Farmer Networks and Forest Conservation in the Brazilian Amazon

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1 Introduction

Sanctions for environmental infractions aim to deter future offenses and punish perpetrators. Social networks are important for mediating both objectives, yet are often overlooked by researchers and policymakers who design sanction regimes. On one hand, networks facilitate the spread of information about enforcement events, which may deter infractions by other individuals [Hargrave and Kis-Katos, 2013, Börner et al., 2014, Vieira et al., 2023]. On the other hand, networks provide information, resources, and social capital that allow perpetrators to evade and insulate themselves from the consequences of environmental policies [Bayer et al., 2009]. In this paper, we assess how the application of rare but costly sanctions for illegal deforestation affect the network structure of cattle ranchers who clear forests, and whether sanctions deter deforestation by other ranchers in the sanctioned ranchers' networks. We leverage a rich dataset that allows us to observe millions of network connections among hundreds of thousands of cattle ranchers in the Brazilian Amazon. The results underscore the importance of considering network-related externalities when designing environmental policies.

Our primary specification uses property and time fixed effects to identify the effect of environmental sanctions on deforesting ranchers' transaction networks and their network connections' deforestation behavior. Our explanatory variable is whether a rancher is embargoed by Brazil's main environmental enforcement agency. One set of dependent variables relates to the network characteristics of the cited rancher (e.g. the cited rancher's network degree centrality, number of new connections). Another set of outcome variables include deforestation behavior of the cited rancher's network connections (i.e. deforestation on properties of ranchers whose first-degree connections were embargoed).

We find significant reductions in deforestation likelihood and area on both embargoed properties and their first-degree connections. Our analysis of the supply chain suggests that embargoed properties reduce sales due to loss of their relationships with existing and potential buyers.

Cattle production is the leading driver of deforestation in Brazil, which has led to numerous private- and public-sector policies that aim to deter clearing by imposing sanctions, embargoes, and fines on deforesting cattle ranches. This paper contributes to an extensive literature on the effects of these policies on farmer behavior and deforestation c.f. [Alix-Garcia et al., 2018, Moffette and Gibbs, 2021, Assunção et al., 2019]. By accounting for network spillovers and externalities, this research helps explain one reason why policy effects vary significantly over space and time. We also contribute to the literature on the role of peer effects in farmers' decisions to adopt sustainable practices [Conley and Udry, 2010, Sampson and Perry, 2019, Kolady et al., 2021], namely conserving forest [Robalino and Pfaff, 2012, Nepal et al., 2007]. Past work in this space primarily infers farmer networks based on geographic proximity. In contrast, we use observed farmer transactions to construct a complete network, allowing us to test how information spreads within non-spatial networks and beyond first-degree connections. Finally, we contribute to the literature on how social networks facilitate crime [Calvó-Armengol and Zenou, 2004, Baccara and Bar-Isaac, 2008, Patacchini and Zenou, 2008], bringing an environmental case study into this space.

2 Background

Cattle production is the leading driver of deforestation in Brazil, leading to policy responses such as the private-sector-led Zero-Deforestation Cattle Agreements and various government conservation strategies [Skidmore et al., 2021]. A body of causally identified work has quantified the effects of these policies. For example, registration of properties with environmental authorities was linked to lower rates of deforestation [Alix-Garcia et al., 2018]. The Priority Municipalities Program, which increases surveillance of properties in high-deforestation municipalities was shown to both reduce deforestation and improve farmer productivity [Assunção et al., 2019, Moffette et al., 2021, Koch et al., 2019]. While there is some evidence of property-level factors associated with deforestation [Skidmore et al., 2021], it is unclear how network effects amplify or mute these factors, a gap that this study attempts to fill.

In this paper we estimate the effects of environmental enforcement actions by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA). IBAMA is the main environmental enforcement agency in Brazil and is charged with acting on illegal deforestation events. It responds to illegal deforestation alerts from a real-time high-resolution satellite detection system (DETER). After a deforestation event is detected, local IBAMA agents and other law enforcement officials go to the deforestation site to inspect. If they find evidence of illegal deforestation, they write a report describing the infraction and recommend a punishment. The offender then goes through an administrative procedure in which a judge decides how to sanction the rancher. Punishments can include fines, embargoes on deforested land, or seizure of assets used to clear forest [Schmitt, 2015]. IBAMA responds to only a fraction of illegal deforestation alerts. Although a MapBiomas Alert platform detects and publishes thousands of alerts a month, IBAMA responded to only 1.3% of deforestation alerts in 2019-2020, or an average of 755 per year [Coelho-Junior et al., 2022].

Several past studies have explored whether IBAMA enforcement actions deter illegal deforestation. With municipal-level data, Hargrave and Kis-Katos (2013), Assunção (2013), and Börner et al. (2015) measured the effects of environmental fines on deforestation. The authors concluded that increasing environmental fines in a municipality in one year leads to less new deforestation in the following year, at least under some conditions. More recently, Vieira et al. (2023) used property-level spatial data to show that enforcement events deterred deforestation on nearby ranches. Our paper expands upon Vieira et al.'s rancher-level analysis by testing how non-spatial networks spread information about IBAMA activities.

Our dataset also allows us to observe how networks restructure in response to sanctions. This is important in the context of the Brazilian cattle sector because there is evidence that ranchers use networks to evade sanctions for environmental and social infractions [Mittelberg et al., 2025, Gibbs et al., 2016, Alix-Garcia and Gibbs, 2017]. The cattle supply chain is complex, and the average animal lives on three different ranches across its life stages such as weaning, rearing, and fattening. However, only some ranches undergo regular monitoring and vetting for illegal deforestation and labor abuses, namely those that sell finished animals to slaughterhouses that signed sustainable sourcing commitments. Due to this incomplete monitoring, ranchers have been found to increase sales to "clean" properties after being blocked by slaughterhouses for environmental or labor infractions [Mittelberg et al., 2025, Gibbs et al., 2016, Alix-Garcia and Gibbs, 2017, Andreoni et al., 2021, Campos et al., 2021]. These findings suggest that sanctioned ranchers rely on others to launder cattle for them, either by forming new connections with clean ranchers or by strengthening existing ones. Although IBAMA embargoes are cause for slaughterhouses to block ranchers, there is currently no causal evidence connecting the timing of IBAMA sanctions with changes in ranchers' network structure. This paper will fill this gap, providing evidence on how networks facilitate sanction evasion.

3 Study Design

The objective of this study is to test how enforcement of zero-deforestation policies ripples through farmer transaction networks.

3.1 Data

To accomplish this, we used a dataset of millions of cattle sales between properties to determine which farmers were connected to whom. The Animal Transit Guide (GTA) is a database that records cattle movements in Brazil for sanitary monitoring purposes. It details the movement of cattle between properties and slaughterhouses and contains information on the date of transaction, number of heads traded, selling and buying properties, selling and buying ranchers, municipality, and purpose of the transaction. The Gibbs Land Use and Environment (GLUE) lab at the University of Wisconsin-Madison has been scraping the GTA for more than a decade, and has data on millions of cattle transactions. Due to data availability, we focus our study on the Brazilian states of Pará and Mato Grosso for the years 2013-2023.

We used GTA data to generate our farmer transaction network data. First, we grouped properties (as reported in the GTA) with shared owners. We consider these sets of co-owned properties an entity and perform our analysis at this level [Skidmore et al., 2021].

We considered a transaction between entities A and B in a given year as a first-degree connection. Multiple transactions indicates a stronger connection. A second-degree network connection would be one where entities A and C do not have any direct transactions with one another in a given year, but they both have a transaction with entity B.

GTA data is matchable with spatial maps of property boundaries from the Rural Environmental Property Registry (CAR), Terra Legal, and National Institute of Colonization and Agrarian Reform (INCRA) databases. Currently up to 75% of GTA transactions in GLUE's database are linked with property boundaries. Property boundary data are important for linking deforestation to specific farmers and transactions. For each entity, we identify the extent of the set of properties that form the entity.

We then measure deforestation on an entity by overlaying property boundaries with satellite deforestation data from MapBiomas.

IBAMA's infraction notices and embargoes are publicly accessible. These notices, which include spatial locations, can be matched to property boundaries to identify whether an entity has faced an IBAMA enforcement action and the year in which it began.

Table 1 reports sample-wide summary statistics for treatment and outcome variables. Table 2 reports summary statistics of outcome variables on the embargoed properties before and after they are embargoed.

Table 1: Sample summary statistics

	Mean	SD
Embargo	0.00	0.02
First-degree embargo	0.00	0.03
Head sold	56.64	640.09
Head bought	56.64	893.07
In degree	0.85	5.95
Out degree	0.85	2.46
Total degree	1.70	7.49
New connections	1.28	5.32
New buyers	0.69	2.03
New sellers	0.69	4.53
Deforestation (ha)	0.11	10.21
Deforestation (0/1)	0.01	0.08

Table 2: Means, SDs, and t-test p-values on embargoed properties before and after embargo

	Mean before	SD before	Mean after	SD after	P-value
Head sold	307.48	882.81	202.98	1160.23	0.12
Head bought	228.00	693.77	171.87	1433.93	0.35
In degree	1.22	2.91	1.16	5.89	0.81
Out degree	1.78	3.85	1.24	3.44	0.05
Total degree	3.00	5.86	2.40	7.62	0.18
New connections	2.50	4.93	1.85	5.92	0.08
New buyers	1.57	3.41	1.04	3.10	0.04
New sellers	1.14	2.89	0.94	4.62	0.39
Deforestation (ha)	6.10	45.10	1.14	25.08	0.12
Deforestation (0/1)	0.08	0.26	0.01	0.11	0.00
N	212		1592		

3.1.1 Empirical Specification

We estimated effects of environmental sanctions on an embargoed rancher with the following equation:

$$Y_{it} = \beta_1 Enforce_{it} + +\theta_t + \theta_i + \epsilon_{it}, \tag{1}$$

where Y_{it} is the outcome of rancher i at time t. We consider the number of head sold, head bought, in degree, out degree, total degree, new sellers, new buyers, new connections, deforestation (Ha), deforestation (1/0)). The binary variable $Enforce_{it}$ equals 1 if entity i includes a property under an IBAMA embargo in year t. Entity fixed effects (θ_i) control for entity-specific factors that are time-invariant such as proximity to roads, enforcement offices, and slaughterhouses. Time fixed effects (θ_t) control for changes in macro-level economic and environmental conditions that affect all properties such as beef prices and the introduction of new regulations. We cluster our standard errors, ϵ_{it}, at the entity level.

Degree and new connections are related to the cited entity's centrality within the network structure. Degree centrality is a measure of how well a node is connected to the rest of the network via direct connections – the extent to which it is a "hub" in a hub and spoke network arrangement [Jackson et al., 2017]. If the IBAMA sanction is effective, other properties should cut direct ties with the cited property to avoid contaminating their own herd with cattle raised on deforested land. One would expect the cited property to have fewer connections, and instead perhaps trade with only a few other firms who tolerate the deforestation activity.

Our analysis of the impact on deforestation illuminates whether enforcement has its intended effect as a deterrent to further illegal activity.

We estimated a similar model for the effects of embargoes on deforestation (hectares and binary) on the entities of first-degree network connections:

$$Y_{jt} = \beta_1 Enforce1st_{jt} + +\theta_t + \theta_j + \epsilon_{jt}, \tag{2}$$

where the variable $Enforce1st_{jt}$ equals 1 if a rancher with whom rancher j was connected before an enforcement event had an enforcement event in year t or later. Entity fixed effects (θ_j), time fixed effects (θ_t), and standard errors (ϵ_{jt}) are as above.

We estimated both specifications as pooled models to assess how outcomes differ on average when a rancher is embargoed by IBAMA compared to when they are not. We also estimated the models with an event study framework with treatment dummies corresponding to the number of years since/until the initial IBAMA enforcement action. This allows us to test for parallel pre-trends and to assess how effects of enforcement actions increase or diminish over time.

3.1.2 Causal Identification and Robustness

The validity of the DiD/Event Study approach depends on the assumption that properties' outcomes would have evolved in parallel in the absence of the IBAMA enforcement event (conditional on property fixed effects, time fixed effects, and time-varying controls). This assumption is not directly testable, but results from our event study specification show that there is no evidence of non-parallel pre-trends. There is also a threat that summarizing DiD effects over time in a single coefficient will lead to a biased estimate in the presence of heterogeneous treatment effects [Goodman-Bacon, 2021]. Future analyses will use methods in the recent DiD/Event Study literature to account for treatment effect heterogeneity e.g. [de Chaisemartin and D'Haultfœuille, 2020, Sun and Abraham, 2021, Borusyak et al., 2022, Callaway and Sant'Anna, 2021].

4 Results

Embargoed properties and their first-degree connections significantly reduce their deforestation in the years following the embargo (Table 3).

Properties with an embargo are 7.4% less likely to have deforestation in a given year after the embargo event. They reduce deforestation by an average of 7.69 hectares per year in the years following embargo. Prior to embargo, properties that were ultimately embargoed had a mean annual deforestation area of 6.096. For the 1,592 entity-year observations in our sample that are under embargo, this is equivalent to 12,242 hectares of avoided deforestation.

Their first-degree connections are also less likely to have deforestation. First-degree connections are 1.6% less likely to have deforestation in a given year, compared to a sample mean of 0.5%. They reduce deforestation by 2.27 hectares in a given year. Prior to their exposure to an embargoed property, these properties have a mean annual deforestation of 2.03 hectares. We observe a total of 2,836 entity-year observations that are the first degree of an embargoed property prior to the embargo. This is equivalent to a 6,437 hectares of avoided deforestation by the first-degree connections in our sample.

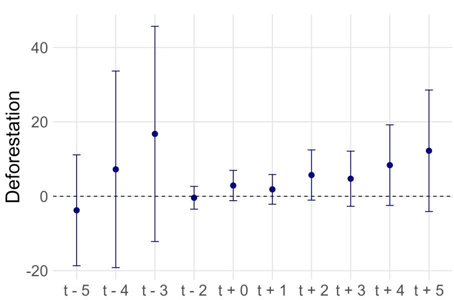
We test the assumption of parallel trends in deforestation using an OLS and Sun and Abraham event study model (Figures 1 and 2). We find no significant evidence that entities had different trends in deforestation two or three years prior to their own embargo or before their connection's embargo. However, we find that first-degree connections had significantly less deforestation five years before (OLS model) and significantly more four years before their connection was embargoed (OLS and Sun and Abraham models). Notably, the standard errors on all coefficients that are four or more years before or after the embargo are large due to the relatively small number of observations that fall into this category. Similarly, we do not find significant single-year effects after the embargo, but we attribute this to the relatively few observations per bin.

An embargo has a modest impact on an entity's supply chain outcomes and network placement. Entities reduce the total head they sell after embargo by 115.1 head. These same entities sold an average of 307.5 head per year prior to embargo. We find no statistically significant change in any other measures of their sales or network placement, including total head bought; in, out, or total degree, or new total, buyer, or seller connections. The sign of the coefficients suggest that embargoed entities lose connections with their existing buyers or potential future buyers after the embargo (out degree and new buyers). We detect a statistically significant decrease in both of these terms after embargo using a simple t-test (Table 2). These coefficients may be noisy after the inclusions of fixed effects due to the small number of total embargoed entities (164).

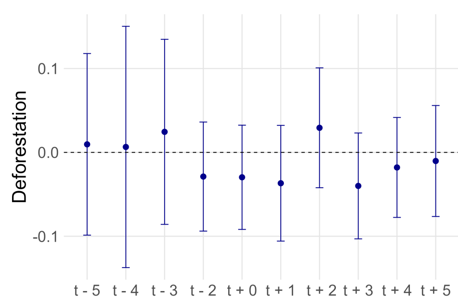
Table 3: Impact of embargo on deforestation on embargoed properties and their first-degree connections

	Embargoed property		First degree	
	Area	Binary	Area	Binary
Embargo	-7.69*	-0.074***	-2.27***	-0.016***
	(4.10)	(0.023)	(0.874)	(0.004)
Dependent variable mean	0.10998	0.00578	0.10992	0.00578
Observations	3,405,105	3,405,105	3,402,113	3,402,113
Adjusted R^2	0.00118	0.05815	0.00117	0.05814
Entity fixed effects	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓

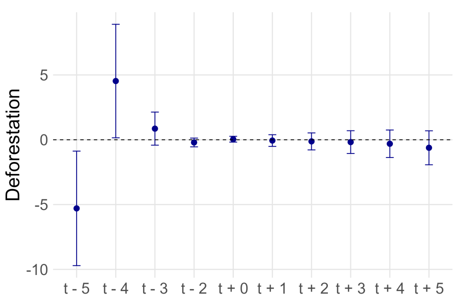
Note: Observations are at the entity-by-year level. Models include entity and year fixed effects. Standard errors are clustered at the entity level. * p< 0.10, ** p<0.05, *** p<0.01.



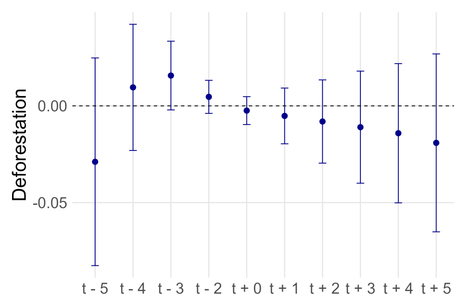
(a) Embargoed property, deforestation area



(b) Embargoed property, deforestation (0/1)

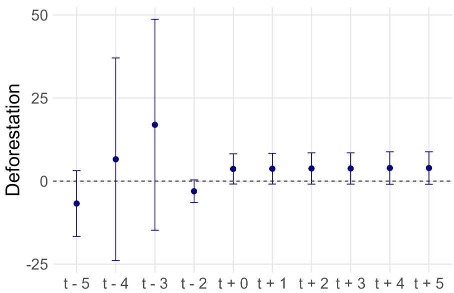


(c) First-degree property, deforestation area

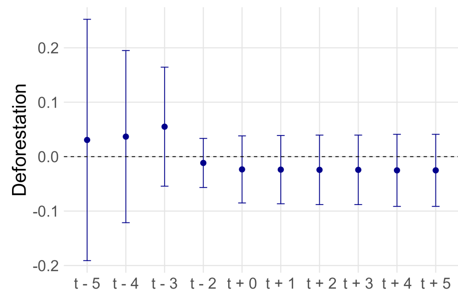


(d) First-degree property, deforestation (0/1)

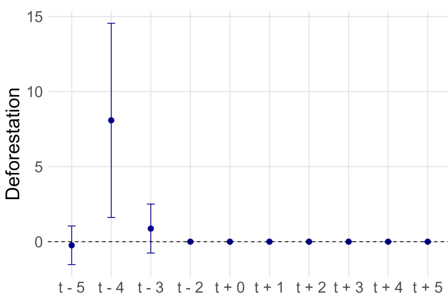
Figure 1: OLS event studies of deforestation outcomes



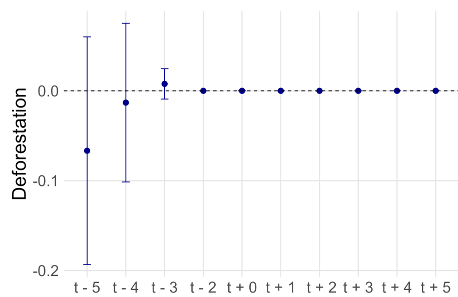
(a) Embargoed property, deforestation area



(b) Embargoed property, deforestation (0/1)



(c) First-degree property, deforestation area



(d) First-degree property, deforestation (0/1)

Figure 2: Sun and Abraham event studies of deforestation outcomes

Table 4: Impact of embargo on embargoed property supply chain behavior

	Head sold	Head bought	In degree	Out degree	Total degree	New connections	New Buyers	New sellers
Embargo	-115.1**	-103.0	0.212	-0.412	-0.200	-0.311	-0.431	0.059
	(58.4)	(64.1)	(0.414)	(0.272)	(0.575)	(0.500)	(0.289)	(0.341)
Dependent variable mean	56.634	56.634	0.85101	0.85101	1.7020	1.2831	0.69135	0.69080
Observations	3,405,105	3,405,105	3,405,105	3,405,105	3,405,105	3,405,105	3,405,105	3,405,105
Adjusted R^2	0.45973	0.52761	0.44006	0.42368	0.45294	0.36724	0.35447	0.35098
Entity fixed effects	✓	✓	✓	✓	✓	✓	✓	✓
Year fixed effects	✓	✓	✓	✓	✓	✓	✓	✓

Note: Observations are at the entity-by-year level. Models include entity and year fixed effects. Standard errors are clustered at the entity level. * p< 0.10, ** p<0.05, *** p<0.01.

5 Conclusion

This study explores the mechanisms through which networks both hinder and enhance the enforcement of environmental laws. Specifically, we evaluated a) if transaction networks reconfigure to help ranchers evade sanctions for illegal deforestation; and b) if networks spread information about rare enforcement events, leading to a deforestation-deterrence effect among network connections.

We find evidence that embargoes decrease the likelihood of deforestation and total deforested area on both embargoed entities and their first-degree network connections. Both embargoed properties and first-degree connections reduce deforestation by roughly 100% relative to their sample mean before the embargo. Notably, we observe no deforestation on the 428 first-degree connections after their network connection was embargoed.

The area of avoided deforestation on first-degree connections is smaller in magnitude (roughly 30%) than that of the embargoed properties, which had higher baseline rates of deforestation. However, there are 2.5x more first-degree connections than embargoed properties in our sample. Thus, networks have the potential to contribute meaningfully to a policy's total avoided deforestation.

We find that embargoed properties' network characteristics change after the embargo in terms of activity and place. They reduce sales by roughly one-third of their pre-embargo total. Our results suggest that part of this may be due to loss of network relationships with buyers. Embargoed properties have a significantly lower out-degree and fewer new buyers after they are embargoed as measured with a t-test. These results are consistent but noisy when estimated with a two-way fixed effects regression.

In total, we estimate around 100 hectares of avoided deforestation per embargo in at most a ten-year period after the embargo. One-third of avoided deforestation was due to reductions by first-degree connections. The 100% reduction in deforestation we detect on first-degree network neighbors is also meaningfully larger than previous findings [Vieira et al., 2023]. Measuring the impact of embargoes on geographical neighbors, they find that embargoes reduce deforestation by 20% on neighboring properties. Our results demonstrate the importance of considering network-related externalities, defined whenever feasible based on a supply-chain network, when designing and evaluating environmental policies.

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