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The Role of Monitoring and Law Enforcement on Deforestation in the Brazilian Amazon

Sacha M. O. Siani*

ABSTRACT

This paper analyzes Brazil's efforts to reduce deforestation in the Brazilian Amazon between 2004 and 2016. While Brazil's land-use rules stand out compared to any other country in the world, the enforcement of forest laws has been limited by high transaction costs and institutional deficiencies. In 2004, Brazil started using satellite images to detect deforestation nearly in real-time, providing strategic information to environmental agencies. As a result, clearings shrunk by 82% between 2004 and 2012. We use the Combined IAD-SES (CIS) framework to structure our institutional analysis. To estimate the impact of policing on deforestation, we create a novel grid-year panel dataset on enforcement and deforestation, and an instrumental variable approach. Clouds blinding the satellite-based monitoring system serve as a source of exogenous variation for the presence of forest law enforcers. Preliminary analysis indicates that monitoring and enforcement effectively curbed deforestation. Recently, the monitoring and enforcement systems have been dismantled, and deforestation has reached its highest rate since 2008. This paper contributes to understanding the factors behind the initial success and current failure to control deforestation in the Brazilian Amazon.

* Indiana University, Department of Geography, Bloomington, IN, USA

Indiana University, Ostrom Workshop, Bloomington, IN, USA

Indiana University, Center for the Analysis of Social-Ecological Landscapes (CASEL)

Dear workshopers,

I am looking forward to present and discuss this paper on Monday, March 3rd, at the research series. As you will see, this is an initial draft of one of my chapters of my PhD research. I would appreciate your inputs, sure that your experience can substantially improve my project. Here, I have focused the development of the combined IAD-SES framework, but I am still assembling a property-level panel dataset to improve my econometrics estimates.

As you read our current draft, I would especially appreciate thoughts on the structure of the paper, the integration of the Ostrom's frameworks and the econometrics estimates, and relevant literatures I may have ignored.

Thank you in advance for your feedback as I work to shape this manuscript into publishable form.

-Sacha

1. INTRODUCTION

Since the 1980s, deforestation in the world's tropics has become an international issue of major importance, particularly because of its impact on carbon stocks and the forest's role as a carbon sink, as well as the impact on cultural and biological diversity. Globally, the emissions from tropical deforestation and degradation have accounted for approximately 23% of total net anthropogenic emissions of greenhouse gas (IPCC 2019). A wide variety of policies to curb deforestation have been designed since then. Most of these policies establish land use rules under the logic of either increasing deforestation costs – such as the creation of forest laws, protected areas, supply chain interventions and credit access restrictions –, or the benefits of keeping the forest standing – as paying for ecosystem services (PES). A common feature among all these policies based on land use rules is that *monitoring*, *policing*, *judging* and *sanctioning* of rules – *rule enforcement* – are necessary conditions for their effectiveness (Gibson, Williams, and Ostrom 2005). However, the causal effects of enforcement land use decisions lack empirical evidence and an understanding of the underlying causal mechanisms. Can law enforcement prevent deforestation? If so, how, and to what extent?

To contribute to a broader understanding about the effectiveness of enforcing forest laws to deter deforestation, we proposed an analysis of the Brazil's efforts to reduce deforestation in the Amazon between 2004 and 2016, which is considered a success case by policy analysists and land change scholars (Boucher, Roquemore, and Fitzhugh 2013; Nepstad et al. 2014). Brazil's forest use rules stand out in comparison with any other country in the world. However, the enforcement of forest rules is limited by high transaction costs, especially in large and complex areas such as the Amazon. Since 2004, the Brazilian government enacted a set of policies to reduce deforestation, such as the Plan for the Protection and Control of Deforestation in the Amazon

(PPCDAm). As a result, annual deforestation rates in the Brazilian Amazon have decreased from 27,772 km^2y^{-1} in 2004 to 4,571 km^2y^{-1} in 2012 (Figure 1). In contrast, the global loss of tropical forest increased during the same period (Hansen et al. 2013). The backbone of PPCDAm is the strict enforcement of the forest laws (Schmitt 2015). The law enforcement process may be divided into four phases: detection, policing, the judicial process, and sanctioning. For detection, the Brazilian National Institute for Space Research (INPE) launched in 2004 a new monitoring system for detection of deforestation called DETER. It *locates* changes in forest cover in the early stage of the deforestation process at a frequency of 15 days (Anderson et al. 2005), allowing for close-to-real-time detection. Following the introduction of DETER, enforcement of deforestation laws became quicker and more frequent. Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) and Chico Mendes Institute for Biodiversity Conservation (ICMBio), the two federal agencies responsible for enforcement, reported a 30-fold increase in violations from 2004 to 2016 (less than 250 violations in 2004 and almost 7,500 in 2016 (Figure 1).

In this paper, we draw on official panel data on deforestation and forest law enforcement. We seek to explore whether, and how, the enforcement of formal legal rules was effective to limit deforestation in the Brazilian Amazon. We first discuss the recent evidence from experimental studies about the effect of this law enforcement. Then, we frame the complex legal system for forest governance ruling land use in the Brazilian Amazon using the combination of the Elinor Ostrom's IAD (Institutional Analysis and Development) and SES (Social-Ecological Systems) frameworks – CIS – developed by Cole, Epstein, and McGinnis (2019). Finally, we report a preliminary econometric analysis on the essential role played by monitoring and enforcement to reduce deforestation in the Brazilian Amazon region using instrumental variable approach.

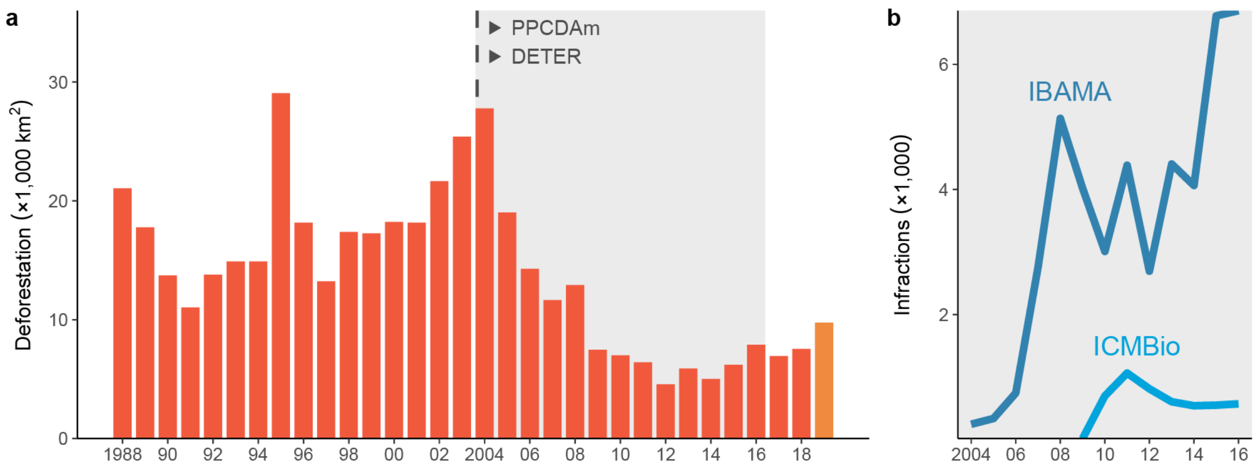

Figure 1. Deforestation rates and infractions carried out by the environmental agencies in the Brazilian Legal Amazon over time. The red bars correspond to annual deforestation in 1,000 km², the dark blue line is the number of infractions. Sources: INPE (2019), IBAMA (2018).

2. LITERATURE DISCUSSION ON THE ENFORCEMENT OF FOREST LAWS

So far, few studies have attempted to evaluate the effects of monitoring and law enforcement actions on deforestation in the Brazilian Amazon, or even in tropical rainforests in general. Most governments institutions from tropical rainforest countries lack proper data on policing efforts, judgement, and sanctioning systems. Finding ways to accurately measure enforcement is one of the central challenges for land change research. To overcome the lack of data on forest policing activities, le Polain de Waroux et al. (2016) the monitoring system and differences in legislation as a proxy for enforcement, assuming that monitoring on its own explain the probability of being punished. Arima et al. (2014) addressed different levels of enforcement by contrasting blacklisted municipalities to non-black listed municipalities in the Brazilian Amazon. The Blacklist is a policy in Brazil that prioritize municipalities with higher rates of deforestation to focus conservation efforts, including law enforcement. Some papers took advantage of the availability of data on illegal deforestation reported by IBAMA, the main environmental agency in Brazil.

A small but growing literature has found that law enforcement reduces deforestation in the Brazilian Amazon. Arima et al. (2014) used municipality-year panel data and a difference-in-difference design to find the effects of prioritizing municipalities to enforce the law and found that heightened enforcement efforts avoided as much as 10,653 km^2 of deforestation from 2009 to 2011. Schmitt (2015) analyzed state-level data to understand the cost-benefit ratio of illegal deforestation and measure a dissuasive monetary value. He found that environmental policing cannot control deforestation, as, on average, the offenders are not punished. This provides evidence that the causal mechanism of law enforcement to curb deforestation must be due to preventive sanctions, as embargoes, market-based interventions and to the differentiated vulnerability of the multiple actors of deforestation to the risk of punishment. Assunção, Gandour, and Rocha (2013) used municipality-year panel data and a novel instrumental variables (IV) approach to estimate the causal effects of law enforcement on deforestation. They estimate that higher enforcement intensity avoids over 22,000 km^2 of cleared forest area per year over the 2006-2011 period. Borner et al. (2015) explore the spatially explicit database of IBAMA's infraction reports during 2009 and 2010 to analyze whether local deforestation patterns have been affected by field-based enforcement and to what extent these effects vary across administrative states. They found that, on average, law enforcement reduced deforestation in the Brazilian Amazon and the policy is highly cost-effective. However, the deterrence effect is a non-stationary process across the states. Inspections have been most effective in reducing large-scale deforestation in the states of Mato Grosso and Pará, in the deforestation frontier. To the best of my knowledge, no previous work has evaluated the deterrent effect of ICMBio's enforcement activities – responsible for enforcing laws in protected areas, which account for 25% of the territory of the Brazilian Amazon.

On the other hand, Assuncao et al. (2017) and Richards et al. (2017) found evidence that monitoring and enforcement in the Brazilian Amazon have done less to protect the forests than previously assumed. In recent decades, the spatial pattern of deforestation in the Brazilian Amazon is changing (Rosa, Souza, and Ewers 2012). Kalamandeen et al. (2018) reported that small-scale deforested area sharply increased from 2008 to 2014. As DETER cannot detect small patches of deforestation (<25 ha), some authors have discussed the monitoring system and the inherently limited capacity to provide information about the location of forest cover changes as the cause for these changes (Assuncao et al. 2017). The authors found evidence, although not causal, that actors strategically adapted to avoid remote detection of the monitoring system. If this prediction holds, it also corroborates to the fact that monitoring and enforcement shape the way agents make land-use decisions. In response to the changes in the size of deforestation patches, INPE started in 2016 the DETER-B, an extension of the former monitoring system, but based on images with 56 m of spatial resolution. The new system can detect patches of deforestation smaller than 25 ha and presents higher detection capability in identifying areas between 25 and 100 ha (Diniz et al. 2015).

The main challenge this empirical literature faces is the simultaneity between deforestation and enforcement. For example, IBAMA focuses on areas where deforestation is likely to occur, while the expected value of illegal deforestation depends on the likelihood of enforcement to take place. Estimating the causal effects of enforcement on deforestation depends on the isolation of these effects. Matching techniques, which is often used in the literature evaluating the effect of policy interventions on deforestation, does not address this simultaneity (Andam et al. 2008; Borner et al. 2015; Soares et al. 2010). The literature on the effects of policing on crime has made progress by the use of instrumental variables, which breaks the two-way causality. Di Tella and Schargrodsky (2004) and Draca, Machin, and Witt (2011) used the variation in policing intensity due to terrorist attacks to estimate the effect of police on crime, and found that more police in the streets led to substantial reductions in crime in Buenos Aires and London, respectively. Assunção, Gandour, and Rocha (2013) suggest using cloud cover at the municipality level as an instrument for enforcement of deforestation laws in the Brazilian legal amazon.

Despite the apparent efficiency of enforcement measures for reducing deforestation in Brazil, several studies have revealed that the lack of accountability that follows intervention (i.e., environmental fines), defies its success. It is important to remember that deforestation remains high even if lower relative to earlier spikes. According to Schmitt (2015), only 26% of the reported infractions of illegal deforestation were adjudicated and it takes on average three years for a fine to be considered in court. The embargoed areas, moreover, represent only 18% of the total deforested land and the number of paid fines corresponds to 10% of those applied, 0.2% of the total amount of fines. Brito and Barreto (2006) analyzed 55 judicial cases against environmental offences in the forest sector in Pará from 2000 to 2003 and found that only 2% of the offenders were criminally punished and, on average, the fines were low. In Protected Areas the punishment of offenders has also been equally ineffective; from 1997 to 2006, only 14% of the cases resulted in some sanction against offenders (Barreto, Araújo, and Brito 2009). In this context, what other factors may help to explain the observed reduction in deforestation rates? An alternative reason for the deterrent effect of enforcement on deforestation is that other instruments can compensate for punishment failures in the legal system (Lambin et al. 2014). Other coercive measures, such as conditional agricultural credit access and the soy and cattle moratoriums imposed by international markets have also contributed to reduce the economic incentives of deforestation, supposedly increasing the uneven deterrence effect of enforcement.

3. INSTITUTIONAL ANALYSIS

Understanding the causal effects and mechanisms of underlying deforestation is challenging theoretically and methodologically. Many explanations stray too far into oversimplification or appear to remain largely unanswerable due to the "irreducible complexity" of phenomena (Lambin et al. 2001). To identify, categorize, and organize the most relevant factors underlying the causal effects between enforcement and deforestation, we used the combination of the Elinor Ostrom's IAD (Institutional Analysis and Development) and SES (Social-Ecological Systems) frameworks – CIS – as proposed by Cole, Epstein, and McGinnis (2019). The CIS framework is populated and described with qualitative data from semi-structured interviews, in addition to archival research and the literature review.

Our breakpoint for analysis is 2004, when the real-time monitoring system has been created and enforcing the laws became a priority with PPCDAm, followed by deforestation rates sharply slowing down. However, the 2004-2016 period was quite dynamic. Several other action situations shaping the governance in the Amazon were in place – e.g.: supply chain governance (2006 and 2008) and the forest code revision (2012). These breakpoints are also important for the analysis of the net of institutions governing the Amazonian forests but are out of the scope of this paper (at least for now).

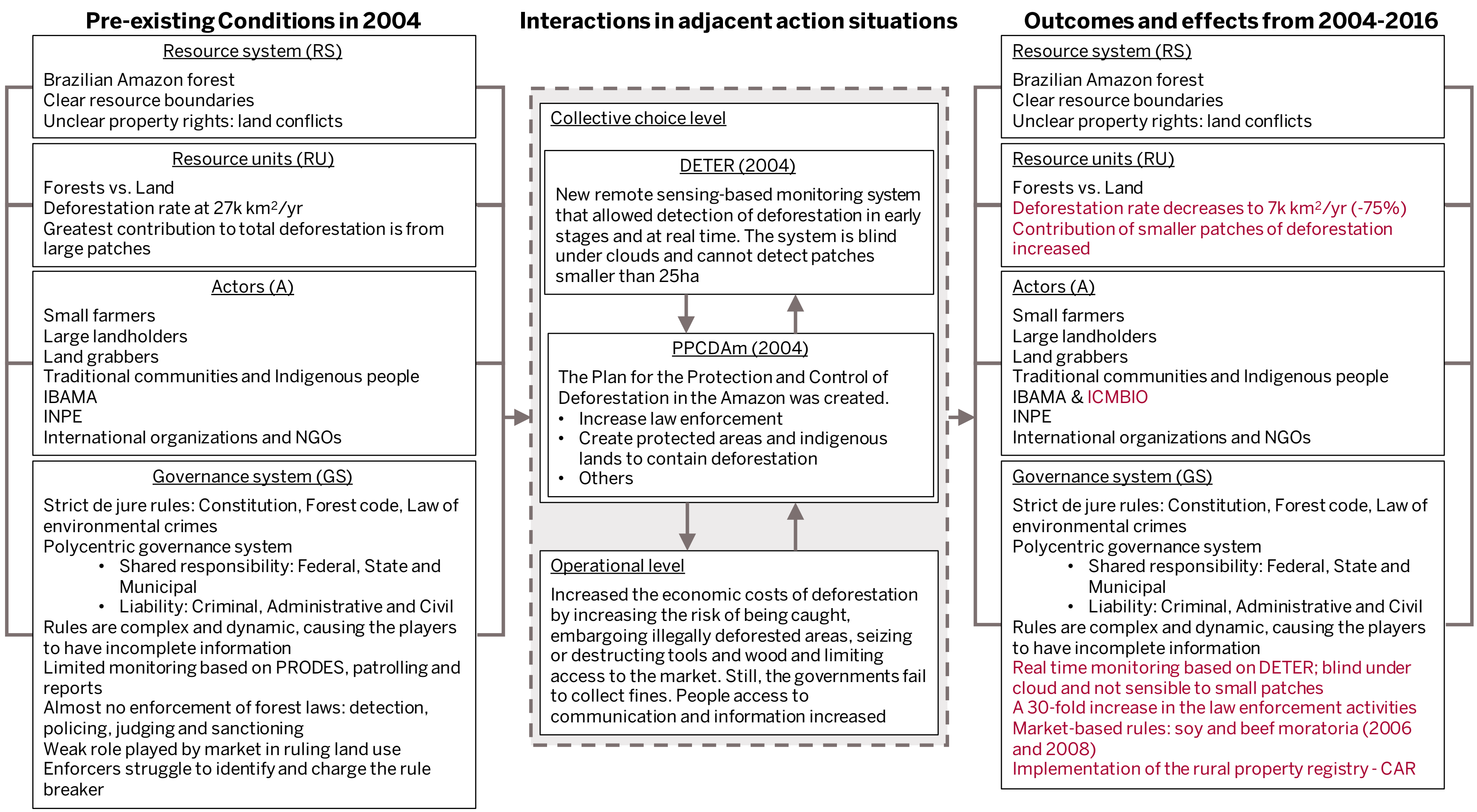

Figure 2. Combined IAD and SES framework applied to the analysis of forest governance in the Brazilian Amazon, 2004–2016.

Note: Significant changes in outcome variables are denoted in red.

3.1. Contextual factors

The Amazonian biome in Brazil covers an area of 3,945,096 km^2 that represents about 40% of total tropical forests in the world (Figure 3). It is also home to 24 million people (IBGE, 2010), including hundreds of indigenous groups, thousands of rural communities, diverse groups of farmers and ranchers, and over 700 small and medium-sized towns in a wide diversity socioeconomic contexts, values, priorities, and cultures. Given the diverse reality of the region – social-economic, cultural, institutional, and environmental –, people value forests in a different way, and have diverse motivations and understandings of benefits derived from deforestation.

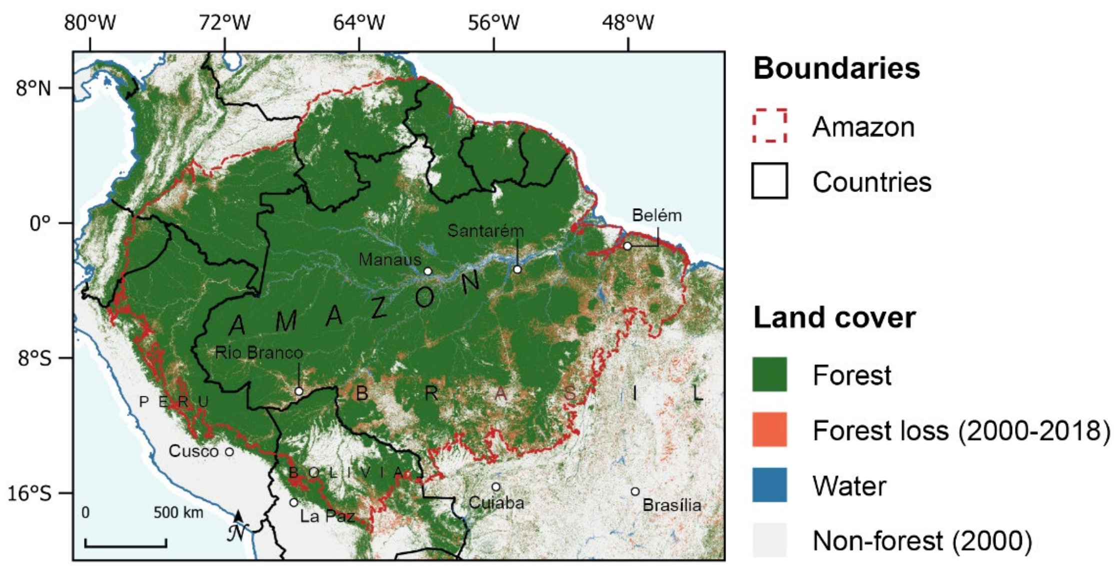

Figure 3. Study area: the Brazilian Amazon.

Unlike problems commonly investigated using the IAD or the SES framework, the Amazon deforestation dilemma is not about single common pool resource. Different actors make their decisions about designing institutions or harvesting resources pondering two different goods, which are valued in different ways. On the one hand, some actors value the *forests* standing. At the local level, forests provide shelter, jobs and security for communities that rely on forests directly for their livelihoods. Also, forests reduce the risk of disasters as floods and severe droughts (Levy et al. 2018; Bagley, 2014). At broader levels, forests play a key role in climate regulation through carbon stocking and sequestration. The Amazonian forest is essential for the conservation of biodiversity, as it is the largest biodiversity reserve in the world. The Amazonian forest also pumps a huge amount of freshwater into southeastern South America through aerial rivers (Arraut et al. 2012). On the other hand, deforesters value *land* to expand commodity production and maximize profits. The main *direct causes* of deforestation in the Brazilian Amazon include cattle ranching, soybean croplands. According to data from TerraClass (2014), 44% of the deforested areas transitioned to pastures between 2004 and 2014, and 5% to annual croplands. However, most of the expansion of annual crops happened over pasturelands, increasing its demand, and indirectly pressing the forests. In addition, mega infrastructure projects and logging activities are also direct drivers of deforestation. Locally, the nature of this goods, together with the historically disordered occupation process, generate conflicts over land use and weaken property rights. Squatters often invade public lands and clear the forest aiming at gaining official recognition with formal property titles afterwards. Farmers deforest preventively to claim a productive use of land and to reduce the expropriation chances (Araujo et al. 2009).

In the Brazilian Amazon, land tenure regimes can be distinguished in public lands – which includes protected areas, indigenous lands, agrarian reform settlements and undesignated lands –, and private properties. Currently, 25% of the Brazilian Amazon is protected by protected areas and 20% of the area belongs to indigenous lands. Even though these areas together cover a great proportion of the Brazilian Amazon territory, they are responsible for only 8% (12,253 km^2) of the total deforestation from 2004 to 2016. In contrast, while covering a similar extension of the

Brazilian Amazon (21%), deforestation in private rural properties contributes seven times more to the total cleared area in the same period – 56% (81,560 km²). Combined with agrarian reform settlements and undesignated public lands, the contribution rises to 92%.

Brazil's forest code stands out in comparison with any other country in the world[†]. Prior to the establishment of DETER, monitoring of the Amazon forest relied on annual PRODES deforestation data, reports and on-site patrols. The transaction costs of monitoring and enforcement were so high that the rules-in-form were not the actual working rules.

Forest governance in the Brazilian Amazon is polycentric in at least two ways. *First*, the Brazilian Federal Constitution establishes that an environmental offender can be held liable in three different ways for the same violation: administratively, civilly, and criminally – i.e. A person accused of illegally logging may be sanctioned with the embargo of their property, seizure of their goods and a fine (administrative sanction), forced to recover the degraded area (civil sanction), besides being fined again and arrested (criminal sanction). Different authorities oversee each of the sanctions. Our empirical analysis is limited to *administrative sanctions*, since it is the most applied liability in the Brazilian legal system and is the only one from which systematized, and spatially explicit data are available. Also, it is also a good representation of the civil and criminal liabilities since the authorities rely on the infraction reports carried out by the environmental agencies to apply the sanctions. *Second*, the responsibility of enforcing the forest laws is not exclusively federal, but instead they are decentralized between federative entities (states and municipalities). Nevertheless, most of the states and municipalities have not been active in

[†] The Brazilian legislation in the analyzed period is dynamic, complex and extensive, and it is not my intention to exhaust them in this paper.

enforcing environmental legislation (Schmitt 2015), with a few exceptions. Therefore, for practical purposes federal environmental agencies – IBAMA and ICMBio – are the environmental law enforcers in the Amazon.

3.2. The creation of DETER and PPCDAm

Brazil turned around what were once the highest rates of tropical deforestation in the world by enacting a set of conservation policies. One of the causes for the observed slowdown after 2004 was the falling of agricultural commodity prices (Walker et al. 2009; Assuncao, Gandour, and Rocha 2015). However, the decline in deforestation rates continued after a recovery in market conditions. After 2007, commodity prices and deforestation, which were historically correlated, showed a decoupling (Arima et al. 2014). Alternative causes are the series of policies and measures for the reduction of deforestation in Amazonia that have been enacted by the Brazilian government after 2004, known as PPCDAm, aiming at continuously reduce deforestation and create the conditions for the establishment of a model of sustainable development in the Amazon. PPCDAm was articulated around four strategic pillars: (1) land and territorial planning; (2) forest monitoring and control; (3) promotion of sustainable production activities; and (4) economic and regulatory instruments. The most successful instruments and measures were the creation of extensive protected areas (PAs) and the increased monitoring capacity that supported the enforcement of the forest laws.

Protected Areas (PAs) were the first conservation policies to be implemented in the Brazilian Amazon. Legally protected territories have long attracted the attention of those who study the effect of policies to reduce deforestation. The first conservation unit in the Brazilian Amazon was created in 1959 and the first indigenous land in 1945. More recently, a huge territorial extension was protected in Amazonia in the 2000s. In total, 507,015 km^2 (75%; 101,403 km^2 y^{-1}) of conservation units in the Amazon was created from 2004 to 2008 (MMA, 2018). Currently, the PA system in the Brazilian covers 1.2 million km^2, equivalent to the size of France, Portugal and Spain combined.

The second strategic axis of the PPCDAm focused on forest monitoring and control. The federal environmental agencies began undertaking high-profile law enforcement actions to send the message that illegal forest conversion would no longer be tolerated. After the beginning of the DETER monitoring system, in 2004, the capacity of the environmental agencies to enforce the forest laws sharply increased (Figure 1). The increased enforcement of forest laws is considered by scholar and policy analysts as the backbone of the PPCDAm, because every effort to rule land use in the Brazilian Amazon rely on enforcement.

In parallel to the PPCDAm, a set of market-based approaches were implemented. In 2006, major soybean traders signed the Soy Moratorium, agreeing not to purchase soy grown on lands deforested after July 2006 in the Brazilian Amazon. After the soy moratorium, the soy has expanded into previously deforested areas, such as pasture lands, rather than forests (Gibbs et al. 2015). Later in 2009, it was the turn of cattle raising. The largest players in the global cattle industry have agreed to ban the purchase of cattle from newly deforested areas of the Brazilian Amazon from their supply chains. Gibbs et al. (2016) demonstrated that (1) after the cattle agreement the slaughterhouses avoided purchasing from properties with deforestation, (2) supplying ranchers were more likely to follow the rules than non-supplying ranchers as a result of the agreement and (3) supplying properties had significantly reduced deforestation after the agreements. However, Lambin et al. (2018) claim that such supply chain-based policies may be insufficient to reduce deforestation due to leakage, lack of transparency and traceability, selective adoption and smallholder marginalization. Beginning in July 2008, the rules for the granting of agricultural credit in the Amazonian biome began to require documentation of regularity with environmental agencies. The decrease in rural credit associated with this policy has curbed deforestation by14% from 2009 through 2011, particularly where cattle ranching was the main land-use (Assunção et al. 2013).

Recently, environmental policies have been severely weakened (Rochedo et al. 2018; Bernard, Penna, and Araujo 2014). After the reduction of deforestation in Amazonia, the agribusiness lobby took advantage of favorable political momentum to propose a new forest code, which regulates the land use on rural properties in Brazil. In 2012 the new law was approved with harsh criticism for being lenient with the landholders by granting amnesty to illegal deforesters. According to Soares et al. (2014), the new forest code reduces, by 58%, the areas that should be reforested in addition to forgive fines related to illegal deforestation.

4. ECONOMETRICS ESTIMATES OF DETERRENCE

We have developed and tested two hypotheses to investigate the effects of monitoring and law enforcement on deforestation:

H1. Enforcement decreases deforestation in the Brazilian Amazon

Illegal deforestation is a function of the expected benefits minus the expected costs (e.g., Assunção et al., 2017b; Börner et al., 2015; Schmitt, 2015b). In line with the deterrence hypothesis in classical criminology (Becker, 1968), violators are expected to respond to the deterring incentives created by the criminal justice system. The higher the likelihood of law enforcement, the higher the expected costs of illegal deforestation. I observe in this paper policing, and I interpret the effect I estimate to capture the total effect of law enforcement (policing, the judicial process and sanctions).

H2. Enforcement has a larger effect for deforestation of detectable patch size

In recent years, the average size of the patches deforested has decreased in the Brazilian Amazon (Assunção et al., 2017a; Diniz et al., 2015; Escada et al., 2011; Kalamandeen et al., 2018; Richards et al., 2017; Rosa et al., 2012). As DETER does not detect deforestation in patches below the size of 25 ha and it has a poor precision detecting areas smaller than 100 (Escada et al., 2011), I expect policing as tested in this paper to reduce deforestation in the form of large patches and hence decrease the mean patch size.

4.1. Data and methods

The relationship between police presence and illegal deforestation is characterized by strong endogeneity; that is, the resources available for policing generally targets areas at higher risk of deforestation. Thus, the correlation between the presence of environmental agencies and deforestation is determined both by the strategy of targeting based on this risk and by the inhibitory effect of policing on deforestation. Estimating any causal effect of these policies on deforestation will depend on the possibility of isolating these effects, as well as understanding their contextual underpinnings. To deal with this empirical issue, we used an instrumental variables approach.

We used two instruments to provide a source of exogenous variation in the likelihood of detection across time and space. The first is the proportion of days in the year that a cell is covered by clouds. As recommended by Assunção, Gandour, and Rocha (2013), it is assumed that the presence of environmental agencies is partially determined by cloud coverage because the Detection of Deforestation in Real Time (DETER) system, the main source of qualified information on deforestation to direct policing efforts, is not able to issue deforestation alerts in cloud-covered areas. We used the quality band from Terra/MODIS to construct a measure of the annual frequency of cloud cover at the 10 km spatial resolution. The images are available at a 2-day frequency and a spatial resolution of 250 meters. Our measure is the fraction of days in a year that of each 10 km cell is covered with clouds over the year, on average.

Second, we took advantage of the variation in monitoring efforts associated with the list of priority municipalities (PMs). The list was introduced in 2008 and was a policy induced reform that implied relative concentration of detection efforts for the municipalities on the list (Arima et al., 2014; Assunção and Rocha, 2014). The environmental agencies use the list of PMs to focus the monitoring and control efforts. Even though PMs selection is associated with historical deforestation, the criteria is based only on the absolute deforested area, without considering the extension of the municipality. For example, a municipality with higher deforestation density may be off the list if it has a smaller territory and, therefore, a smaller absolute deforested area. Another factor that contributes to the exogeneity of PMs on deforestation is that prioritization considers as homogeneous the deforestation within a municipality, which is a coarser spatial unit than in this analysis (cells). Thus, within a PM it is possible to have cells with low rates of deforestation that were probably more policed than cells with high rates in non-PMs. We used the fraction of a cell located in a priority municipality as my second instrument (which is zero for all municipalities before the list was introduced in 2008). Both of these instruments affected the likelihood of detection of illegal deforestation without a long time lag, which is a pre-requisite for effective enforcement (Hansen et al., 2008).

To measure enforcement, we used infractions reported by IBAMA and ICMBio with georeferenced precise locations. We estimated a kernel density function of these infractions to represent the exposure to infractions of different grid-cells. The intensity was calculated using a 25 km bandwidth and a Gaussian function. We rely on official data from PRODES to measure deforestation. Compared to the rest of the literature, we used a longer time span (2004-2016) and higher spatial resolution (10 km). Given the panel structure of our dataset, we could control for any time-invariant differences across our 10 km cells by the inclusion of cell fixed effects. This is an important improvement compared to the use of matching, which relies on constructing the control group based on observable, and often non-time varying, characteristics. We included year fixed effects, to consider common shocks across cells from year to year. Finally, we controlled for the share of each cell covered by land regulation in the form of protected areas and indigenous people's land, also central parts of PPCDAm, as well as remaining forest.

We estimated the causal effect of policing on deforestation in cell, s, and time (year), t, using the following two-stage least squares (2SLS) model with cell-year fixed effects:

$$Infractions_{st} = \theta_1 Cloud_{st} + \theta_2 PM_{st} + \sum_k \theta_k X_{kst} + \omega_s + \psi_t + \eta_{st} \quad (1)$$

$$Deforestation_{st} = \beta_1 \widehat{Infractions}_{st} + \sum_k \beta_k X_{kst} + \phi_s + \lambda_t + \epsilon_{st} \quad (2)$$

In the first stage (Equation 1), the dependent variable, $Policing$ is the number of infractions reported; $Cloud$ is the proportion of days in the year that a cell is covered by clouds; θ_1 picks up the effect of the inability to monitor on policing activities. PM is the percentage of the cell that is inside a priority municipality; the k controls are represented by vector X; $\omega_s$is the cell fixed effect; ψ_s is the year fixed effect; and, η_{st} is the idiosyncratic error.

In the second stage (Equation 2), the predicted variable, $Deforestation$, is the outcome and measures the deforestation in hectares; $\widehat{Policing}_{st-\ell}$ is the time lagged number of infractions instrumented by cloud cover frequency and PMs proportion, predicted based on the first stage model; β_1 picks up the effect of policing on deforestation and is the coefficient of interest to address **Q2**; the k controls are represented by vector X; ϕ_s is the cell fixed effect; λ_t is the year fixed effect; and, ϵ_{st} is the idiosyncratic error.

4.2. IV Estimates and Discussion

Clouds and priority municipalities are valid instruments for policing. Column 1 in Table 1 presents my first stage estimates. The priority municipality dummy (PM) takes a positive sign, consistent with concentration of policing efforts in those municipalities. The cloud variable takes a negative sign, consistent with higher cloud cover resulting in less detection and hence less policing. I assess that the instruments are valid, see the Materials and Methods section for the discussion.

Local presence of the environmental enforcement agencies had a deterrent effect on deforestation. The estimates show that a one standard deviation (0.24) increase in policing efforts (measured as infraction intensity), leads to 67%, 95%-CI [-77%, -54%], less deforestation (Table 1, Column 2). This estimate, together with the observed policing efforts in my data, implies that the policing efforts saved 58,643 km² of forest over the period 2004-2016. Total deforestation in this period was 143,037 km². If the deforestation rates instead had been kept at the 2004-level, the deforested area would have been 361,036 km². Of the saved deforestation of 217,999 km², policing accounts 27%. Figure 3 shows the actual deforestation together with the counterfactual deforestation according to my analysis. Although the mean implies a large area of forest saved due to policing, the 95%-confidence intervals also depicted in the Figure 3 suggest large uncertainty.

Table 1 Estimates of the effect of policing on deforestation.

	Dependent variable:				
	1st stage Infractions	2nd stage *asinh* Deforestation			
		Total, ha	Detectable, ha	Undetectable, ha	Undetectable, %
	(1)	(2)	(3)	(4)	(5)
Treatment					
Infractions		-4.740***	-5.239***	-0.865***	1.053**
		(0.750)	(0.795)	(0.249)	(0.481)
Controls					
asinh $RF_{(t-1)}$, ha	-0.149***	1.647***	1.453***	1.048***	-0.461***
	(0.022)	(0.228)	(0.210)	(0.139)	(0.139)
asinh SU-PA, ha	-0.004***	0.018***	0.012**	0.013***	-0.011
	(0.001)	(0.006)	(0.006)	(0.003)	(0.021)
asinh SP-PA, ha	-0.001	0.019***	0.016**	0.012***	-0.008
	(0.001)	(0.006)	(0.007)	(0.002)	(0.029)
asinh IL-PA, ha	-0.003***	0.007	0.003	0.007**	0.038*
	(0.001)	(0.008)	(0.008)	(0.003)	(0.023)
Instruments					
PM, %	0.001***				
	(0.0002)				
Cloud, %	-0.002*				
	(0.001)				
F-statistic (excl. instr.)	23				
Observations	512,694	512,694	512,694	512,694	51,899
R2	0.418	0.227	-0.078	0.351	0.453
Adjusted R2	0.369	0.163	-0.168	0.296	0.261
Residual Std. Error	0.187	1.637	1.504	1.170	2.064

Notes: Significance: *p<0.1; **p<0.05; ***p<0.01. Standard errors clustered at cell and year-municipality level. Coefficients were estimated using a cell-by-year panel dataset from 2004 to 2016. The sample included cells in the PRODES mapping area, which refers to the Amazonian biome in the Brazilian Legal Amazon. Dependent variable: Deforestation, in hectares, of a 10,000ha cell, in a given year. *Infractions* is my regressor of interest that picks up the effect of policing on deforestation. I controlled for, lagged remaining forest cover, $RF_{(t-1)}$; separately for sustainable use, SU-PA, strictly protected, SP-PA, and indigenous land, IL-PA, protected areas; and cell-year fixed effects. Columns (1) is the first and (2) the second stage results for 2SLS regression using cloud coverage frequency and the priority municipalities as instruments for the number of infractions.

In Supplementary Information, Tables X (NOT INCLUDED) present robustness tests of my estimates with respect to different specifications, outcomes, instruments, treatments, and controls.

After adequately address the endogeneity between the deforestation and the presence of environmental agencies, all the estimates show a negative and significant relationship with the deforestation outcomes, indicating that my findings are not driven by my choices.

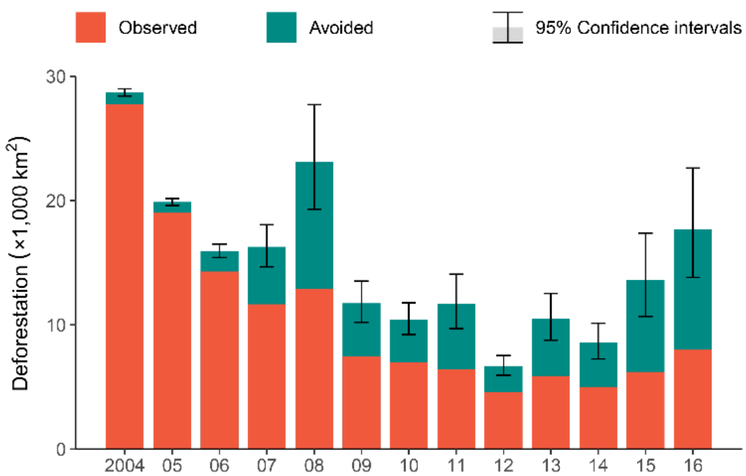

Figure 3. Counterfactual analysis.

Law enforcement has a greater deterrent effect on detectable patches of deforestation. Panel A, Figure , splits the deforestation in the – Brazilian Amazon over 2004-2016 into patch sizes detectable (>25 ha) and undetectable (<25 ha) by DETER, and shows that the detectable deforestation decreased markedly stronger than the undetectable deforestation. Panel B, Figure 4, shows that the share of undetectable deforestation increased from 28% in 2004 to 63% in 2010, before it slid down to 46% in 2016. I estimate that policing a one standard deviation increase in policing, decrease the detectable deforestation by 71% and the undetectable deforestation by 18% (Column 3 and 4, Table 1). This stronger effect on the detectable deforestation supports the conclusion that policing has reduced deforestation in the Brazilian Amazon, as the effect is stronger for the type of deforestation for which IBAMA and ICMBio have had information to react. I also estimate that a standard deviation increase in policing increases the share of undetectable by 28 percentage points (Column 5, Table 1, coefficient of 18).

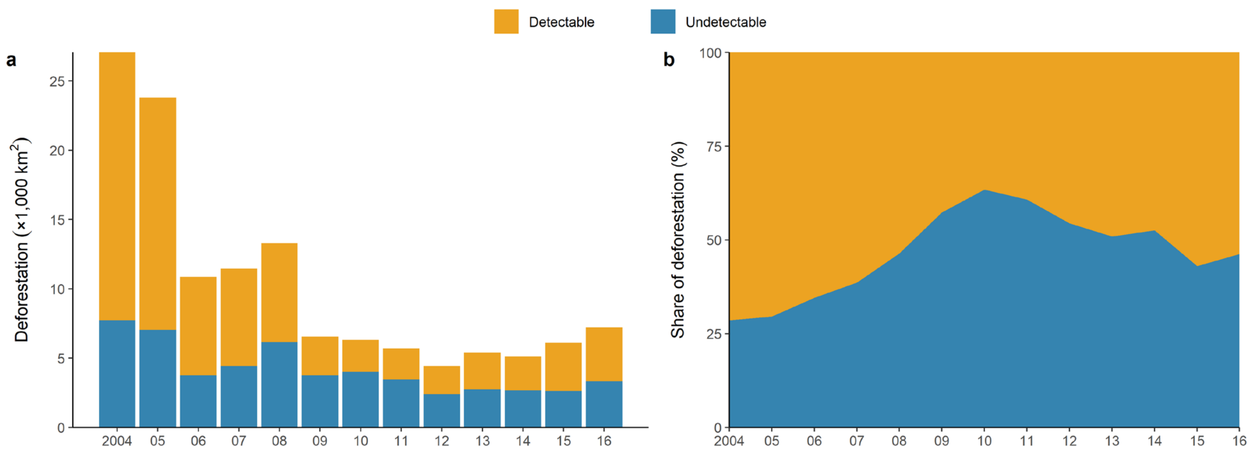

Figure 4. Dynamics of the deforestation patches size. (A) Deforested area, in thousands of km², over years, by DETER system detectability. (B) Contribution of each group of DETER system detectability on total deforestation, in percentage, over years.

Other papers have documented the decline in the mean size of the deforestation patches in the Brazilian Amazon (Assunção et al., 2017a; Börner et al., 2015; Kalamandeen et al., 2018; Richards et al., 2017; Rosa et al., 2012). Assunção et al. (2017a) argued that "*landholders strategically responded to the monitoring system by adapting their forest clearings practices to elude monitoring in both Mato Grosso and Pará*". Börner et al. (2015) found that enforcement missions during 2009 and 2010 were most effective in reducing large-scale deforestation in the states of Mato Grosso and Pará. Kalamandeen et al. (2018) show that the Brazilian Amazon has differed compared to the rest of the Amazon, by great reductions in the number of forest loss patches larger than 50 ha. The patterns for patches below 6.25 ha are similar in the Brazilian and non-Brazilian Amazon, whereas the intermediate cases of patches between 6.25 ha and 50 ha show a slight decline in the Brazilian Amazon compared to the remaining Amazon. My results align well with these papers that the mean size of the deforestation patches have gone down in the Brazilian Amazon, and I provide evidence that this is directly related to the monitoring and resulting enforcement. However, I cannot conclude that actors have strategically adapted to the detecting capability of the environmental agencies. In contrast, I find evidence that policing also reduced the non-detectable deforestation, consistent with a diffusion of the deterrence effect across sizes of deforestation. Note that my estimates are based on cell fixed effects, meaning that I estimate changes within cells across time. Although I do not follow actors across time, as I would have like to if I were to conclude that actors strategically change their patch sizes to avoid detection, this is close to following actors across time to the extent actors are operating within the same cells across time. The remaining literature has not controlled for unobserved heterogeneity across space, and hence may be confusing strategic adaption among the same actors for changing composition of actors doing the deforestation across time. It is plausible that certain areas are dominated by small scale farmers and hence small deforestation patches and other areas are dominated with large scale farmers and hence large deforestation patches. Although Assunção et al. (2017a) use data on property size, they do not present evidence that, for example, large properties have increased their use of small patches. They simply show that the share of deforestation accounted for by small patch sizes and by small properties have increased, which could be the result of a reduction of deforestation in terms of large patches and in terms of large properties, respectively.

5. CONCLUSIONS

The Amazon plays an important role in regulating the global climate, in addition to harboring a great biological and cultural diversity. Conversely, Amazonia is marked by development contradictions, social inequalities, and accelerated environmental change. This paper evaluates the effectiveness of law enforcement to reducing deforestation and, consequently, its impact on carbon emissions and biodiversity more broadly. Our findings suggest that Brazil's increased law enforcement efforts, encompassing policing, the judicial process, and sanctions, saved 59,000 km² in the period 2004-2016, 16% of the saved deforestation had the deforestation rates been unchanged since 2004.

Much research efforts have gone into understanding the causes of the extraordinary reductions of deforestation in Brazil since 2004, which has saved in total X Gt C. As more than 60 countries has reported that curbing deforestation rates will an essential part of their approach to reach their commitments in the Paris agreement, this question is higher on the global policy agenda than ever. Several papers have suggested that law enforcement has been an important ingredient of Brazil's success (Arima et al., 2014; Assunção et al., 2017b; Börner et al., 2015; Nepstad et al., 2014). Additionally, our estimates suggest that enforcement can explain one quarter of the reductions in deforestation seen in Brazil from 2004 to 2016.

Land systems are the result of a complex and adaptive social-ecological systems driven by interactions between the different actors and demands for land, and the institutional, technological and cultural factors through which societies shape land use (Meyfroidt et al. 2018). This paper contributes to the field of land system science by advancing in the comprehension about the causal effects of law enforcement on deforestation and the causal mechanisms of this relationship in the Brazilian Amazon. Methodologically, this research contributes to the land systems and the general deterrence literature by applying econometric techniques and spatial data analysis capable of adequately handling the synergistic causality between enforcement and deforestation. We also use a longer time span (2004-2016) than the rest of literature and test for robustness in different spatial scales.

This paper gains importance in Brazil's current political moment when the progress achieved in the forest governance of the Amazon is under severe threat. The elected president Jair Bolsonaro dismantled the forest governance system in order to favor agroindustry and mining interests (Artaxo 2019). Under Bolsonaro's command, Brazil has approved 57 pieces of legislation that weakened environmental laws (Vale et al. 2021). Bolsonaro used a geopolitical rhetoric accused INPE of manipulating the DETER data on deforestation to support international interests in the region's resources. The focus on Covid-19 crisis was used to hide the government actions towards relaxing forest protection. Almost half of changes (27 bills) in environmental legislation occurred during Covid-19 pandemic, from March to September 2020. Also, the number of environmental fines decreased by 70% in the same period.

Additionally, the U.S. government is considering to charge for remote sensing data that is key for forest monitoring (Popkin 2018), threatening the ability of tropical forest . A greater understanding of factors behind the initial success and current failure to policies intended to curb deforestation in the Brazilian Amazon can support the design of conservation policies, including improving forest laws, sustain and improve remote sensing-based monitoring systems and policing strategies.

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