Estimating the Value of Near-real-time Satellite Information for Monitoring Deforestation in the Brazilian Amazon

Katrina Mullan[1], Thales A. P. West[2], Jill Caviglia-Harris[3], Erin Sills[4], Thaís Ottoni Santiago[1], Jime Rodrigues Ribeiro[4], Trent Biggs[5]

Affiliations:
[1] Department of Economics, University of Montana
[2] Environmental Geography Group, Institute for Environmental Studies (IVM), Vrije University Amsterdam
[3] Economics and Finance Department, Environmental Studies Department, Salisbury University
[4] Department of Forestry and Environmental Resources, North Carolina State University
[5] Department of Geography, San Diego State University

Abstract

We estimate the amount of avoided deforestation due to the use of near-real-time satellite imagery (DETER) to support the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), the conservation of indigenous and other protected areas, and compliance with the Brazilian Forest Code (FC). We develop a Directed Acyclical Graph (DAG) that outlines some of the econometric challenges that arise from the role of policy in the estimation of satellite data on deforestation and consider that policy could be a mediator and/or a moderator along this causal chain. We control for policies that were introduced simultaneously with DETER, and allow for changes in the influences of prices, agricultural settlement, and forest conservation policies on deforestation after near-real-time monitoring was introduced. We find both direct impacts of DETER on deforestation, and indirect impacts via changes in the influences of commodity prices on deforestation. In total we estimate the amount of avoided deforestation is approximately 467-471 thousand km^2 between 2001-2015, an area that is larger than the state of California, more than twice the amount of deforestation recorded in that region in the same time period, and translates to approximately 12 billion tons of avoided CO2. The net benefits of satellite monitoring range from US$1-5.4 billion per year when estimated using the WTP to preserve Amazon rainforest and between US$54 US$197 billion per year when estimating using the social cost of carbon.

Keywords
value of information; satellite monitoring; mediators; moderators; directed acyclical graph (DAG); deforestation; Brazilian Amazon

1. Introduction

Remotely sensed data provides enormous societal benefits when mobilized to address global issues such as climate change, natural disasters, and disease outbreak; national challenges related to land cover and land use change; and regional emergencies such as dangerously impaired air quality (Kansakar and Hossain 2016). However, the value of satellite data is largely invisible because the benefits are not communicated to the general public, the data are used by many private and public agencies and governments in unknown ways, and because the quantification of these non-market benefits is challenging. Remote sensing data from satellites have been used to monitor deforestation in the Brazilian Amazon beginning in 1988 with the launch of the PRODES (Portuguese acronym) monitoring system, which publishes annual deforestation rates for use by policy makers, government agencies, and the broader public. These data have been crucial to the enforcement of environmental policy because the Earth's largest contiguous tropical rainforest is too vast to otherwise monitor. The Brazilian Amazon is home to a third of the world's rainforests (FAO 2011), contains one of the most biologically diverse biomes, (Dirzo and Raven 2003; Mittermeier et al. 2003) and significantly influences global climate (Cao and Woodward 1998; Foley et al. 2007; D. C. Nepstad et al. 2008). Approximately 47% of the existing native forests in this region are protected within conservation units and indigenous territories. The remainder of the Brazilian Amazon (with the exception of a few contested public land areas) includes private properties that fall under the protection of the Forest Code (FC), the central piece of legislation designed to protect the public good aspects of forests (Sparovek et al. 2010).

The DETER satellite system, launched in 2004 as part of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), changed the deforestation policy landscape in Brazil. The DETER system enables near real-time detection of deforestation and has served as an effective way to monitor ongoing land cover change (Hargrave and Kis-Katos 2013). The system is used to send daily DETER alerts to the enforcement agency Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA; Portuguese acronym) and state environmental agencies for planning inspection actions to make sure that private properties are in compliance with the FC and public lands are not encroached upon. These data are also used to implement policies like the Priority List (a public listing of municipalities with high levels of deforestation defined using PRODES data) and to target ground inspections that can result in environmental fines.

Large scale deforestation of the Brazilian Amazon began in the mid-1960s with government settlement programs, large infrastructure projects, and investment in industrial agriculture (Andersen 2002; Barreto, Pereira, and Arima 2008). This time period saw one of the most extensive frontier colonization programs to occur in the past century, settling over one million individuals in the Amazon with oversight from the National Institute of Colonization and Agrarian Reform (INCRA; Portuguese acronym). By the 1980s, these programs resulted in a substantial change to land cover dynamics in the region. Deforestation became closely linked to market forces, increasing at historically high rates in the 1980s and 1990s, specifically with the expansion of cattle ranching and soybean operations. Reductions in deforestation rates after 2004 have been explained by a series of policy responses (including the use of satellite imagery for monitoring and enforcement) that are believed to have effectively decoupled potential agricultural revenue from deforestation (Caviglia-Harris et al. 2016; Nepstad et al. 2014). These policies at least partially contributed to the more than 70% reduction in deforestation between 2004-2012 (T. A. P. West and Fearnside 2021; INPE 2021); one estimate is that they reduced deforestation by approximately 47% below what would have otherwise occurred (Busch and Engelmann 2017). Existing evidence suggests that the satellite-based system alone has had an important impact. Assunção et al. (2019) estimate that deforestation would have been four times greater between 2006-2016 in the absence of the system.

This study estimates the amount of deforestation that would have occurred (i.e. counterfactual deforestation) if the near real-time satellite monitoring system (DETER) was not launched in 2004 and the amount of carbon that would have been released into the atmosphere had the deforestation occurred. We begin with the development of a Directed Acyclical Graph (DAG) tracing the causal pathway from satellite data (the treatment) to deforestation (the outcome) as is informed by interviews with public officials and desk review of policy documents. We consider that policy could be a mediator and/or a moderator along this causal chain. We then outline our methods, specifically addressing econometric challenges including a lack of spatial and temporal variation in the use of real-time satellites at our unit of analysis (i.e., municipalities), selection bias, and the implementation of multiple policies that rely on the use of satellite data, in different periods and with strong selection bias. Our estimations include the impacts of macroeconomic influences (such as commodity prices), pro-development policies and programs (such as INCRA settlements), and pro-conservation policies (such as environmental fines and supply chain initiatives) and quantify the value of satellite imagery as the value of carbon stored due to avoided deforestation.

2. Policy context

The Brazilian government began monitoring deforestation in the Amazon forest largely using Landsat satellite data through the PRODES program (monitoring of Brazilian Amazon deforestation project) in 1988 (INPE 2021), in response to international pressure to reduce deforestation resulting from the government incentivized settlement of the region (Achard and Hansen 2012b; 2012a). This monitoring system recorded more than 500,000 km² of deforestation through 2020 (INPE 2021), revealing historical correlations between annual deforestation rates and political and economic changes (Margulis 2003; Hargrave and Kis-Katos 2013; Assunção et al. 2013). Despite the use of satellites to monitor deforestation beginning in 1988, annual deforestation remained relatively high through the following decade (Achard and Hansen 2012a) in part due to the relatively long lag between the time the images were taken and analyzed, and information was made available to the government and other environmental enforcement agencies. In response, a new monitoring system based on MODIS images, DETER, was developed in 2004 for rapid detection of deforestation patches greater than 25 hectares (Shimabukuro et al. 2006). DETER's main objective was to provide deforestation alerts to enforcement agencies on potentially illegal forest-clearing activities in the Amazon, which could then be used to support on-the-ground actions (Achard and Hansen 2012b; INPE 2021). DETER issued more than 70,000 alerts from 2004 to 2017, covering an area of ~88,000 km² of deforestation (INPE 2021). The DETER system has since supported the Federal Government's PPCDAm; Achard and Hansen, 2012) and has been attributed with helping to slow illegal deforestation in the Amazon (Hargrave and Kis-Katos 2013).

The post-2004 slowdown of deforestation in the Brazilian Amazon that we are modeling can be explained by a series of responses to efforts designed to meet different, and often conflicting, policy objectives, many of which have been supported by satellite data (Figure 1). Brazil's interventions to slow Amazonian deforestation have been credited with successfully decoupling potential agricultural markets from deforestation (Caviglia-Harris et al. 2016; Assunção, Gandour, and Rocha 2015; Nepstad et al. 2014) , thus contributing to the approximately 75% reduction in the deforestation rate between 2004 and 2012 (West and Fearnside, 2021; INPE, 2021). Throughout the four phases of PPCDAm supported by DETER there was a significant expansion of the protected areas network (Jusys 2018; Pfaff et al. 2015; Barber et al. 2014; Nolte et al. 2013), the creation of a monitoring priority list of municipalities with illegal deforestation (Cisneros et al. 2013; Arima et al. 2014a; Assunção and Rocha 2014), restrictions on public credit access for illegal deforesters (Assunção et al. 2013), and the 2012 revisions to the Forest Code (Soares-Filho et al. 2014). This series of policies was accompanied by private supply chain actions including the "Soy Moratorium" of 2006, a pledge from the Brazilian Association of Vegetable Oils Industries and the National Association of Cereal Exporters to ban soybeans produced in deforested areas in Amazonia after 2008 (Fearnside 2017; Gibbs, Munger, et al. 2015), and the "Cattle Moratorium" of 2009, a pledge from the largest meatpacking companies in the country not to purchase beef products from farms linked to illegal deforestation (West and Fearnside 2021; Gibbs, Munger, et al. 2015).

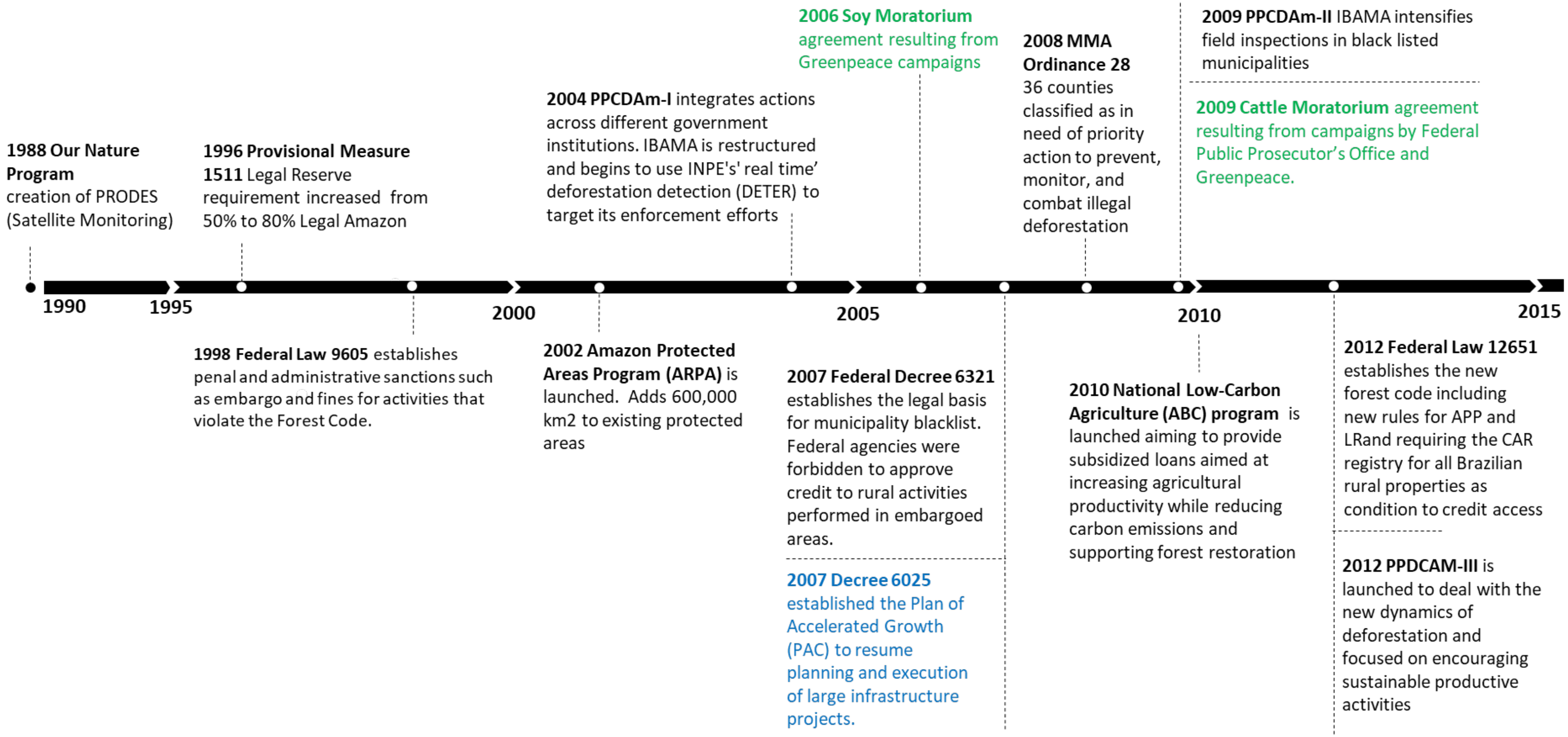

Figure 2.1: Outline of Major Deforestation and Development Policies Impacting the Brazilian Amazon

2.1 Priority list of municipalities

In January 2008, Brazil's federal government announced a priority list of Amazonian municipalities with rising deforestation rates (West and Fearnside 2021). The original list, from Decree 6321 of 2007, included 36 municipalities (43 after March 2008) that together represented 46% of all Amazonian deforestation. "Blacklisted" municipalities were subjected to more intense environmental surveillance, restrictions on the issuance of (legal) deforestation permits, embargoes of illegally cleared areas, and limited access to rural credit (Fearnside 2017). Studies associate the Priority List with significant reductions in deforestation (Arima et al. 2014a); in particular, Cisneros et al. (2015) estimated the policy to have reduced the expected 2008–2012 forest loss by 13%–36%.

2.2 Revision to the Brazilian Forest Code

The Brazilian Forest Code (FC) was revised in 2012 to include more flexible rules for the restoration of conservation areas on private lots (i.e., Permanent Preservation Areas and Legal Reserves) and granted amnesty to areas illegally cleared prior to 2008. A result is that the 2012 FC reduced Brazil's "environmental debt" (i.e., areas illegally cleared before 2008 and that would have to be restored according to the previous version of the code) by 58% (West and Fearnside 2021; Soares-Filho et al. 2014). At the same time, the new code enabled mechanisms to more efficiently monitor the environmental compliance and forest restoration required for all rural properties in the country (Azevedo et al. 2017), and authorized the creation of an environmental market to trade "forest certificates" that can be used to offset landowners' restoration requirements (Soares-Filho et al. 2016). However, a fully functioning market has not yet been established for these credits. Compliance with the new code can now be checked against the national Rural Environmental Registry (CAR; Brazilian acronym), a self-reported, spatially-explicit registration system.

2.3 Supply-chain interventions

Initiatives to reduce deforestation from agricultural supply chains were led by private sector actors and NGOs beginning in the early 2000s (Lambin et al. 2018; Nepstad et al. 2014). In 2006, soybean trading companies pledged to limit grain purchases from farms with post-2008 deforestation. This agreement is known as the "Soy Moratorium" (Gibbs, Rausch, et al. 2015). Then, in 2009, Greenpeace negotiations with the support of the Federal Public Ministry (MPF; Brazilian acronym) resulted in agreements with meat packing companies to purchase cattle exclusively from deforestation-free ranchers (Arima et al. 2014a; Klingler, Richards, and Ossner 2018), in what we refer to as the "Cattle Moratorium." Still, despite high expectations for the effectiveness of these supply-chain commitments, studies found that the Brazilian moratoria had small (Heilmayr et al. 2020) to potentially no impacts on deforestation (Klingler, Richards, and Ossner 2018; Alix-Garcia and Gibbs 2017; Svahn and Brunner 2018; Macedo et al. 2012). In particular, the soy moratorium has been linked to a process of "indirect land-use change," as soybean fields started replacing pastureland more intensively, leading to an increase in the rates of cattle-driven deforestation in Amazonian agricultural frontiers (Arima et al. 2011; Barona et al. 2010; Richards, Walker, and Arima 2014). Similarly, other studies have identified loopholes in the monitoring of cattle supply chains allowing farms with illegal deforestation to sell cattle indirectly to slaughterhouses signatory to zero-deforestation commitments (Klingler et al 2018, West et al 2022).

2.4 Land tenure policies

Land tenure policies, such as the expansion of the protected area (PA) network and the official recognition of indigenous lands (ILs) are a key component of the PPCDAm (West and Fearnside 2021). Among the targets set by these policies was the creation of 50 million ha of PAs as part of the Protected Areas Program (ARPA; Portuguese acronym; established by Decree 4326 of 2002). Pfaff et al. (2015) found PAs in the Brazilian Amazon to have reduced deforestation by ~2% in comparison to counterfactuals during 2000–2008, whereas a similar analysis by Jusys (2018) found declining avoided deforestation in PAs, with the greatest conservation gains occurring between 2001–2004 and gradual reductions in avoided deforestation through 2005–2014. While PAs are generally associated with positive, but moderate, conservation outcomes (Miteva, Pattanayak, and Ferraro 2012), many Amazonian PAs continue to experience forest loss and fragmentation, often due to pressure from cattle ranching activities and illegal forest fires (Cabral et al. 2018).

Land tenure policies have also been influenced by the establishment of rural settlements established by INCRA (National Agency for Land Reform) that began in the 1970s and 1980s with a supporting road and highway network built to connect the northeastern and southeastern edges of the Amazon with the ports and markets in São Paulo, Brasília, and Belém (Barber et al. 2014; Nelson and Hellerstein 1997). INCRA settlements are strongly associated with deforestation (Brandão Jr., Barreto, and Souza Jr. 2012) including in nearby protected areas (Jusys 2018; Oldekop et al. 2016; Nolte et al. 2013). Yanai et al. (2017) estimated a loss of 41% of the original vegetation in these INCRA settlements established throughout the Brazilian Amazon.

2.5 Macroeconomic Influences

Deforestation is also influenced by macroeconomic trends including agricultural commodity prices and currency exchange rates (Arcand, Guillaumont, and Jeanneney 2008; Hargrave and Kis-Katos 2013). Assunção et al. (2015) estimated that nearly half of the avoided Amazonian deforestation during 2005–2009 was due to less-favorable economic conditions for agricultural expansion instead of the conservation policies in Brazil. Arima et al. (2014b) find deforestation to be positively correlated with soybean prices during 2008–2011, but to be negatively correlated to agricultural GDP and uncorrelated with cattle prices. In addition, Faria and Almeida (2016) argue that increased openness to trade also increased deforestation in the

Amazon between 2000 and 2010. On the other hand, the relationship between per-capita gross domestic product (GDP) and forest loss depends on national and regional contexts. Several studies suggest the marginal impact of per-capita GDP on deforestation is positive for low levels of income, but to become negative past a given income threshold level (Arcand, Guillaumont, and Jeanneney 2008; Barbier and Burgess 2001; Köthke, Leischner, and Elsasser 2013).

3. The Causal Chain from Satellites to Forest Cover

Satellite data do not impact deforestation rates directly. Policy must be in place to incentivize the use of the data to a specific end, but how policy enters into the causal relationship from satellites to forest cover is unclear. To understand this role of policy, we interviewed public agents (government officials and representatives of civil society organizations) and conducted a desk review (of laws, regulations, and government websites). We reviewed around 60 specific enforcement environmental laws, accounting over 500 pages of public documentation. In addition, we conducted interviews with 8 policy makers (majory career civil servants) from different Northern States (Para and Amazonas) and the Federal District (Brasilia), including Federal Environmental Agencies (IBAMA and MMA), State Environemtal Agency (SEMAS), Public Company that leads with CAR (EMATER), plus consultants and NGO representant . These interviews were initially guided by open ended questions with 5 number of follow ups. A second round of interviews were conducted with semi-structured questions to support the construction of our causal chain picture (Figure 3. 1).

Causal chains, or box and arrow diagrams that display a logical and order sequence of effects, are used across disciplines and policy domains to visualize such causal relationships (Qiu et al. 2018). Directed Acyclic Graphs (DAG) are a type of causal chain particularly helpful for visualizing the assumptions that underlie model specification and identification of effects (Sills and Jones 2018). These diagrams include three elements: (1) representations of dependent and independent variables (words or abbreviations in boxes), (2) arrows indicating the direction of causal effects, and (3) paths, (the combination of variables and arrows that link the treatment, or the independent variable to the outcome, the dependent variable) (Elwert and Winship 2014). These diagrams are parsimonious, focusing on the most important elements of the causal path (Huntington-Klein 2022). We use a DAG to represent insights obtained from open-ended interviews with public agents (representatives of Brazilian government agencies and civil society organizations) and distill their implications for our empirical analysis.

Our reduced form DAG can be expressed as follows, where satellite data is the treatment and deforestation is the outcome:

Figure 3.1. Reduced DAG

We expand upon this reduced model by considering the role of mediators (mechanisms that lie on the causal chain between treatment and outcome) and moderators (factors that lie off the causal chain but influence the level, direction, or presence of a relationship between treatment and outcome) in this relationship (VanderWeele 2009). Mediators[1] lie on the causal pathway, that is, they are caused by the treatment and they have a causal effect on the outcome. Moderators, on the other hand, are contextual factors not influenced by satellite data. Unlike confounders (variables that directly influence both assignment of treatment and the outcome), moderators can be omitted from empirical models without biasing the estimate. However, they are useful to include because they show for whom, when, or under what circumstances a relationship will hold. Moderators are also relevant to the external validity of a study because they identify the conditions under which a causal relationship holds. When there is no variation in a moderator in the study site, it is still important to recognize it as a potential necessary condition. On the other hand, mediators should only be included in "causal mediation analysis" (Keele, Tingley, and Yamamoto 2015) and not when the goal is to estimate the total effect of a treatment on an outcome.[2] Thus, the assumptions visualized in the DAG have direct implications for the empirical analysis, and in turn, the estimation results reflect those underlying assumptions about causality and our understanding of how satellite data is related to deforestation.

Empirical evidence suggests that monitoring and enforcement are significant determinants of environmental compliance in general (Gray and Shimshack 2011), and this is particularly important in the Brazilian Amazon, where strict laws have long been poorly enforced (Bauch et al. 2009), recent years have seen dismantling of enforcement capacity (Escobar 2020), and some have even argued that the public nature of satellite data can be used to compensate for law enforcement shortcomings resulting from weak institutional environments (Assunção, Gandour, and Rocha 2019). Further, the vast size of the Amazon means that effective enforcement depends on effective monitoring, which can both mediate the relationship between satellites and deforestation. Our interviews also suggest that policies themselves may also function as both mediators and moderators, and thus our causal assumptions in this realm also are key to developing specifications and interpreting results of empirical models.

[1] The term "mediator" is used differently in different fields and disciplines. In this paper, we use the term mediator to refer only to mechanisms on the causal chain between treatment and outcome. We use the term moderator to refer to conditions that are off the causal chain but influence effect sizes, acknowledging that in some literature, the term mediator is also used in this case. We use the term "external validity moderator" to refer to conditions on the causal chain that vary across countries and are therefore important to consider when thinking about applying this DAG to different countries.

[2] Another type of variable that can bias estimation results when included in an empirical model is a "collider", e.g. something caused by both the treatment and the outcome.

3.1 Policy as a Moderator (off the causal path)

Brazilian policies such as the Forest Code have long laid out definitions of what constitutes legal vs. illegal deforestation and thus determine how, where and for whom satellite data are used for monitoring and enforcement. In this sense, forest policies can be treated as moderators: in their presence, satellite data has a larger causal effect on deforestation. Because they are located off the causal pathway, they can be included as controls (possibly interacted with the treatment) in the estimation of the effect.

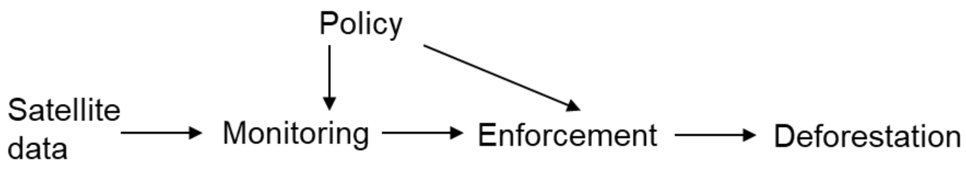

Figure 3.1a: *Suggested DAG having Polic*y as a Moderator.

3.2 Policy as a Mediator (on the causal path)

Brazilian policies such as the Priority List, colloquially known as the Black List, were conceived at least in part due to the existence of satellite data showing the spatial concentration of deforestation in a small fraction of the jurisdictions in the Amazon. In this sense, forest policies can be treated as mediators, located on the causal pathway, and therefore not included as controls (although possibly considered in causal mediation analysis) in the estimation of the effect.

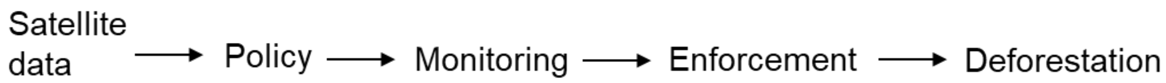

Figure 3.2: Suggested DAG having Policy as a Mediator.

For policies implemented after our treatment, we obtain upper and lower bounds of the treatment effect by assuming that the policies are either mediators or moderators, respectively, generating two different counterfactual estimates.

4. Data

We collected and merged data from eight different sources and reclassified and corrected the land-use/cover data from MapBiomas to create a 2000-2015 deforestation time-series that controls for the implementation of conservation and development policies, as well as a large number of controls and biophysical characteristics at the municipality level (Table 1). Our study region includes the 783 municipalities in the Legal Amazon.

4.1 Deforestation and Carbon Stock Data

Following West et al. (2020), we reclassify, filter, and summarize pixel-wise deforestation at the municipality level for the 2000–2015 period base on annual land-use/cover (LUC) raster maps (30 m resolution) from the MapBiomas (v.6) project (Souza et al, 2020)[3]. Spatiotemporal filters were applied to ensure consistency in annual deforestation across the time series by: (i) replacing each cloud pixel with the pixel's LUC class in the next observable year or when the pixel's land use cover class was unobserved throughout the study period mask them from the analysis; (ii) masking pixels that transitioned from forest to water (and vice-versa); (iii) masking forest pixels that transitioned to another class in one year, but transitioned back in the next; and (iv) masking natural non-forest pixels that transitioned to forest, which included natural savannas that were classified as non-forest in some years but forest in others.[4]

Table 1: Variable Definitions and Sources

	definition	Source
Annual deforestation	thousands km^2 (MapBiomas)	https://mapbiomas.org
Forest Area	thousands km^2 (MapBiomas)	https://mapbiomas.org
Soy Price	world soy price, US$/mt, real	https://databank.worldbank.org/databases/commodity-price-data
Soy Suitability	Suitability of soils for soy	author calculations
Beef Price	world beef price, US$/kg, real	https://databank.worldbank.org/databases/commodity-price-data
Pasture Suitability	Suitability of soils for pasture	author calculations
INCRA	Amount of land formally settled INCRA settlement size, thousand km2	http://painel.incra.gov.br/sistemas/index.php
Protected areas	protected areas (sum of state, federal and indigenous), ten thousand km2	http://www.icmbio.gov.br/
Environmental Fines	total environmental fines paid, ten thousand reais	https://servicos.ibama.gov.br/ctf/publico/

[3] The full description of the project can be found at **http://mapbiomas.org**.
[4] The algorithm was implemented in Google Earth Engine and is publicly available (https://github.com/KA-Jones/Voluntary_REDD_Analysis_GEE) and compared with other sources of deforestation in the Amazon

Priority list of municipalities	dummy variable indicating membership on list	http://www.mma.gov.br/informma
Soy moratorium	dummy for 2006+	author calculations
Cattle moratorium	dummy for 2009+	author calculations
Gross Domestic Product (GDP)	Value of all final goods and services, real reais	https://sidra.ibge.gov.br/Tabela/5938
Election	Dummy for election years	author calculations
Exchange rate	Real effective exchange rate with International $	https://data.worldbank.org/indicator/PX.REX.REER

4.2 Policy Data

The dataset includes policies that existed prior to the introduction of DETER and policies that were introduced after. Protected Areas include the total area per municipality of all categories of state and federal protected land and all indigenous territories, based on shapefiles from ICMBIO, the Brazilian federal conservation agency. In some cases, land classified under different designations overlapped, for example a given area of land fell within an indigenous reserve and a state protected area. These areas were subtracted to ensure the total area protected under any designation was correct. Data on environmental fines are published by IBAMA, the federal Forest Police. We use reported information on fines that were actually paid as many of the issued fines are later waived on appeal. The area of INCRA settlement is provided by INCRA in the form of shapefiles, which we processed for each municipality.

The Priority List variable is a binary variable, equal to 1 if the municipality was included on the Priority List in any prior year. 35 municipalities were placed on the list in 2008, and others were added in later years, totaling 52 by 2012. Some municipalities were taken off the list, but we consider them 'treated' for the full period because the effects of policy may persist even after their removal. The soy moratorium was introduced in 2006 and the cattle moratorium in 2009 for all municipalities in the Amazon biome. Other studies have used measures of soy or beef production to distinguish between municipalities affected by the supply chain measures and municipalities that were not affected. However, production is likely to be endogenous to the policies themselves. In addition, the policies are targeted at new deforestation, which is more likely in places with remaining forested land. We use binary variables for before and after the introduction of each of the moratoria, and interact these with lagged forest area and the average suitability of remaining forest area for soy or beef production respectively.

4.3 Biophysical and Macroeconomic Controls

We constructed suitability maps for soy and pasture also based on the MapBiomas data (v.6). First, we mapped the areas of both land uses in 2000. These areas were sampled and used to parameterize a machine-learning algorithm, SimWeight (Sangermano, Eastman, and Zhu 2010), available from the TerrSet software (v.18.2), which was used to construct the suitability maps for both land uses in the forest area in the Brazilian Legal Amazon. Suitabilities were computed based on 16 biophysical maps obtained from Brazil's National Space Research Institute (INPE; Portuguese acronym): (1) average annual temperature; (2) average diurnal temperature variation; (3) isothermality; (4) temperature seasonality; (5) maximum temperature of the hottest month; (6) minimum temperature of the coldest month; (7) annual thermal range; (8) annual precipitation; (9) precipitation in of the wettest month; (10) precipitation in of the driest month; (11) seasonality of precipitation; (12) drainage potential; (13) elevation; (14) slope; (15) soil type, and; (16) height above the nearest drainage. Lastly, we computed annual average suitability indices at the municipality level, for the Brazilian Legal Amazon region, based on the forest cover left within each municipality in each year from 2000 to 2020.

Soy and beef prices, expressed in real Brazilian reais, are from the World Bank Global Commodities database. These do not vary spatially, so we include them in the regression model interacted with 1-year lagged forest area and with average suitability for soy and pasture respectively. This is on the basis that the greatest response to changes in prices is expected in locations with land available to deforest and with land that is suited to the commodity in question. Municipal GDP in real Brazilian reais is published by IBGE, the federal statistics agency. We constructed a binary variable equal to 1 in years that a federal election was held and included annual values of the real effective exchange rate compared with international values from the World Bank database. These variables do not vary spatially within Brazil and are used to capture annual variation across the sample.

4.4 Descriptive Statistics

Annual deforestation rates in the Brazilian Amazon declined post-2004. Our data suggest that the 5-6 year averages between 2000 and 2015 fell from approximately 38,000 km^2 in 2000-2004 to 14,500 between 2010-2015 (Table 2).

At the same time, protected areas have been expanded and policies to counter deforestation have increased, which should act to constrain deforestation.

Table 2: Descriptive Statistics
(mean with standard deviation in parentheses)

	2000-2004	2005-2009	2010-2015
Annual deforestation, thousands km^2	38.48	23.94	14.50
	(81.88)	(57.20)	(27.89)
Forest Area, thousands km^2	4922.43	4777.32	4691.29
	(12647.69)	(12538.23)	(12468.39)
Soy Price	3.07	3.92	4.71
	(0.41)	(0.78)	(0.45)
Soy Suitability	4.64	4.62	4.61
	(7.71)	(7.68)	(7.67)
Beef Price	2.84	2.97	4.00
	(0.18)	(0.14)	(0.49)
Pasture Suitability	17.03	16.99	16.96
	(7.25)	(7.24)	(7.23)
INCRA	0.26	0.55	0.68
	(0.81)	(2.06)	(2.44)
Protected areas	0.15	0.23	0.28
	(0.57)	(0.85)	(0.99)
Environmental Fines	8.39	9.01	4.22
	(38.33)	(64.18)	(62.24)
Priority list of municipalities	0.00	0.02	0.06
	(0.00)	(0.14)	(0.24)
Soy moratorium	0.00	1.00	1.00
	(0.00)	(0.00)	(0.00)
Cattle moratorium	0.00	0.20	1.00
	(0.00)	(0.40)	(0.00)
Gross Domestic Product (GDP)	1.5e+05	2.7e+05	5.3e+05
	(8.8e+05)	(1.5e+06)	(2.7e+06)
Election	0.25	0.20	0.33

	(0.43)	(0.40)	(0.47)
Exchange rate	60.73	84.43	89.31
	(2.25)	(6.23)	(11.05)

5. Estimation of counterfactual outcomes

We use the following model to estimate annual area of deforestation for municipality i (Y_{it}) as a function of the implementation of near real-time satellite monitoring ($DETER$), municipality fixed effects (μ_i), covariates with time-space variation including agricultural commodity prices, lagged forest area, lagged GDP, and policies that encourage and deter deforestation (X_{jit}), and macroeconomic controls (including the real effective exchange rate and real soy and beef prices) that vary over time but not between municipalities (Z_{kt}):

$$Y_{it} = \beta_0 + \beta_1 DETER_t + \gamma_j X_{jit} + \sum \delta_j DETER * X_{jit} + \sum \delta_i Z_{kt} + \mu_i + u_{it}$$

All explanatory variables (Table 2) are interacted with *DETER* to capture changes in their impacts on deforestation before and after 2004. The exception to this is conservation policies that were implemented subsequent to 2004.

The effects of the near real-time satellite monitoring (*DETER*) are estimated using a binary variable for pre- vs. post-2004, the year of the introduction of the PPCDAm. While the initiation of the DETER program was a major feature of this package of policies, other measures were implemented at the same time with the same objective of reducing deforestation. In particular, Protected Areas and application of environmental fines were expanded after 2004. We include these variables in the model to control for independent effects of their expansion as part of PPCDAm in order to isolate the satellite monitoring component of the package. Although the other PPCDAm initiatives did not rely on DETER, the use of near real-time monitoring is likely to have increased their effectiveness. We therefore also interact the Protected Areas and environmental fines with DETER to account for any changes in their effectiveness when combined with real-time monitoring.

This model is used to predict a simulated baseline deforestation, in which *DETER* is equal to 1 from 2004 onwards, and two estimates of counterfactual deforestation in which *DETER* is equal to 0 in all years (i.e. under the assumption that it was never introduced). The simulated deforestation differs from actual satellite-derived measurements (our Reference Case, Figure 2) because our model captures the impacts of commodity prices, forest conservation policies, and federal economic development programs, but does not account for other idiosyncratic influences on deforestation. We estimate the difference in deforestation that can be attributed to use of the *DETER* monitoring system by comparing the simulated baseline deforestation under the assumption that *DETER* was implemented in 2004 and used for policy enforcement in all subsequent years with counterfactual estimates of deforestation simulated by the same model under the assumption that *DETER* was not implemented, but other explanatory variables remained unchanged.

We estimate two different counterfactuals to account for the fact that important policies were introduced to control deforestation after 2004, namely the Priority List and the soy and cattle moratoria. We cannot estimate the impacts of DETER on the effectiveness of these policies since there is no spatial variation in DETER that could be used to identify these models. However, it is likely that the availability of near real-time satellite monitoring contributed to their impacts on deforestation. It is also possible that the availability of satellite information may have increased public pressure for forest conservation policies. In this case, it could be argued that in the absence of DETER the policies would not have existed at all. The two versions of our without-satellites counterfactual scenarios are therefore based on different assumptions about where the Priority List and the soy and cattle moratoria (policies) lie on the causal path from satellites to deforestation.

In Counterfactual 1, which represents a lower bound on the impact of satellite monitoring, we assume that the policies introduced after 2004 would have been fully effective without near real-time satellite monitoring, and therefore were not influenced or impacted by the introduction of DETER. In this case, the policies lie off the causal path from satellites to deforestation, and act as moderators on the effect of DETER in our regression model. To estimate deforestation in this scenario, we include the policies in the estimation as controls and hold the policies at their baseline levels (i.e., either 0 or 1) when predicting deforestation area with DETER assumed to be zero.

Counterfactual 2 represents an upper bound on the impact of satellites. For this scenario, we assume that the Priority List and soy and cattle moratoria would have had zero effectiveness if near real-time satellite data on deforestation were not available. This lack of effectiveness could be because the policies existed, but could not be successfully enforced, or because they were not implemented at all. In either case, the policies are assumed to be a function of DETER and to lie on the causal path between satellite monitoring and deforestation, and represent one of the mechanisms through which satellite information reduces deforestation. To estimate deforestation under this scenario, we follow the literature on causal mediation analysis (Keele, Tingley, and Yamamoto 2015). This involves setting the Priority List and soy and cattle moratoria to the values they would have taken in the absence of DETER (i.e. 0 in all cases) to simulate the no-satellites estimate of deforestation, and to their actual values for the with-satellites estimate.

6. Results

We estimate the direct impact of DETER on deforestation and the extent to which DETER alters the impacts of other drivers of deforestation, including prices; biophysical characteristics such as municipal forest area and suitability for soy and pasture; and pre-existing policy instruments such as protected areas, environmental fines and INCRA settlements.

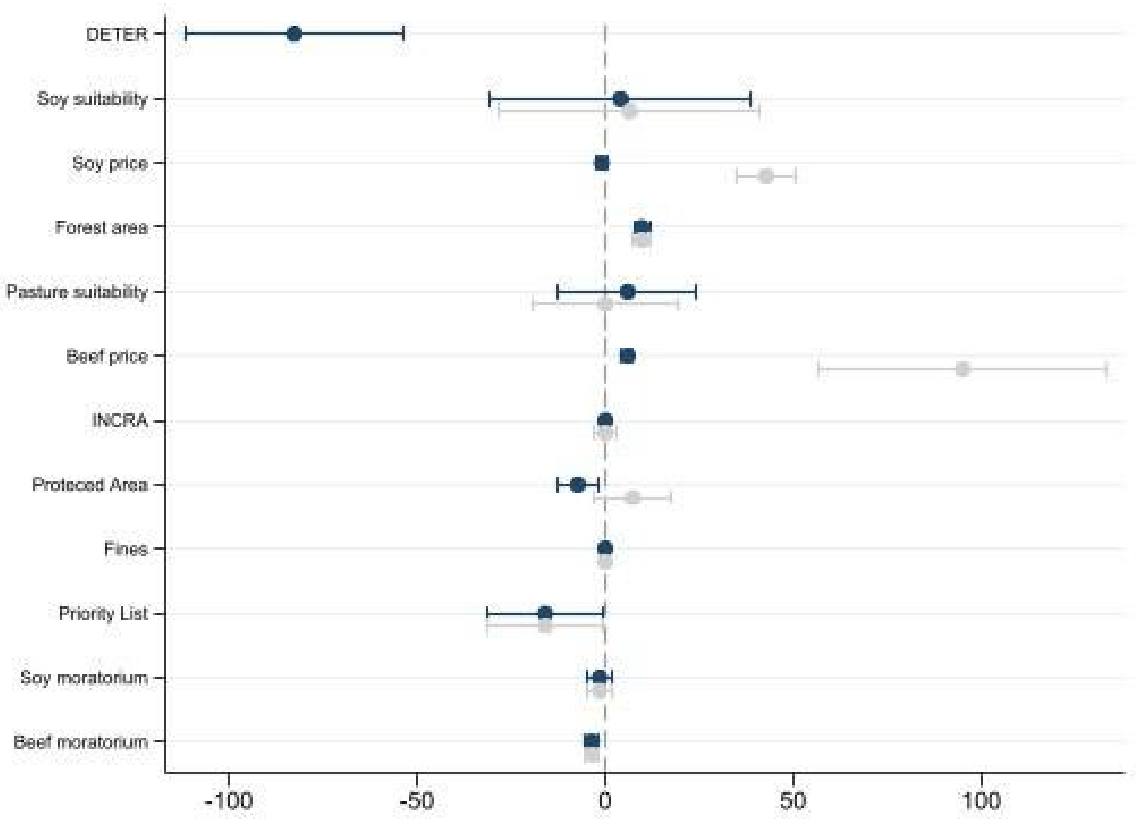

Figure 1: Average Marginal Effects of DETER. The blue point estimates are the impacts with DETER, with 95% confidence intervals represented with the blue bars around these points. The gray point estimates are the impacts without DETER, and the 95% confidence intervals are represented by the gray bars around these points. DETER is shown to have significant impacts when the bars do not overlap.

Table 3 and Fig. 1 show the marginal effect of each variable on deforestation before and after the introduction of DETER. We observe a large decrease in deforestation as a direct response to the introduction of DETER as well as indirect effect through changes in the effects of other variables. In particular, there are large reductions in the responsiveness of deforestation to prices of key agricultural commodities, soy and beef. Prior to the introduction of near real-time monitoring, deforestation increased in years with high commodity prices. After the introduction of DETER, beef prices still positively affect deforestation but to a lesser extent, and soy prices are not significantly related to deforestation. Among the policies that were expanded as part of the PPCDAm package of measures, we find that Protected Areas are not effective in reducing deforestation prior to DETER, but do have a negative and significant effect afterwards. We do not observe any effect of environmental fines, with or without satellite monitoring. This may be because the fines were frequently not enforced, but could also be because we do not account for the inherent selection bias in environmental fines, which are typically imposed where there are environmental infractions (such as high deforestation).Figure 2 compares estimates of total annual deforestation under a baseline scenario in which near real-time satellite monitoring (DETER) was adopted in 2004 and subsequent policies such as the Priority List and soy and cattle moratoria were also implemented with two counterfactual scenarios in which DETER was not implemented. Counterfactuals 1 and 2 are representations of deforestation without real-time satellites, both allowing for differential impacts of commodity prices and pre-existing policies on deforestation before and after DETER. Deforestation is substantially higher post-2004 in both the Counterfactual 1 and 2 simulations, where DETER is not introduced, than in the baseline simulation where DETER is initiated in 2004. These differences can be attributed to both the direct effect of the introduction of DETER on deforestation, and the effect of DETER on the relationship between commodity prices and policies on deforestation.

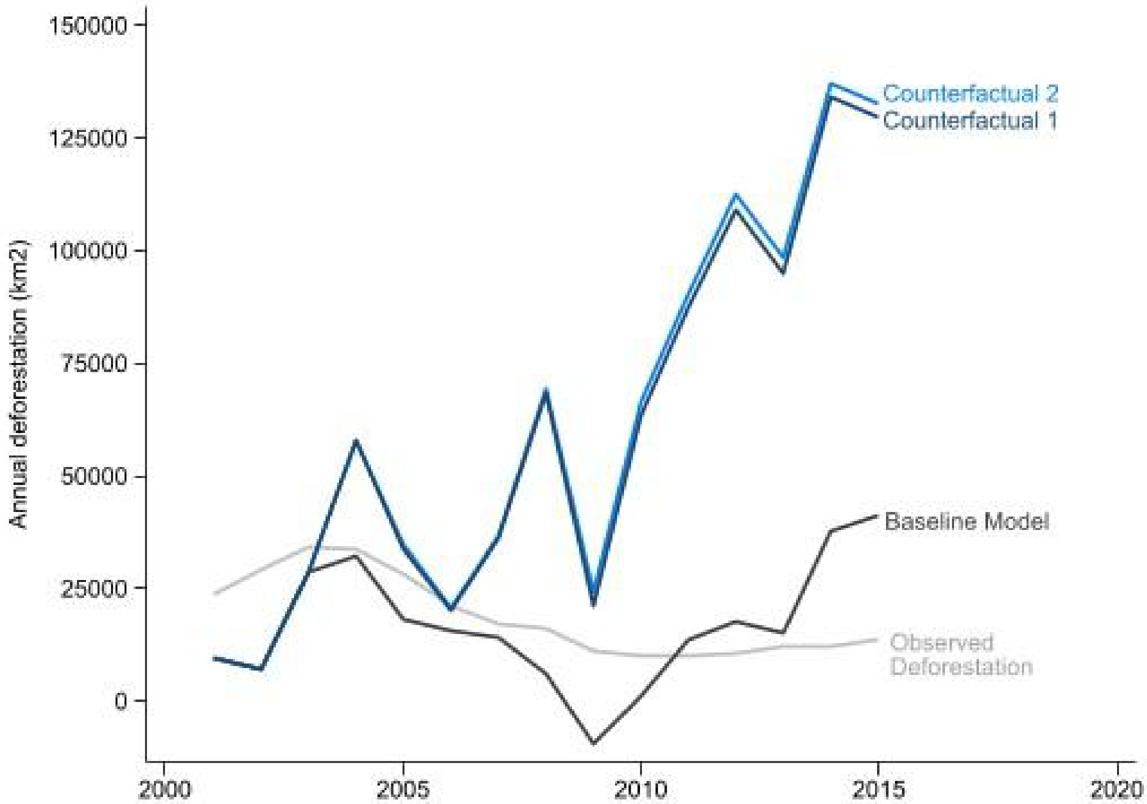

Figure 2: Estimated Total Annual Deforestation with and without Satellites. Counterfactual 1 assumes that deforestation policies act as moderators of DETER, are not on the causal path and should be controlled for in the estimations of causal impact. Counterfactual 2 assumes that deforestation

policies act as mediators of DETER, are on the causal path, and should not be controlled for in the estimations of causal impact.

The Counterfactual 1 Lower Bound scenario in this figure assumes that the Priority List and the soy and cattle moratoria would have been as effective in the absence of DETER as they were in the Baseline scenario where DETER was introduced in 2004. The Counterfactual 2 Upper Bound scenario assumes that the Priority List and the soy and cattle moratoria would not have had any impact on deforestation in the absence of DETER. In other words, it assumes that if near real-time satellite data had not been available the policies either would not have existed at all or would have had zero effectiveness. In this case, their additional impacts should also be attributed to the satellite monitoring. The Priority List and the soy and cattle moratoria significantly reduce deforestation in our model (Table 3). Because of this, estimated deforestation is higher in Counterfactual 2 where we assume that if DETER had not been in place, these policies would not have had the effects that they did in practice. However, their effects are relatively small in aggregate because they only influenced deforestation in a relatively small subset of municipalities. The Priority List measures were only ever implemented within our study period in 52 out of 783 municipalities, and the effects of the soy and cattle moratoria were only observed in municipalities with suitable biophysical conditions for soy production or pasture.

We estimate avoided deforestation under our two counterfactual scenarios based on the difference between baseline and each counterfactual, for every municipality-year. The total avoided deforestation for the region as a whole is estimated at approximately 467 million square km. As suggested by the annual deforestation estimates, we do not see a large difference in aggregate deforestation whether we assume that the effectiveness of later policies was due to DETER or that they would have been effective regardless.

We also disaggregate the estimates of avoided deforestation by state. We see the largest absolute areas of avoided deforestation in Mato Grosso, Pará, and Amazonas, which is unsurprising as these states also have the largest total area. We therefore also estimate these differences as a percent of the state size (Figure 3). The old frontier states of Mato Grosso, Pará, and Rondônia have somewhat higher percentages of avoided deforestation on average than other states; followed by the interior states of the new frontier: Acre, Amazonas and Roraima. Avoided deforestation is highest as a percent of total area in Maranhão, Tocantins Rondônia and Mato Grosso. These states lie within the old frontier regions of the Amazon. Due to the effect of DETER in mitigating the responsiveness of deforestation to soy and beef prices, our results suggest that deforestation would have been even higher in this active frontier region without near real-time satellite monitoring.

In the majority of states, we do not see large differences between the two counterfactuals, but there is a general pattern that Counterfactual 2 is higher in some of the old frontier states and none of the new frontier states. This suggests that the policies implemented after 2004 had a larger effect in the states in the old frontier, where deforestation rates have been historically higher. While the effects of the Priority List and the cattle moratorium were distributed fairly broadly across the region, the effects of the soy moratorium were greatest in locations that were suitable for soy production. These are concentrated in Mato Grosso, so assumptions about whether the moratorium would have been effective in the absence of DETER have greater effects on these estimates of avoided deforestation.

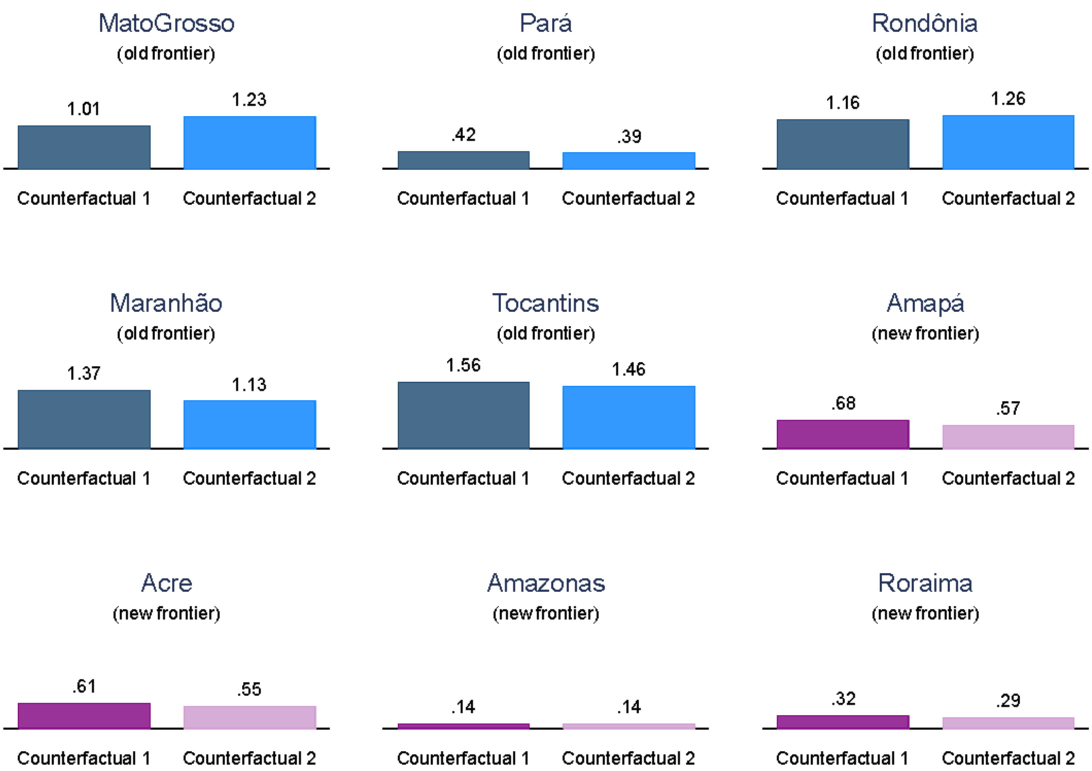

Figure 3: Amount of Avoided Deforestation, Percent of the State Area. The percent of the state that avoided deforestation according to Counterfactuals 1 and 2 for 2000-2015 is no more than 2% of the total area of any state. The old frontier are states that were largely settled during the initial development phase overseen by INCRA and beginning in the late 1960s- early 1970s, while the new frontier includes states that have historically been protected from large scale deforestation due to their distance from Brasilia and the more populated south (Schielein and Börner 2018). The impact of Counterfactual 2 (which assumes that policies are on the causal path and are not controlled for in the estimations) is larger in some of the old frontier where more of the deforestation policies have been focused and smaller in the new frontier.

6.1 Avoided carbon emission estimates

We estimated the volume of avoided carbon emissions due to the non-use of satellites to inform conservation actions at the municipality level for 2000-2015 using four carbon/biomass-density maps available for the Brazilian Amazon (Avitabile et al. 2016; Baccini et al. 2012; 2017; Englund et al. 2017; Figure 4). Following West et al. (2019), carbon/biomass values were converted to tCO_2 ha^{-1} and pixel-wise averages were computed for the remaining forest areas in the Legal Amazon region by 2015 per municipality (Figure 5). Standardized carbon emission reductions were estimated based on our Counterfactual 1 deforestation (km^2; lower boundary) times the average CO_2 stock per km^2 of the remaining forest areas by 2015 within each municipality, divided by the size of the municipality (km^2).

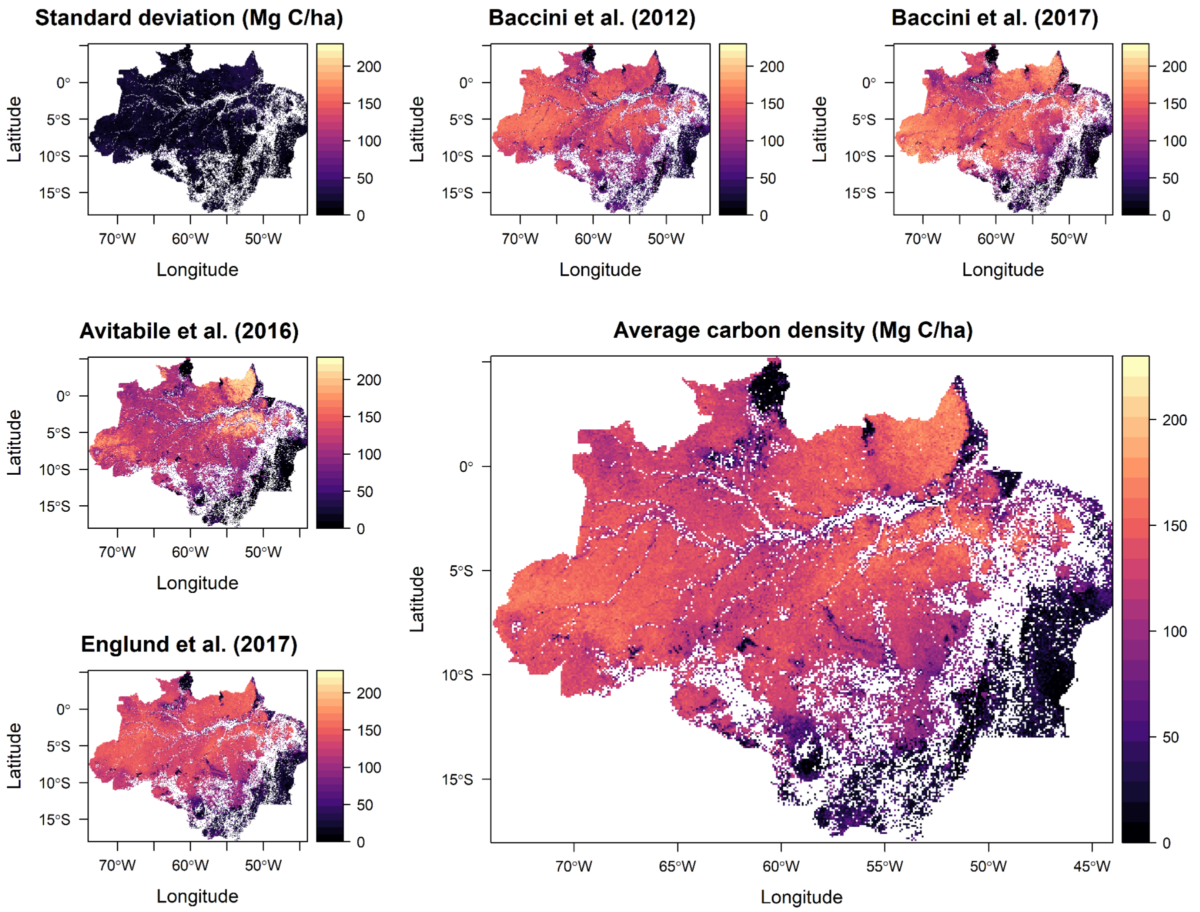

Figure 4. Carbon-density maps for the 2015 forest areas in the Legal Brazilian Amazon. Average and standard deviation maps computed based on Avitabile et al. (2016), Baccini et al. (2012; 2017), and Englund et al. (2017).

Based on the Counterfactual 1 estimates, 466,904 km^2 of forest were saved from 2000 to 2015 in the Legal Amazon region due to the presence of satellites. This amounts to an average avoided emission of 12.4billion tCO_2 to the atmosphere during our study period. At the municipality level, standardized carbon emission reductions ranged from -9 to 288,611 tCO_2 per municipal km^2 (Figure 5). Most reductions were linked to municipalities in Northern Amazon, but substantial within-state differences can be observed across the whole region.

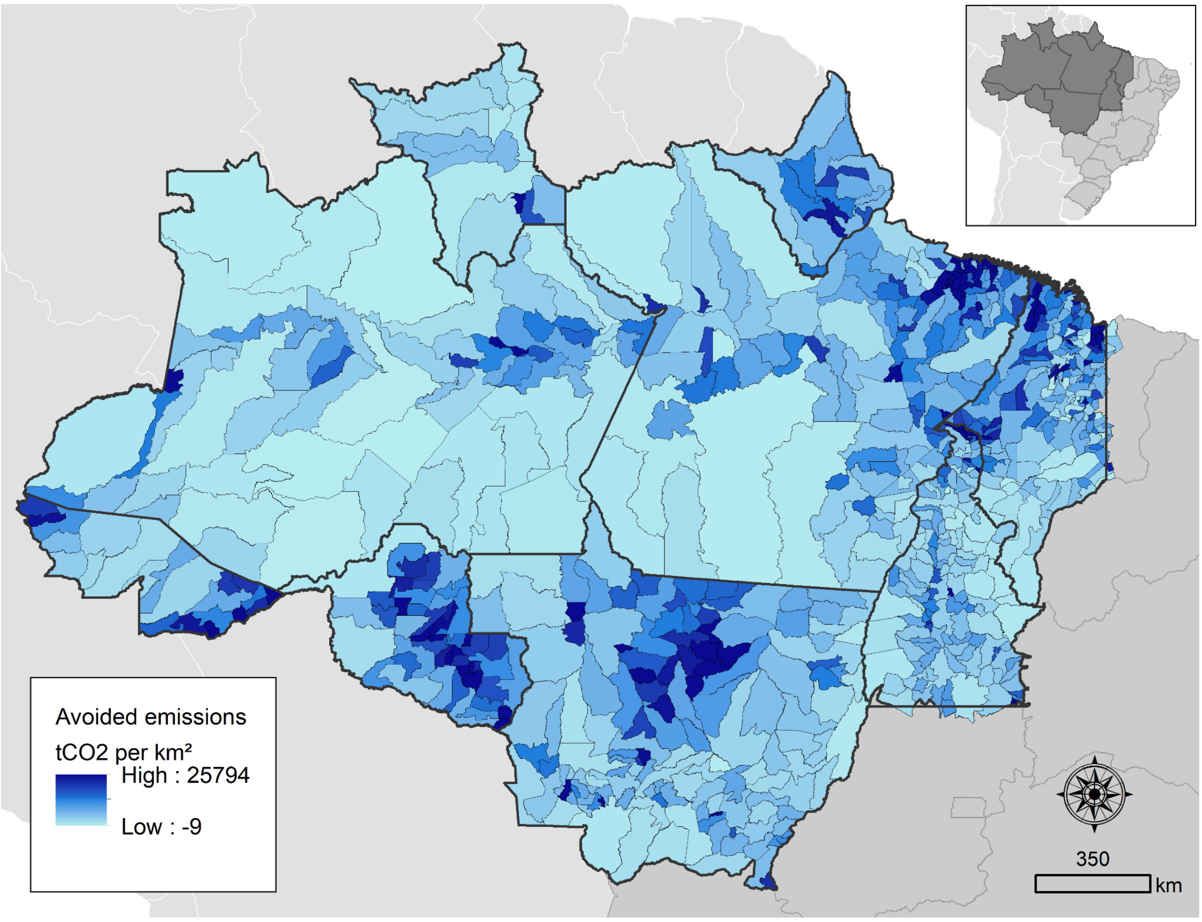

Figure 5. Estimates of Avoided Carbon Emissions 2000-2015. Carbon and biomass values are converted to tCO_2 and pixel-wise averages were computed for the remaining forest areas in the Legal Amazon region by 2015 per municipality. These values are applied to estimates of avoided deforestation per municipality to determine the amount of avoided carbon.

6.2 Benefits and costs of satellites: avoided deforestation and avoided CO_2 emissions

We estimate the benefits of satellites in two ways. First, we estimate the benefits of each hectare of avoided deforestation in regards to the value of ecosystem services preserved (the provision of habitat for species, carbon sequestration, water regulation, recreation and ecotourism). These estimates of the willingness to pay to avoid deforestation range from US$410-3,168/ha/year (Brouwer et al. 2022; Abdeta 2022; Siikamäki and Newbold 2012; Strand et al. 2014). Our lower bound is from a meta-analysis of the Brazilian valuation literature (Brouwer et al. 2022). Our upper bound is derived from U.S. and Canadian household WTP to finance the protection of the Amazon (Siikamäki and Newbold 2012)[5]. Second, we estimate the average amount of CO_2 avoided in an average year (in this declining deforestation time period) and estimate the social costs of carbon (SSC) avoided. Estimates of the SSC range from $24-$185 (Rennert et al. 2022; van der Ploeg, Emmerling, and Groom 2022; Lemoine 2021;

[5] This value of $3,168/ha/year translates to $92 per household per year, which fits within the upper bounds of the values reported in Abdeta (2022) and Strand et al. (2014).

Reguant 2021; Pindyck 2019; Cai and Lontzek 2019; Tol 2019). We use the \$51/tCO2 (IWG 2021) as lower bound, \$185/tCO_2 (Rennert et al. 2022) as an upper bound and \$85/tCO2 (van der Ploeg, Emmerling, and Groom 2022) as a mid-range estimate (Table 4).

Table 4: Cost and Benefit Ranges for Avoided Deforestation and CO2 Emissions

	Lower bound	Middle bound	Upper Bound
Benefits			
Avoided deforestation	\$410/ha/year		\$1,368/ha/year
Avoided CO2	\$51/tCO2	\$85/tCO2	\$185/tCO2
Costs			
PRODES and INPE budgets	\$3.5 million/year	\$227 million/year	\$543 million/year

To estimate the average benefits of satellites for an average year in this declining deforestation time period, we first sum the hectares of avoided deforestation and carbon emissions by year and estimate the yearly average for this time period: 2004-2015 (we assume no deforestation is avoided prior to the implementation of DETER in 2004).

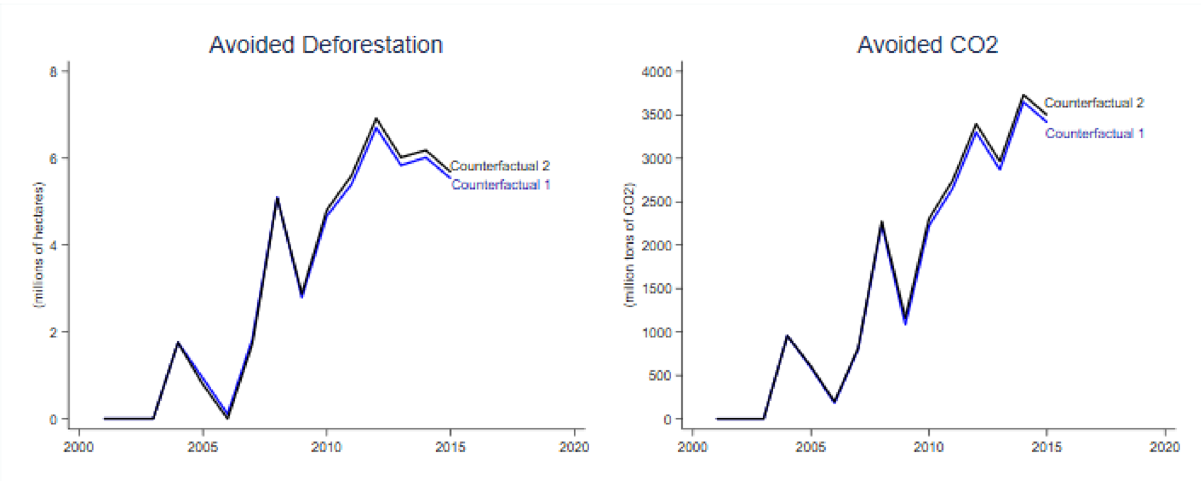

Figure 6. Estimates of Avoided Deforestation and CO_2 Emissions 2001-2015. Estimations are in millions of hectares per year and the millions of tons of CO_2. The annual average of these values are used in the calculations in Table 4.

These annual averages calculated over this time period are multiplied by the values above in Table 4 and presented in Table 5.

Table 5: Estimation of the Costs and Benefits of DETER
(millions of US$)

	Lower Bound		**Middle Bound**		**Upper Bound**	
	Counter-factual 1	Counter-factual 2	Counter-factual 1	Counter-factual 2	Counter-factual 1	Counter-factual 2
Benefits						
Avoided deforestation	1,595	1,621			5,323	5,408
Avoided CO_2	52,748	54,291	87,913	90,486	191,341	196,940
	Lower bound		Middle Bound		Upper Bound	
Costs						
	3.5		227		543	

According to our calculations, the benefits range from US$1.6-5.4 billion/year when the estimate is made using a willingness to pay to preserve the Amazonian forest (which includes the benefits of a suite of ecosystem services). This represents the benefits to the average household in Brazil (the lower bound) and the Global North (the upper bound). The total benefits are orders of magnitude higher, ranging from US$53-197 billion/year, when including the global costs of avoided CO_2 emissions.

The costs of satellites can be inferred from the program costs of PPCDAM (Table B1) and compared to the INPE (Instituto Nacional de Pesquisas Espaciais) annual budget (Table B2) from the Ministry of the Environment's budget. The PPCDAM mean annual expenses were approximately US$543 million per year between 2007-2014 (Castelo et al. 2018). This upper bound includes the budget for land planning, monitoring, and sustainable development (Table B1). We use the average annual budget for the later time period (20011-2014) US$227 million as the middle bound, assuming the program became more cost effective over time. A lower bound on the costs of satellites is the annual budget of the Brazilian space agency. This is approximately US$4 million per year for our time period according to data downloaded from Sistema Integrado de Planejamento e Orçamento do Governo Federal (Table B2). A second source of information on the INPE budget estimates the annual budget of INPE (specifically to address PPCDAM and DETER) at approximately US$3 million per year for the time period of 2010-2020 (Monteiroa et al. 2020). We use the average of these two values as our lower bound. Finally, our last source of data on costs is the Ministry of the Environment budget. This includes expenses for the management (US$11.4 billion/year) and control (US$1.4 billion) of environmental laws, and used to confirm that the PPCDAM is below and a portion of this budget (Table B4).

According to our estimates, the net benefits of satellite monitoring in this time period of declining deforestation (2004-2015) are positive at the local scale, that is when considering the suite of ecosystem services and the WTP to preserve Amazon rainforest for the average household. Depending on the benefit and cost assumptions, this value is as low as US$1 billion per year[6] and as high as US$5.4 billion per year[7]. The net benefits are also positive at the global scale, that is when estimating the benefits of the avoided CO_2 emissions using the social cost of carbon. Depending on the benefit and cost assumptions, this value is as low as US$54 billion per year[8] and as high as US$197 billion per year[9].

7. Discussion and conclusions

In 2004, Brazil began using near-real-time satellite information through the DETER program to detect and report illegal deforestation. This was the start of a substantial drop in rates of deforestation in the Brazilian Amazon that coincided with a period of overlapping public and private deforestation and development policies. Multiple changes in the macroeconomic and policy environments occurred simultaneously, including an expansion in protected areas, increased application and enforcement of environmental fines, and changes in commodity prices. To account for and control for these factors, we estimate the change in deforestation after 2004 while conditioning on the other changes that occurred simultaneously to separate the effects of DETER from other influences on deforestation. It is also possible that real-time satellite monitoring changed the effectiveness of fines and protected areas while also altering the incentives for deforestation provided by high commodity prices or regional development policy. We use interactions within our empirical model to account for ways that DETER changed the effects of pre-existing drivers of deforestation, and incorporate this in our estimates of counterfactual deforestation in the absence of DETER. Our DAG highlights two possible assumptions about policies that were implemented after DETER: we obtain a lower bound on counterfactual deforestation by assuming that those policies are completely independent and off the causal path, and we obtain an upper bound on counterfactual deforestation by assuming that those policies are mediators on the causal pathway and thus part of the effect of DETER..

We find that the initially positive relationship between commodity prices and deforestation and the positive relationship between areas of INCRA settlement and rates of deforestation no longer exist after 2004. Our results indicate that DETER has a large direct, and immediate, effect on deforestation in 2004 and that DETER alters the estimated future rates through indirect effects on other factors that influence deforestation. In total, annual deforestation is substantially higher in the counterfactual scenarios where DETER was not introduced, with

[6] The Counterfactual 1 lower bound minus the upper cost bound.
[7] The Counterfactual 2 upper bound minus the lower cost bound.
[8] The Counterfactual 1 lower bound minus the upper cost bound.
[9] The Counterfactual 2 upper bound minus the lower cost bound.

the difference increasing towards the end of the study period. In total we estimate the amount of avoided deforestation is approximately 467-471 thousand km^2 between 2001-2015 according to our lower and upper bounds identified in Counterfactuals 1 and 2. This is an area that is larger than the state of California and more than twice the amount of deforestation recorded in that region in the same time period (282 thousand km^2). We also estimate the amount of CO_2 emissions avoided and find these totals to be about 12 billion tons.

Our benefit-costs analysis suggests that the net benefits of satellites are substantial (US$1-5.4 billion/year) when estimating benefits using the WTP to preserve Amazon rainforest, and between US$54 billion/year and US$197 billion/year when estimating the benefits of avoided CO_2 emissions.

Brazil was an early adopter of near-real-time satellite deforestation alerts, but high-frequency satellite data has become more widely available to tropical countries in recent years. For example, Global Forest Watch has worked with varied partners in the tropics to provide GLAD rapid deforestation alerts since 2014, and in 2020, Norway's International Climate and Forest Initiative offered freely available high-resolution monthly deforestation data to any user. Our findings suggest that this type of data can make important contributions to reducing deforestation, but these contributions will depend on how the satellite data are used, made public, and the corresponding support (or lack of support) by public and private agencies. We found that public and private forest conservation policies that were implemented after the introduction of DETER significantly reduced deforestation. However, we cannot determine how effective they would have been in the absence of DETER. Certainly, these policies relied on satellite information, but they used both low- and high-frequency data. We therefore estimate lower and upper bounds based on the assumptions that the policies would have been equally effective without DETER or totally ineffective without DETER. The reality is likely to lie between these bounds, which would indicate that the combination of access to near-real-time satellite data and the motivation to use the data in novel ways can be even more effective than using the data for pre-existing policies and enforcement.

Finally, we estimate the benefits of satellites using a time period of declining deforestation. Deforestation started to increase in the Brazilian Amazon after 2012, and has been at decade highs in recent years. Actually, rates in 2021 were the highest since 2006 (INPE 2021) and are on target to be higher in 2022. This reversal highlights that the effectiveness of deforestation alerts and satellite data depends on the willingness to enforce existing forest laws and penalize violations. In the absence of political will to constrain deforestation, the increasing public availability of high-frequency data raises global awareness of increases in deforestation. This can generate external pressures for conservation, for example through supply chain initiatives developed through global commodity markets, and external pressure from NGOs, international organizations and individual foreign governments to enforce and strengthen policy.

Table 3: Marginal effects of time-varying covariates before and after DETER on annual area of deforestation 1: Before DETER; 2: After DETER

	(1) Area of deforestation, no munic FE, no year FE	(2) Area of deforestation, with munic FE, no year FE
1.DETER		
1._at	-48.81	-66.33***
	(38.99)	(15.68)
2._at	-48.81	-66.33***
	(38.99)	(15.68)
soy suitability index for Amazon biome		
1._at	4.842***	6.769
	(1.469)	(17.78)
2._at	1.810***	4.320
	(0.220)	(17.68)
world soy price, $/mt, real		
1._at	27.58***	39.17***
	(7.765)	(4.416)
2._at	-1.306	-0.160
	(2.524)	(0.954)
Lag Forest Area (1000km-sq)		
1._at	1.317	9.838***
	(1.567)	(1.228)
2._at	0.780***	9.721***

	(0.0535)	(1.108)
pasture suitability index for Amazon biome		
1._at	-2.145	-0.434
	(4.069)	(9.785)
2._at	2.053***	5.448
	(0.140)	(9.367)
world beef price, $/kg, real		
1._at	55.49	72.86***
	(53.63)	(20.05)
2._at	9.899***	7.469***
	(2.872)	(1.411)
incra settlement size, number of hectares		
1._at	1.626	0.109
	(3.199)	(1.645)
2._at	-0.733**	0.126
	(0.297)	(0.285)
protected areas (sum of state, federal and indigenous), thousands km2		
1._at	-1.967	7.432
	(11.99)	(5.179)
2._at	-3.599	-7.145***
	(3.507)	(2.728)

environmental fines paid, reais		
1._at	0.169	0.00233
	(0.109)	(0.0226)
2._at	0.0313	0.0114
	(0.0283)	(0.00929)
1.PL_dum		
1._at	29.04***	-16.37**
	(3.464)	(7.870)
2._at	29.04***	-16.37**
	(3.464)	(7.870)
1.soy_mor_year		
1._at	-5.591	1.861
	(6.046)	(2.026)
2._at	-5.591	1.861
	(6.046)	(2.026)
1.cattle_mor_year		
1._at	-9.639***	-3.083***
	(1.986)	(0.953)
2._at	-9.639***	-3.083***
	(1.986)	(0.953)
Observations	7555	7555
Adjusted R^2		

Standard errors in parentheses
* $p < .10$, ** $p < .05$, *** $p < .01$

Acknowledgements
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Appendix A

This appendix distills key findings from meetings with public agents (government officials and representatives of civil society organizations) and desk review (of laws, regulations, and government websites) conducted by Thais Ottoni Santiago and Jime Ribeiro. The last column in table A1 describes how these findings informed the development of our Directed Acyclic Graph (DAG).

The term "mediator" is used differently in different fields or disciplines. In this appendix, we use the term mediator to refer only to mechanisms on the causal chain between treatment and outcome. We use the term moderator to refer to conditions that are off the causal chain but that influence effect sizes, acknowledging that in some literature, the term mediator is also used in this case. We use the term "external validity moderator" for conditions off the causal chain that vary across countries and are therefore important to consider when thinking about the broader applicability of the DAG and our findings across countries.

As also suggested by the literature on deforestation in the Amazon, our meetings and review identified enforcement and monitoring as critical to the relationship between satellite data and deforestation. We also explored the role of policy in enforcement and monitoring (via different institutions) and the roles of monitoring and enforcement in shaping policy impacts. One key implication for our DAG is that policies can be both moderators and mediators in the causal relationship between satellite data and deforestation, which in turn influences the specification of our empirical models.

Table A1: Summary of key findings from meetings and desk review		
Year	Facts	Components of the DAG
	INPE's PRODES was launched in 1988 as the first system to monitor the Amazon using satellite images. The frequency and the processing methodology has evolved over time. Initially, there was a 2-3 year delay to generate and disseminate the LULC maps. In the first 15 years (till 2002), PRODES used computerized classification and visual interpretation. Starting in 2003, only computerized classification.	**External validity moderator:** human resources and capacity for processing remote sensing **Mediator:** **Monitoring:** classification, interpretation and dissemination of satellite data. Speed and accuracy of monitoring influence size of the effect of satellite imagery on deforestation.
	PPCDAM was created by Decree on July 3, 2003 and launched in 2004, as a mechanism to coordinate enforcement actions across agencies. Policies evolved to include economic incentives. One of the most effective was to embargo properties where excess deforestation was detected. This instrument of "areas embargadas" was a revolution. Banks started to veto credit for activities in embargoed areas, and then they embargoed the owner based on their national ID number (CPF). This caused deforestation to plummet.	**Moderator:** PPCDAM policy package sets the institutional context **Mediator:** Monitoring only has an effect if used for enforcement. PPCDAM policies evolved to include embargos that were made possible by existence of satellite data that could show illegal deforestation on particular properties.
2004	DETER-A (uses images from the MODIS sensor with 250 meters of spatial resolution) developed by INPE with the objective of monitoring in real time. DETER-B was created in 2015 to support inspection. Changing the pattern of deforested areas in the Amazon identifies and maps, in real time,	**Mediator** **Monitoring:** DETER-A **Enforcement:** DETER-B Data speed important here

	deforestation and other changes in forest cover with a minimum area of 3 hectares.	
	Civil society uses satellite data to support monitoring. For example, IMAZON developed SAD (Deforestation Alert System) in 2008. As an independent system detached from government and national policy, SAD introduced redundancy that made the monitoring system more resilience, reinforced impartial debate in civil society and the press, and promoted awareness and discussion of deforestation. In collaboration with Google Earth, Imazon developed the SAD-EE system to operate within the Google Earth Engine platform.	**Mediator:** civil society develops new ways to use satellite data, in parallel to public sector **Monitoring:** technical and financial capacity of civil society
2017	SAD abandoned the use of Modis images and started using Landsat 7 (ETM+ sensor), Landsat 8 (OLI), Sentinel 1A and 1B and Sentinel 2A and 2b (MSI) satellites. By combining these satellites, it is possible to see the same area again every 5 to 8 days. Sentinel images allow detecting deforestation even with the presence of clouds and even at night. This is especially useful for identifying loggers who traditionally cut down the forest in the rainiest months of the year to escape satellites. But it is not enough to have a modern monitoring system if there is no inspection.	**Mediator** **Monitoring:** SAD-EE improvements - at night and under cloud detection
2017	other monitoring systems such as GLAD (all biomes) carried out by the University of Maryland. This system is global, but it has a number of problems, for example, it is not so accurate at the municipal level.	**Mediator** **Monitoring:** GLAD (independent from government)
2017	Projeto Amazônia Protege - MPF is a project conceived by the Federal Public Ministry (MPF). The MPF receives satellite images produced by INPE recording areas of illegal deforestation in the Amazon. Ibama analyzes the images, cross-references the information on the land with public databases and issues reports confirming illegal deforestation. Then, to identify those	**Moderator/Mediator:** I believe that the Brazilian Public Ministry (MPF) can assume a role as a mediator and also as a moderator (once it *per si* is a powerful institution as an essential function of Justice). In this particular

	responsible for the environmental damage, the MPF team conducts research in public databases.	context, it is assuming a role of Enforcement Mediator in the project Amazonia Protege - MPF.
2018	MapBiomas Alerta was created to enhance the usability and effectiveness of the alerts already generated by these three systems (SAD, DETER and GLAD). Given the resolution used in these systems (20 to 60 m), the alerts need to go through a detailed validation process, often followed by field verifications before they can be useful to direct measures such as the embargo and assessment of illegal deforestation areas. MapBiomas Alert is, therefore, a system for validating and refining alerts on deforestation, degradation and regeneration of native vegetation with high resolution images. It is the result of consultations with government agencies that use alert systems (eg MMA, IBAMA, SFB, ICMBio, MPF, SEMAs, MP-State, Environmental Military Police and TCU) and alert providers (eg INPE, IMAZON , University of Maryland, CENSIPAM, ISA, JICA+JAXA) that revealed the best contribution that the MapBiomas network could support to support environmental monitoring. Federal Public Ministry (MPF). Prosecutors use the reports generated in Mapbiomas Alerta so that they can be used in decision making and in establishing an embargo. The MPF usually sends documents to Congress containing SAD reports to avoid the reduction of protected areas.	**Mediator** **Monitoring:** MapBiomas Alerta **Enforcement:** on the ground verification
2018	IBAMA unofficially uses data from SAD monitoring, but every month Imazon sends the historical series. "I know that Mato Grosso state inspectors use our deforestation alerts" (Imazon interview).	**Mediator** **Monitoring:** IBAMA

2018	The reference base used to leave the list of illegal deforestation (LDI) is information from PRODES, however, throughout the year, they use data from SAD and DETER to find out if the measures to combat deforestation are having an effect. In addition, within the scope of the green municipalities program, for example, it has already provided training for local technicians who work in monitoring and supporting local pacts against deforestation. LDI was not being updated, but they will update it.	**Mediator** **Enforcement:** combined use of settle, green municipalities, illegal deforestation
2021	Imazon planned to launch the Deforestation Risk in the coming weeks, a project in partnership with Microsoft and Fundo Vale that uses artificial intelligence to predict in the short term where deforestation will occur. SAD prevents deforestation from continuing, this system wants to prevent it from happening. Based on SAD alerts, this system will predict deforestation within two months to three months before it happens. See: https://previsia.org/	**Mediator** **Monitoring:** deforestation predictions by IMAZON (collaboration with Microsoft and Fundo Vale)
	CAR - Rural Environmental Registry - States use satellite images to conduct the state management and monitoring policy.	**Mediator** **Monitoring:** CAR
	PRA - Environmental Regularization Program - States use satellite images in conducting the state management and monitoring policy	**Mediator** **Monitoring:** PRA
2006	Public forest management law institutes, within the framework of the Ministry of the Environment (MMA), the Brazilian Forest Service (SFB)	**Mediator** **Enforcement:** creation of framework for MMA and SFB
	Environmental Protection Directorate (DIPRO). IBAMA also has an intelligence area that is little publicized for national security reasons. DIPRO is related to Agência Brasileira de Inteligência (ABIN). This one, like the general agencies, uses satellite images. Satellite images are used as an indication of deforestation, but there must be field inspections to identify offenders.	**Mediator** **Monitoring:** deforestation monitoring **Enforcement:** creation of framework for MMA and SFB

2002	In order to make effective use of satellite images, IBAMA had to hire and train technical staff, and acquire computing technology. Starting in 2002, IBAMA hired technical staff through a periodic competitive hiring process (*concurso publico*). In recent years, IBAMA has not had budget to hire new staff.	**Mediator:** The availability of satellite imagery led IBAMA to run concursos for staff with geotechnological skills. These staff are part of the mechanism for translating satellite images into useful information for enforcement. This means that satellite imagery is unlikely to reduce overall costs (because of the personnel needed).
2014	IBAMA's Center for Remote Sensing (CSR) competed with INPE (in monitoring). After the launch of DETER-B in 2014, the CSR closed and monitoring within IBAMA became remote. In 2016 started Operation Remote Control of IBAMA: DETER-B data, crossed with CAR data, made the history of deforestation in that area, made the infraction notice, and embargoed the area. They took the CAR from IBAMA. A lot of political pressure on IBAMA.	**Mediator** **Monitoring:** CSR (via DETER-B)
	In 2014, IBAMA led an armed operation at the request of indigenous people to identify deforesters in Baú and Menkragnoti villages (BR 163). They found that the people involved in deforestation were using satellite imagery to plan their illegal actions, having contracted a geoprocessing team that understood satellites, analyzed INPE data and helped plan deforestation. Field crews were instructed to clear the understory and maintain the forest canopy to avoid detection. The geoprocessing team monitored where DETER found active deforestation (which polygons were flagged) and warned the field teams so they could flee before IBAMA arrived.	**Moderator:** Organized indigenous groups engaged in real-time on the ground monitoring of deforestation and communicate with IBAMA **Mediator** Agents of deforestation learn how to use satellite imagery
	Satellite images are shared among agencies involved in monitoring and enforcement through institutional partnerships. State agencies mostly use free imagery, such as Landsat (with revisit time of 16 days) and recently Sentinel (revisit time of just 5 days).	**Moderator:** Institutional partnerships expand use of satellite data

	Pará even bought Planet images, but those were no well used, because of the way that they were archived.	**Mediator:** Storage and sharing of satellite data determine use
	After fines are issued, there is a long process of review before they are paid. In 2019, the Bolsonaro administration created the so-called "conciliation" chamber that effectively dismantled the process of collecting environmental fines. From October 2019 to May 2021, this chamber held fewer than 15 meetings and no fines were upheld.	**Moderator:** Political context
	Extension agencies, such as Emater-PA, work with small properties, which requires high resolution imagery. In some regions (e.g. in Altamira and São Félix do Xingu) they have been using drones for the past couple of years (since 2019).	**Moderator:** Existence and capacity of extension programs **Mediator:** Adoption of high resolution imagery to support extension
	Agencies like IBAMA/MMA now have remote sensing technology with sufficient precision to allow them to identify infractions and apply fines without visiting properties on the ground. This is the future of enforcement, just not happening yet because there is no supporting case law.	**Future Mediator:** Case law and enforcement systems are expected to evolve in response to new technology for higher precision remote sensing.

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Fonseca, Antônio Victor. Interview by Thais Santiago. Open questions. Phone call. June, 2, 2021.

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Pereira, Diego Henrique. Interview by Jime Rodrigues Ribeiro. Semi-structured questions. Google meet. December, 02, 2021.

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Viana, Jamerson. Interview by Jime Rodrigues Ribeiro. Semi-structured questions. Marituba, PA, Brazil. November, 25, 2021.

Table A2: Deforestation and Satellite Laws by Category (Policies for the prevention, monitoring and/or control of deforestation in the Amazon biome from 1934 to 2021)									
Law	Year	Monitoring (one word description)	Enforcement (one word description)	Institutions (who/what)	Public Partnerships (who)	Other Partnership (who)	Municipality Impacts (how)	Level (municipality, state, federal)	Notes (description of policies)
DECRETO No 23.793, DE 23 DE JANEIRO DE 1934	1934	Guardas	Multas	N/A	N/A	N/A	Guardas ou vigias, encarregados da vigilância direta das florestas, serão nomeados habitantes no próprio local.	Federal	Codigo florestal Revogado pela lei nº 4.771, de 15 de setembro de 1965.
LEI Nº 4.771, DE 15 DE SETEMBRO DE 1965	1965	Policia	APP		Conselho Florestal Federal	Conselho Monetário Nacional	Criacao de areas protegidas	Federal	Institui o novo Código Floresta Área de preservação permanente (APP)
LEI No 5.868, DE 12 DE DEZEMBRO DE 1972	1972	SNCR	CNIR	INCRA	Instituto Brasileiro de Desenvolvimento Florestal (IBDF); Ministério da Agricultura	Arrendatários e Parceiros Rurais,	Imposto sobre a Propriedade Territorial Rural	Federal	Cria o Sistema Nacional de Cadastro Rural (SNCR), e dá outras providências; Cadastro Nacional de Imóveis Rurais (CNIR); Regulamentado pelo Decreto nº 72.106, de 18 de abril de 1973.
LEI No 5.870, DE 26 DE	1973		CNIR	INCRA	Instituto Brasileiro	Arrendatár	transformar madeiras de	Federal	Acrescenta alínea ao artigo 26 da Lei nº 4.771, de 15 de setembro 1965, que institui

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MARÇO DE 1973					de Desenvolvimento Florestal (IBDF); Ministério da Agricultura	ios e Parceiros Rurais,	lei em carvão, inclusive para qualquer efeito industrial sem licença da autoridade competente		o novo Código Florestal; Sistema Nacional de Cadastro Rural (SNCR); Cadastro Nacional de Imóveis Rurais (CNIR); Instituto Nacional de Colonização e Reforma Agrária (INCRA).
LEI Nº 6.938, DE 31 DE AGOSTO DE 1981	1981	CONAMA	PNMA	IBAMA	SISNAMA		Responsáveis pelo controle e fiscalização dessas atividades, nas suas respectivas jurisdições	Federal	Dispõe sobre a Política Nacional do Meio Ambiente (PNMA), seus fins e mecanismos de formulação e aplicação, e dá outras providências.
Art. 225, da Constituição Federal de 1988	1988							Federal	Consagra o meio ambiente como "bem de uso comum do povo e essencial à sadia qualidade de vida, impondo-se ao poder público e à coletividade o dever de defendê-lo e preservá-lo para as presentes e futuras gerações".
LEI Nº 7.797, DE 10 DE JULHO DE 1989.	1989		Projetos	IBAMA	CONAMA	Secretaria de Planejamento e		Federal	Cria o Fundo Nacional de Meio Ambiente e dá outras providências.

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						Coordenação da Presidência da República (SEPLAN/ PR)			
LEI Nº 7.875, DE 13 DE NOVEMBRO DE 1989	1989		Fiscalizacao						Modifica dispositivo do Código Florestal vigente (Lei nº 4.771, de 15 de setembro de 1965) para dar destinação específica a parte da receita obtida com a cobrança de ingressos aos visitantes de parques nacionais.
LEI Nº 7.803, DE 18 DE JULHO DE 1989	1989		Fiscalizacao	IBAMA	Convênio com os Estados e Municípios		Convênio com os Municípios para ações de fiscalização	Federal	Altera a redação da Lei nº 4.771, de 15 de setembro de 1965, e revoga as Leis nºs 6.535, de 15 de junho de 1978, e 7.511, de 7 de julho de 1986.
DECRETO Nº 1.298, DE 27 DE OUTUBRO DE 1994	1994		FLONAS	IBAMA					Aprova o Regulamento das Florestas Nacionais (FLONAS), e dá outras providências.
DECRETO Nº 1.282, DE 19 DE OUTUBRO DE 1994	1994								

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Law	Year	Monitoring (one word description)	Enforcement (one word description)	Institutions (who/what)	Public Partnerships (who)	Other Partnership (who)	Municipality Impacts (how)	Level (municipality, state, federal)	Notes (description of policies)
RESOLUÇÃO CONAMA Nº 237, DE 19 DE DEZEMBRO DE 1997	1997		Licenciamento	SISNAMA	CONAMA	Convenios	Compete ao órgão ambiental municipal, o licenciamento ambiental de empreendimentos e atividades de impacto ambiental local	Federal	Estabelece a competência do órgão ambiental municipal para o licenciamento ambiental de empreendimentos e atividades de impacto ambiental local, e de outros que lhe forem delegadas pelo Estado por instrumento legal ou convênio.
LEI Nº 9.605 DE 12 DE FEVEREIRO DE 1998	1998							Federal	Dispõe sobre as sanções penais e administrativas derivadas de condutas e atividades lesivas ao meio ambiente, e dá outras providências.
DECRETO Nº 2.661, DE 8 DE JULHO DE 1998.	1998	PREVFOGO	PREVFOGO	IBAMA	SISNAMA	Organismos públicos ou privados	habilitação de técnicos para atuar junto a prefeituras municipais e demais entidades ou	Federal	Regulamenta o parágrafo único do art. 27 da Lei nº 4.771, de 15 de setembro de 1965 (código florestal), mediante o estabelecimento de normas de precaução relativas ao emprego do fogo em práticas agropastoris e florestais, e dá outras providências. Sistema Nacional de Prevenção e Combate a Incêndios Florestais (PREVFOGO)
DECRETO S/N DE 3 DE JULHO DE 2003	2003		PPCDAM					Federal	Criado o Programa de Prevenção ao desmatamento da Amazônia (PPCDAM), lançado em 2004, foi elaborado pelo Grupo Permanente de Trabalho Interministerial

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(Policies for the prevention, monitoring and/or control of deforestation in the Amazon biome from 1934 to 2021)

Law	Year	Monitoring (one word description)	Enforcement (one word description)	Institutions (who/what)	Public Partnerships (who)	Other Partnership (who)	Municipality Impacts (how)	Level (municipality, state, federal)	Notes (description of policies)
									(GPTI), constituído em 2003 por meio do Decreto s/n de 3 de julho, com o intuito de conter o aumento do desmatamento na Amazônia. " Art. 1 Redução dos índices de desmatamento nos biomas brasileiros, por meio da elaboração de planos de ação para a prevenção e o controle dos desmatamentos" Revogado pelo Decreto nº 10.142, de 2019
LEI Nº 11.284, DE 2 DE MARÇO DE 2006	2006	PMFS	PAOF	SFB (Serviço Florestal Brasileiro)	SISNAMA	Convênios, termos de parceria, contratos ou instrumentos similares com terceiros.	Repasses de recursos financeiros oriundos das concessões florestais	Federal	Plano de Manejo Florestal Sustentável (PMFS); Dispõe sobre a gestão de florestas públicas para a produção sustentável; institui, na estrutura do Ministério do Meio Ambiente, o Serviço Florestal Brasileiro - SFB; cria o Fundo Nacional de Desenvolvimento Florestal - FNDF; altera as Leis nos 10.683, de 28 de maio de 2003, 5.868, de 12 de dezembro de 1972, 9.605, de 12 de fevereiro de 1998, 4.771, de 15 de setembro de 1965, 6.938, de 31 de agosto de 1981, e 6.015, de 31 de dezembro de 1973; e dá outras providências.
DECRETO Nº 5.975 DE 30 DE NOVEMBRO	2006	PMFS	PMFS	IBAMA	SISNAMA; SINIMA	CONAFLOR		Federal	Regulamenta os arts. 12, parte final, 15, 16, 19, 20 e 21 da Lei nº 4.771, de 15 de setembro de 1965, o art. 4º, inciso III, da Lei nº 6.938,

Table A2: Deforestation and Satellite Laws by Category (Policies for the prevention, monitoring and/or control of deforestation in the Amazon biome from 1934 to 2021)									
Law	Year	Monitoring (one word description)	Enforcement (one word description)	Institutions (who/what)	Public Partnerships (who)	Other Partnership (who)	Municipality Impacts (how)	Level (municipality, state, federal)	Notes (description of policies)
DE 2006.									de 31 de agosto de 1981, o art. 2º da Lei nº 10.650, de 16 de abril de 2003, altera e acrescenta dispositivos aos Decretos nºs 3.179, de 21 de setembro de 1999, e 3.420, de 20 de abril de 2000, e dá outras providências. Sistema Nacional de Informações Ambientais (SINIMA).
DECRETO Nº 6.321, DE 21 DE DEZEMBRO DE 2007.	2007	INPE	(Re)cadastro	INCRA	IBAMA ICMBIO	Municipios	Lista de municípios prioritários situados no Bioma Amazônia para monitorar de forma preventiva e controle de desmatamento ilegal.	Federal	Dispõe sobre ações relativas à prevenção, monitoramento e controle de desmatamento no bioma Amazônia. Definição, ações, correlação, prevenção, controle, desmatamento, fauna, flora, região amazônica. " § 1º O objetivo precípuo da atualização cadastral é reunir dados e informações para monitorar, de forma preventiva, a ocorrência de novos desmatamentos ilegais, bem como promover a integração de elementos de controle e gestão compartilhada entre as políticas agrária, agrícola e ambiental".
DECRETO Nº 6.514, DE 22 DE JULHO DE	2008	Georreferenciamento	Fiscalizacao	SISNAMA	MP	N/A	As infrações administrativas são punidas	Federal	Ministerio Publico (MP); Dispõe sobre as infrações e sanções administrativas ao meio ambiente,

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Law	Year	Monitoring (one word description)	Enforcement (one word description)	Institutions (who/what)	Public Partnerships (who)	Other Partnership (who)	Municipality Impacts (how)	Level (municipality, state, federal)	Notes (description of policies)
2008							com o embargo de obra ou atividade e suas respectivas áreas, entre outras sanções.		estabelece o processo administrativo federal para apuração destas infrações, e dá outras providências.
DECRETO Nº 6.527, DE 1º DE AGOSTO DE 2008	2008	CTFA	PPCDAM	BNDS	Comitê Orientador (COFA)	Sociedade civil		Federal	Cria o Fundo Amazônia; Comitê Técnico (CTFA) com a atribuição de atestar as Emissões de Carbono Oriundas de Desmatamento (ED) calculadas.
RESOLUÇÃO Nº 3545/2008 BANCO CENTRAL	2008	CCIR	MCR	Banco Central	INCRA			Federal	Cria restrições para acesso a créditos bancários para aqueles que não comprovem a regularização ambiental; Altera o MCR 2-1 para estabelecer exigência de documentação comprobatória de regularidade ambiental e outras condicionantes, para fins de financiamento agropecuário no Bioma Amazônia; Manual de Crédito Rural (MCR). Certificado de Cadastro de Imóvel Rural (CCIR)
PORTARIA 28, DE 24 DE	2008	INPE					Lista de municipios		Lista de municipios prioritarios

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Law	Year	Monitoring (one word description)	Enforcement (one word description)	Institutions (who/what)	Public Partnershi ps (who)	Other Partnershi p (who)	Municipalit y Impacts (how)	Level (municipali ty, state, federal)	Notes (description of policies)
JANEIRO DE 2008							prioritarios		
PORTARIA MMA Nº 103, DE 24-03-2009 - SOGI	2009		CAR						Condicionou a exclusão da lista de municípios embargados, a execução do Cadastro Ambiental Rural (CAR) em 80% de seu território.
LEI Nº 12.651, DE 25 DE MAIO DE 2012	2012	CAR	PRAs	Secretarias Estaduais e Municipais de Meio Ambiente	EMATER	Terceiro setor	Regularizaç ão ambiental das propriedade s	Federal	Cadastro Ambiental Rural (CAR); Programas de Regularização Ambiental (PRAs); "Art. 1o - A. Esta Lei estabelece normas gerais sobre a proteção da vegetação, áreas de Preservação Permanente e as áreas de Reserva Legal; a exploração florestal, o suprimento de matéria-prima florestal, o controle da origem dos produtos florestais e o controle e prevenção dos incêndios florestais, e prevê instrumentos econômicos e financeiros para o alcance de seus objetivos"
DECRETO Nº 7.830, DE 17 DE OUTUBRO DE 2012	2012	CAR	PRA					Federal	Dispõe sobre o Sistema de Cadastro Ambiental Rural, o Cadastro Ambiental Rural, estabelece normas de caráter geral aos Programas de Regularização Ambiental, de que trata a Lei no 12.651, de 25 de maio de 2012, e dá outras

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(Policies for the prevention, monitoring and/or control of deforestation in the Amazon biome from 1934 to 2021)

Law	Year	Monitoring (one word description)	Enforcement (one word description)	Institutions (who/what)	Public Partnerships (who)	Other Partnership (who)	Municipality Impacts (how)	Level (municipality, state, federal)	Notes (description of policies)
									providências.
INSTRUÇÃO NORMATIVA No 3, DE 18 DE DEZEMBRO DE 2014	2014	SICAR	PISI	SFB/MMA	Órgãos e entidades da administração pública	Acordos de Cooperação Técnica	Sistema de Cadastro Ambiental Rural (SICAR)	Federal	Institui a Política de Integração e Segurança da Informação (PISI) do Sistema de Cadastro Ambiental Rural (SICAR) e dá outras providências; Termo de Compromisso de Manutenção de Sigilo (TCMS)
INSTRUÇÃO NORMATIVA No 2, DE 5 DE MAIO DE 2014	2014	CAR	SISCAR	Órgão estadual, distrital ou municipal competente	Órgãos do Sistema Nacional de Meio Ambiente (SISNAMA)	Órgão competente e a instituição ou entidade representativa dos povos ou comunidades tradicionais; FUNAI	A análise dos dados declarados no CAR será de responsabilidade do órgão estadual, distrital ou municipal competente.	Federal	Dispõe sobre os procedimentos para a integração, execução e compatibilização do Sistema de Cadastro Ambiental Rural (SICAR) e define os procedimentos gerais do Cadastro Ambiental Rural (CAR).
DECRETO Nº 8.235, DE 5 DE MAIO DE 2014	2014	CAR	PRA	MMA	Estados e Municípios	N/A	A localização da Área de Preservação Permanente ou Reserva Legal ou área de uso	Federal	Estabelece normas gerais complementares aos Programas de Regularização Ambiental dos Estados e do Distrito Federal, de que trata o Decreto n o 7.830, de 17 de outubro de 2012, institui o Programa Mais Ambiente Brasil, e dá outras providências.

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Law	Year	Monitoring (one word description)	Enforcement (one word description)	Institutions (who/what)	Public Partnerships (who)	Other Partnership (who)	Municipality Impacts (how)	Level (municipality, state, federal)	Notes (description of policies)
							restrito a ser recomposta, recuperada, regenerada ou compensada ;		
PORTARIA Nº 360, DE 8 DE SETEMBRO DE 2017	2017			Secretarias Estaduais e Municipais de Meio Ambiente			Lista de municípios prioritários	Federal	Edição anual da lista de municípios prioritários para ações de prevenção,monitoramento e controle do desmatamento e da edição anual da lista de municípios com desmatamento monitorado e sob controle
PORTARIA Nº 161, DE 15 DE ABRIL DE 2020	2020			Secretarias Estaduais e Municipais de Meio Ambiente			Lista de municípios prioritários	Federal	Dispõe sobre os requisitos para a inclusão na lista de municípios prioritários para ações de prevenção e controle do desmatamento e na lista de municípios com desmatamento monitorado e sob controle.
PORTARIA MMA Nº 475, DE 21 DE OUTUBRO DE 2021	2021			Secretarias Estaduais e Municipais de Meio Ambiente			Lista de municípios prioritários	Federal	Dispõe sobre a atualização das listas de municípios prioritários para ações de prevenção e controle do desmatamento e de municípios com desmatamento monitorado e sob controle, a que se refere o Decreto nº 6.321, de 21 de dezembro de 2007.

Definitions (for Table A2)

- **Law:** Policies for the prevention, monitoring and/or control of deforestation in the Amazon biome
- **Monitoring:** the remote sensing, classification and publication of satellite data (actions that are linked to what's happening in space)
- **Enforcement:** the efforts needed on the ground to enforce laws
- **Institutions:** evidence that riles, laws and government are needed for enforcement or monitoring
- **Public Partnerships**: partnerships between different government agencies
- **Other Partnerships**: partnerships between government agencies, private organizations and/or NGOs
- **Municipality Impacts:** evidence that municipalities impac one another - or that a law/enforcement of a law impact another municipality

Appendix B

This appendix outlines the different sources used to estimate the costs of satellites.

Table B1 outlines the program costs of PPCDAM. This budget includes separate line items for land planning, monitoring and sustainable development. The PPCDAM mean annual expenses are the average of the annual mean for the two budget time periods. This eight-year annual mean is approximately US$543 million per year.

Table B1: PPCDAM Expenses (millions)

	2007-2010	Annual Average (R$)	Annual Average (US$)	2011-2014	Annual average (R$)	Annual Average (US$)
Land Planning	820	205	111	436	109	56
Monitoring	959	240	129	703	176	90
Sustainable Development	4584	1146	619	638	159	81
Total	**6363**	**1591**	**859**	**1777**	**444**	**227**

Source: (Castelo et al. 2018). Average annual exchange rate in 2008: 1BR$=US$0.54. In 2012 1BR$=US$0.51, OECD https://data.oecd.org/conversion/exchange-rates.htm

Table B2 outlines the annual budget of the Brazilian space agency, INPE between 2011 and 2021. Annual expanses decline each year in this time period. They are highest in 2011 at over US$4 million and lowest in 2021 at $492,000, representing an 88% budget reduction. The annual average is approximately US$1.9 million per year, but given that the decline in budget larger happened after our time period of consideration, US$4 million is what we use as our lower bound for satellite costs.

Table B2: Brazilian Space Agency (INPE) Annual Budget

	R$	US$
2011	6,726,000	4,020,323
2012	6,726,000	3,443,932
2013	6,389,700	2,963,683
2014	6,389,700	2,715,555
2015	6,389,700	1,920,559
2016	5,916,200	1,694,701
2017	5,379,000	1,685,678
2018	3,220,000	881,226
2019	3,220,000	816,430
2020	3,220,000	624,636
2021	2,655,812	492,364
Annual Average	**5,112,010**	**1,932,644**

Source: Sistema Integrado de Planejamento e Orçamento do Governo Federal (https://www.siop.planejamento.gov.br/modulo/login/index.html#/) Infographic here: https://infogram.com/evolucao-orcamento-i-1h7k230q8qggv2x
Exchange rates from https://data.oecd.org/conversion/exchange-rates.htm

Table B3 outlines the average annual budget of the Brazilian space agency, INPE between 2010 and 2020 as their budget specifically relates to PPCDAM and DETER. These budget items are divided between satellite monitoring, supervision (salaries of heads of agency), the provision of DETER and PRODES alerts, and DETER. The largest budget item is the DETER and PRODES alerts. The sum of all these items is approximately US$ 3million per year.

Table B3: INPE PRODES and DETER Annual Budget		
	R$	US$
Monitoring	3,000,000	901,713
Supervision	500,000	150,286
DETER & PRODES alerts	5,000,000	1,502,855
DETER	2,000,000	601,142
Total	**10,500,000**	**3,155,996**

Source: (Monteiroa et al. 2020). Exchange rate for 2015:https://data.oecd.org/conversion/exchange-rates.htm

Table B4 includes our last source of data on costs is the Ministry of the Environment budget. This includes expenses for the management (US$11.4 trillion/year) and control (US$1.4 trillion of environmental laws, and used to confirm that the PPCDAM is below and a portion of this budget.

Table B4: Ministry of the Environmental Budget for Combined Municipality and State Expenses for Environmental Management and Control in the Amazon

	Management (state and municipality)		Control (state and municipality)	
	R$ million	US$ million	R$ million	US$ million
2004	7,420	2,537	1,003	343
2005	8,476	3,482	922	379
2006	12,659	5,820	2,224	1,022
2007	14,459	7,426	2,083	1,070
2008	22,742	12,400	3,682	2,008
2009	23,995	12,004	4,656	2,329
2010	27,732	15,766	6,901	3,923
2011	23,931	14,304	3,815	2,281
2012	29,471	15,090	4,850	2,483
2013	39,014	18,096	4,573	2,121
2014	47,826	20,326	3,512	1,493
2015	35,143	10,563	3,678	1,106
Average Annual	**24,406**	**11,484**	**3,492**	**1,713**

Source: Sistema de Informações Contábeis e Fiscais do Setor Publico Brasileiro, Ministério do Economia https://siconfi.tesouro.gov.br/siconfi/pages/public/consulta_finbra/finbra_list.jsf

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