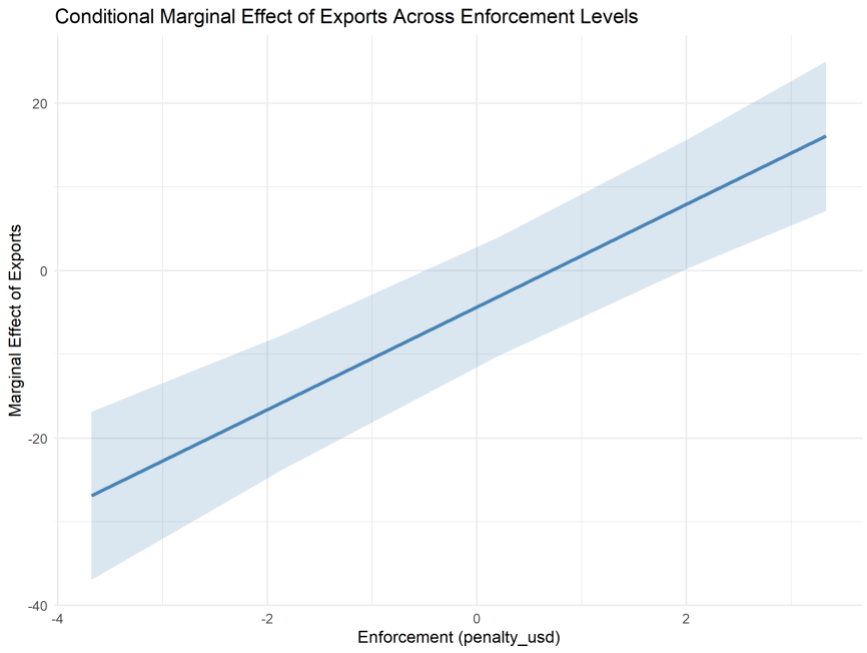


Figure 1. Marginal effects of the value of exports across the range of enforcement levels.

Lagged Model Results

To determine whether the unexpected relationships observed in the previous models reflect reverse causality or the intentional targeting of enforcement in municipalities with greater rates of deforestation, I repeated the model specification with a one-year lag on the enforcement and export variables. A one-year lag has been used throughout the literature to determine whether decision makers respond to enforcement and change their behavior in response to changes in their expected utility with higher enforcement. Assunção et al. (2019) determined that forest clearing at time *t* can trigger increasing distribution of fines in the area and increases the presence of law enforcement at time *t.* Therefore, offenders may perceive this change in the presence of law enforcement and increases to the probability of being fined for illegal clearing at *t+1* which may deter further clearing. To test whether this is the case, Table 3 includes the same models as above with a one-

year lag on the enforcement and export variables. This provides a clearer test of whether environmental fines and export values impact future deforestation.

Model 1 in Table 3 demonstrates a statistically significant relationship between the enforcement variable and deforestation with a positive coefficient of 13.346 and a standard error of 2.343. This means that increased fines at *t-1* correlate with an increase in deforestation at time *t* when exports are at the mean. The coefficient for the export variable is 0.487 with a standard error of 2.957 which is not statistically significant at standard levels. This result indicates when enforcement is at the mean, a marginal increase in the value of exported soy and beef products correlates with an increase in deforestation which aligns with expectations but is not significant. Similar to the previous models, GDP remains statistically significant with a coefficient of 0.003 and a standard error of 0.002 which indicates a positive relationship between GDP per capita and deforestation.

	Dependent variable:	
	deforestation	
	(1)	(2)
lag_penalty	13.323***	12.762***
	(2.344)	(2.335)
lag_exports	0.487	1.344
	(2.957)	(2.949)
gdp	0.003*	0.002
	(0.002)	(0.002)
pop	-0.0002	-0.0002
	(0.0002)	(0.0002)
area_km2	0.002	0.002
	(0.002)	(0.002)
lag_exports:lag_penalty		3.251***
		(0.788)
Constant	-657.608***	-661.862***
	(108.613)	(108.044)
Municipality FE	Yes	Yes
Year FE	Yes	Yes
Observations	1,680	1,680
R^2	0.995	0.995
Adjusted R^2	0.994	0.994
Residual Std. Error	177.243 (df = 1506)	176.307 (df = 1505)
F Statistic	1,666.036*** (df = 173; 1506)	1,674.203*** (df = 174; 1505)
Note:		*p<0.1; **p<0.05; ***p<0.01

Table 3. OLS regression: Lagged enforcement and exports on deforestation.

Model 2 in Table 3 includes the interaction term between lagged enforcement and lagged exports which produces similar coefficients for the key independent variables. The lagged enforcement variable has a coefficient of 12.762 and a standard error 2.335 which is statistically significant at the 1% level and indicates an increase in deforestation with the marginal increase in enforcement when exports are at the mean. The coefficient for the export variable is also similar with a coefficient of 1.344 and standard error of 2.949 which is not statistically significant at standard levels. The coefficient for the interaction term between the lagged enforcement and lagged export value is positive with a coefficient of 3.251 and a standard error of 0.788 which is significant at the 1% level. This relationship indicates that the marginal effect of exports on

deforestation becomes more positive as enforcement increases. Ultimately, these results remain substantively similar to the non-lagged models with enforcement continuing to exhibit a positive and significant relationship with deforestation while exports remain insignificant and the interaction term remains positive and significant.

Discussion

The results of this analysis reveal a more complex relationship between enforcement, exports, and deforestation than expected. Rather than supporting a correlation between fines and reduced clearing, the models consistently show that enforcement is positively associated with deforestation. Furthermore, there is no clear relationship between agricultural exports and deforestation with coefficients indicating an insignificant relationship between the variables. Furthermore, the interaction term indicates a strong positive marginal effect that is statistically significant across model specifications.

The positive association between enforcement and deforestation suggests that fines are issued in response to clearing and do not effectively deter future clearing behavior. Given the above expected utility function, I would theoretically expect this to be the case if the cost of fines is not high enough to impact potential benefits of clearing or the perceived probability of being caught was not high enough to dissuade clearing behavior. While it is not possible to clearly determine which of these factors is truly responsible, available data does allow for us to determine the rate of fines issued compared to detected instances of clearing. Table 4 demonstrates the relationship between the number of DETER alerts and the number of fines issued. With a coefficient of 0.053 and a standard error of 0.002, there is a statistically significant positive relationship between the number of alerts and the number of fines. This result indicates that for each additional DETER alert, there are approximately 0.05 additional fines or approximately one fine for every 20 alerts.

Substantively, this indicates a relatively low probability of punishment which may reduce the effectiveness of fines as deterrents and may contribute to the relationship observed between enforcement and deforestation.

	Dependent variable:
	count_fines
alert_count	0.053^{***}
	(0.002)
Constant	7.651^{***}
	(0.778)
Observations	2,353
R^2	0.230
Adjusted R^2	0.230
Residual Std. Error	33.925 (df = 2351)
F Statistic	703.202^{***} (df = 1; 2351)
Note:	*p<0.1; **p<0.05; ***p<0.01

Table 4. OLS regression: Number of DETER alerts on the number of distributed fines.

Furthermore, the absence of a statistically significant relationship between exports and deforestation contradicts the *international market demand* hypothesis, which hypothesized a positive relationship between exports and deforestation. While it is not within the scope of this paper to determine why exactly this is, it is possible that production for domestic consumption may muddy the relationship between exports and deforestation. It is possible that the decision to clear forest area is driven by domestic demand as some previous literature has highlighted. As this empirical approach focuses on the role of exported products, that lack of significance in the output may be because producers are not responding to international market demands or are more influenced by domestic demands. Future research should further explore the relationship between

agricultural products for domestic consumption to determine whether there is a significant difference between goods produced for different markets.

The interaction term in each of the models being positive and statistically significant is the most consequential finding. Consistent results across model specifications indicate that the marginal effect of exports is higher in municipalities with higher enforcement intensity. This suggests two mechanisms. First, enforcement and exports seem to be co-located geographically. Municipalities with higher exports tend to be areas that have higher historical clearing which makes it a priority for enforcement. Therefore, enforcement and export activity rise together leading to a positive interaction coefficient. Second, in municipalities with higher exports, agricultural goods for the international market may be particularly profitable. Therefore, fines may be a relatively low compared to potential trade profits and not seen as a relevant deterrent. Referencing the expected utility function, in municipalities with more exports, the expected B from trade may be sufficiently large to incentivize clearing. Particularly as the data indicates only 1 in 20 detected clearing events result in a fine, it is likely that the cost of the interaction term pF is relatively small. Together, these mechanisms indicate that enforcement is less effective where clearing incentives are strongest.

While the results of this study contradict the hypothesized relationships, they are also a valuable contribution to our understanding of agricultural production for international markets as a driver of deforestation and punitive fines as a deterrent of deforestation in the Brazilian Amazon. The findings challenge the negative role of agricultural exports in deforestation and highlight the necessity of further research to better understand agriculture and trade as drivers of deforestation. While the positive relationship between fines and deforestation is unexpected and does not support a clear association between fines and reduced deforestation, it does indicate that the value of fines

is increasing with deforestation. This is indicative of the enforcement agency actively responding to alerts and taking steps to deter deforestation. By addressing limitations on the availability of data for the probability of detection, future research may provide a clearer answer to how and whether enforcement of forest management policy is effectively mitigating deforestation. Furthermore, utilizing different modeling strategies to account for endogeneity in future research will be an important development to our understanding of the relationships between these variables and deforestation.

Conclusion

The objective of this study was to determine how the interaction of exported agricultural goods and the enforcement of forest management policy influence deforestation in the Brazilian Amazon. Previous literature has highlighted agricultural production as a key driver of deforestation in the Amazon, yet there remains some discourse on whether participation in international markets has increased the rate of deforestation. This study contributes to this gap by isolating municipality-level production of soy and beef produced for the export market and ultimately found there is no clear relationship between these exports and deforestation. This ultimately highlights a need for further investigation into whether deforestation is more driven by domestic markets as has been suggested in previous literature.

This study also explored the role of punitive fines as a deterrent for clearing to address some disagreement in the literature on the effectiveness of such measures. Literature in this area has found support for fines as a deterrent, however, some research has indicated that the most influential aspect of forest mitigation policy is the credibility of enforcement or the perceived probability of punishment. This study contributes to better understanding this gap by utilizing municipality level fine data from IBAMA to determine whether there is a clear relationship

between fines and deforestation. While it was hypothesized that fines would have a negative relationship with deforestation, the results ultimately indicate a positive relationship across model specifications. While it is not within the scope of this paper to determine a causal relationship between these variables, it is likely that this relationship may be due to the targeting of fines in municipalities that have higher historical deforestation. Therefore, the number of fines may be responsive to historical deforestation and while it does not demonstrate clear deterrence, it does indicate there is greater enforcement in areas with greater deforestation.

The main contribution of this study is in the inclusion of the interaction term between the export and enforcement variables. This interaction term is used a reduced-form test of two mechanisms: export intensity and the probability of detection. While I had hypothesized that municipalities with higher enforcement would have lower marginal effects of exports on deforestation, the results across models contradicted this expectation. Instead, there was a significant and positive coefficient for the interaction term across the lagged and not lagged models. This instead indicates that the marginal effects of exports increase across levels of enforcement and are highest where enforcement is highest.

The unexpected results of this study are not indicative of enforcement being irrelevant or agricultural exports having no effect on deforestation in the Brazilian Amazon. Instead, these results highlight the need for a clearer understanding of this interaction through future research. This study is limited by observational data and the likely presence of endogeneity. In particular, the limited availability of data from DETER alerts meant using a less direct measure for the probability of detection. As this data becomes increasing available, future research results may be clearer and more informative for policy decisions. Furthermore, the results of this study indicate there is likely endogeneity that is impacting the model outcomes. Different modeling approaches

may be beneficial in addressing this concern and producing clearer results on the relationship between enforcement and deforestation. As Brazil continues to navigate the balance between growth and protecting the rainforest, understanding the drivers and solutions to deforestation will be essential. This study begins to address some gaps in our understanding of this balance but there is much room for furthering our understanding through future research.

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