The Deforestation Menace: Do Protected Territories Actually Shield Forests?

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Abstract

The paper tests whether legal territorial protection grants actual protection against advancing deforestation. Using a measure of neighboring clearing activity to capture local deforestation risk, the analysis compares forest clearing outcomes in unprotected and protected territories under equivalent deforestation pressures. The empirical strategy draws on the dataset's raster structure to mitigate concerns of potentially confounding unobservables via the use of raster cell fixed effects. Results document protection's efficacy in a high-risk context, with significantly less forest being cleared in protected cells than in unprotected ones. Yet, although protected territory effectively shields vegetation under its domain from advancing deforestation, it appears to deflect clearings to unprotected areas. Protection therefore affects regional forest clearing dynamics, but not the overall level of deforestation.

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1. Introduction

Territorial protection is one of the leading conservation policies worldwide (Nolte et al., 2013; Pfaff and Robalino, 2017). It has long been used in the Brazilian Amazon, well before the onset of the PPCDAm. By 2004, nearly two fifths of Amazon biome territory were already under protection. Yet, the action plan introduced a novel siting strategy for protection. Henceforth, although biological and ecological factors remained important allocation criteria, current and future deforestation risks were to be taken into account when granting protection. In addition to their original goals of conserving biodiversity and protecting natural habitats, Amazon protected territories in high-risk zones were also meant to serve as shields against advancing forest clearings.

In theory, protection's shielding capacity stems from its ability to deter environmental offenders. Amazon protected territory is under greater scrutiny and monitoring attention, which increases an offender's chance of getting caught. Moreover, Brazil's regulatory framework allows for harsher punishment of environmental infractions committed within protected territory. As such, because there is a higher cost of clearing protected versus unprotected forest, legal protection could grant actual protection against deforestation to the extent that offenders refrain from acting within protected territory. However, shielding is only effective if the forest under protection faces an actual threat of deforestation — areas that are not under forest clearing pressure are unlikely to see deforestation with or without protection. This is one of the main challenges in evaluating protection effectiveness, since protected territory is often located in remote areas (DeFries et al., 2005; Joppa et al., 2008; Joppa and Pfaff, 2011). In light of this, the empirical setting of the post-PPCDAm Brazilian Amazon, in which protection was intentionally allocated in high-risk areas, offers a unique opportunity to assess protection effectiveness against deforestation.

This chapter uses a spatially explicit panel dataset to empirically test the shielding capacity of protected territory. It starts by establishing a means of capturing areas under greater deforestation pressure. The satellite-based monitoring system adopted under the PPCDAm issued alerts for recent changes in forest cover, such that regions with greater alert intensity typically held more intense clearing activity. As forest clearings exhibit spatial persistence, it seems reasonable to posit that areas close to deforestation are under greater threat of being themselves deforested. Drawing on the dataset's raster structure to mitigate concerns of potentially confounding unobservables via the use of cell fixed effects, the analysis shows that this relationship indeed holds in the data. For a given cell and year, greater alert intensity within 50km of the cell is associated with increased forest clearings inside the cell the following year. Thus, neighborhood alert intensities serve as a measure of local deforestation risk.

The empirical strategy then builds on this measure of exposure to compare forest clearing outcomes in unprotected and protected territory under equivalent deforestation pressures. Results document protection's efficacy in a high-risk context, with significantly less forest being cleared in protected cells than in unprotected ones. Estimates indicate that, under an increase of one standard deviation in the intensity of neighborhood alerts, the difference in clearings for unprotected and protected cells amounts to 3% of the sample standard deviation, or 26% of the sample mean. Findings therefore corroborate protected territories' effectiveness in shielding vegetation within their domain from deforestation activity.

To shed light on the economic significance of this effect, observed aggregate forest clearing trends are compared to counterfactual ones in which protection has been revoked. Annual deforestation trends for cells that lose protection in the hypothetical scenarios are significantly affected. Particularly in high-pressure periods, protected cells saw less forest clearings than if they had not been granted legal protection. This pattern holds across protection types, but is weaker for indigenous lands than for protected areas. Yet, counterfactual exercises that estimate deforestation outcomes across both protected and unprotected cells reveal that aggregate deforested area does not change when protection is revoked. Protected territory therefore seems to affect spatial forest clearing dynamics, but not the overall level of deforestation. I interpret this as evidence that, although protected territories effectively shield forests under their domain, they essentially deflect deforestation to unprotected regions.

This chapter is closely related to the literature that assesses the effectiveness of protected territory. Being one of the most widely used conservation policies in the world, protection has long been the subject of empirical impact evaluation. Cross-country assessments typically find that protected areas see less deforestation than unprotected ones, but highlight that protection is often located in remote areas that are not subject to high deforestation pressures (DeFries et al., 2005; Joppa and Pfaff, 2011; Nelson and Chomitz, 2011; Abman, 2018). Similar results are found in country-specific analyses, many of which try to account for varying forest clearing pressures to mitigate bias when estimating protection impact. Examples include studies for protected territory in Chile (Arriagada et al., 2016), Costa Rica (Andam et al., 2008; Pfaff et al., 2009), Indonesia (Gaveau et al., 2012; Shah and Baylis, 2015), Mexico (Honey-Rosés et al., 2011), Peru (Miranda et al., 2016), and Thailand (Sims, 2010, 2014).

Several works have looked specifically at protection in the Brazilian Amazon, albeit not necessarily within the scope of the PPCDAm. Protection is typically shown to work as a means of conserving forest cover, though authors have found relevant variations in effectiveness across time and space (Nepstad et al., 2006; Nolte et al., 2013; Pfaff et al., 2014, 2015). Anderson et al. (2016) is an exception to the extent that it finds no significant impact of protection on forest preservation in the Amazon. The authors speculate that this null average effect might result from protection being assigned mostly to remote areas that are not under significant deforestation pressure. This study advances the literature on protection effectiveness by proposing an empirical approach that focuses on assessing protected territory's shielding capacity specifically in areas that face actual threats of suffering forest loss.

The chapter proceeds as follows: Section 2 describes the institutional context for environmental monitoring and protection in the Amazon; Section 3 details the empirical strategy; Section 4 presents dataset and variable construction procedures; Section 5 reports and discusses estimation results and counterfactual simulations; and Section 6 concludes with policy implications.

2. Institutional Context

This section provides background information on the legality of Amazon deforestation, the satellite-based monitoring system, and protected territory policy. It closes with a discussion on how this institutional context might influence a potential offender's land use decision-making process.

2.1. Amazon Deforestation as an Illegal Activity

Brazil's 1988 Federal Constitution determined that offenders who engage in actions that are harmful to the environment can be held thrice responsible, being subject to legal penalties in civil, administrative, and criminal spheres (Brasil, 1988). These penalties need not be mutually exclusive and accumulate across spheres. The illegal clearing of native vegetation is thus punishable by law.

Regulations setting the legality of forest clearing in the Amazon vary across private and public lands. Inside private properties, deforestation is only legal if the clearing of a specific area has been duly authorized or licensed by subnational (usually state-level) environmental authorities. Landholders must also comply with the Brazilian Forest Code, which sets legal guidelines for land cover conversion and protection of native vegetation inside private properties.[1] For properties inside the Amazon biome, the Forest Code is particularly restrictive. It requires landholders to preserve at least 80% of their property as native vegetation, and determines areas of permanent protection, such as riparian forests, which cannot be cleared in any circumstance (Brasil, 2012). Public lands in the Amazon are largely composed of protected territory or undesignated lands. In the former, forest clearing is either fully prohibited or is permitted only under strict licensing; in the latter, it is always prohibited.

[1] See Chiavari and Lopes (2015) for an explanation of the Brazilian Forest Code.

Existing data on Amazon deforestation do not allow legal clearings to be distinguished from illegal ones. There is compelling, albeit only anecdotal or localized, evidence that the vast majority of areas deforested since the launch of the PPCDAm were cleared under illegal circumstances. The Brazilian Amazon biome extends over more than 420 million hectares. By 2014, protected territory, where forest clearing practices are mostly illegal, covered nearly half of this area. The remaining unprotected territory is a combination of as-of-yet undesignated public lands and private properties. Clearing in the former is also illegal. Recent estimates for the extent of private property in the Amazon biome set total private land area at approximately 180 million hectares (SFB, 2017). While clearings inside these properties could be legal if both duly authorized/licensed and in accordance with Forest Code requirements, property-level assessments indicate compliance with the Forest Code in the Amazon is generally very poor (Michalski et al., 2010; Godar et al., 2012; Börner et al., 2014). Because forest clearings in non-compliant properties are carried out in irregular circumstances from an environmental legislation standpoint, they are deemed illegal. In light of this, although some deforested areas captured in this analysis may refer to legal clearings, I assume that they represent only a small fraction of total sample deforestation.[2] Hence, forest clearings detected by the monitoring system most likely capture illegal activity punishable by law.

2.2. Monitoring and Law Enforcement

Since its implementation in the mid-2000s, DETER has served as the main tool for targeting law enforcement efforts in the Amazon. The system regularly scans the full extent of the Brazilian Amazon for signs of tropical degradation or deforestation, which, when detected, generate georeferenced alerts. Law enforcers visit alert locations and, upon finding evidence of illegal clearing activity, charge offenders. Criminal charges are later processed via the public prosecution system, but on-site law enforcement personnel can apply administrative penalties.

Although law enforcement operations need not be exclusively based on DETER alerts, the system is the official cornerstone of Amazon deforestation monitoring (Börner et al., 2015; Schmitt, 2015). In addition to providing fast, frequent, and spatially far-reaching information on recent degradation and deforestation activity, DETER also increased law enforcers' capacity of catching offenders red-handed and, thus, of punishing them.[3] Anecdotal evidence provided by Ibama personnel

[2]In informal conversations, law enforcement personnel have suggested that less than 10% of deforested areas are actually legal. Souza-Rodrigues (2018) reports a similar estimate, also based on informal interactions.

[3]Catching offenders red-handed enhances punishment capacity to the extent that it enables law enforcers to hold someone accountable for the illegal activity. This is particularly relevant in the Amazon's context of unclear and insecure property rights (Mueller et al., 1994; Alston et al., 2000), and for a subset of sanctioning instruments — namely the establishment of embargoes and seizure

support the idea that the new monitoring system effectively captured recent forest clearing hot spots and allowed for more efficient targeting of enforcement operations. It is therefore plausible to argue that areas with greater intensity of DETER deforestation alerts are also areas that are currently undergoing more intense forest clearing activity.

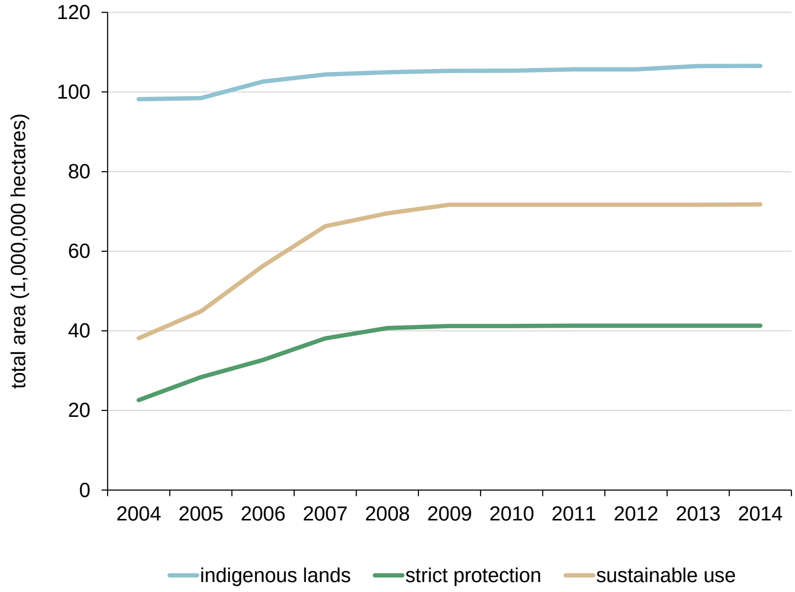
2.3. Protected Territory

Brazilian protected territory is composed of protected areas and indigenous lands. Although both categories fall into the larger public lands domain, protected areas and indigenous lands are governed by separate authorities and are subject to different regulations. Protected areas can be either strictly protected, where no deforestation of any form is legal, or of sustainable use, where forest clearing may be legal if duly licensed and in accordance with the area's management plan. Deforestation licensing requirements are stricter inside areas of sustainable use than in private properties. Following a period of technical assessment and public consultation, protected areas are created via laws or decrees. They can be managed at federal, state, or municipal levels, but federal and state areas are far more common in the Amazon. In contrast, indigenous lands cannot be created, only recognized. Typically, this means that areas assigned as indigenous lands have traditionally been occupied by indigenous peoples. Full recognition is only granted after the area completes a multi-stage administrative process. The recognition process can be roughly broken into the following stages: assessment, physical demarcation, declaration, presidential ratification, and registry. Clearing of native vegetation in indigenous lands is only legal if performed by indigenous peoples as part of their traditional way of life.

When the PPCDAm was launched in 2004, about 38% of Amazon biome territory was under protection as protected areas (61 million hectares) or indigenous lands (98 million hectares). Over the next decade, the extent of protected areas nearly doubled to 113 million hectares, and indigenous lands expanded to a total of 107 million hectares (see Figure 1). By 2014, more than half of the Amazon biome was under protection. In addition to promoting expansion, the action plan also inaugurated a novel siting strategy for protected territory. Through the mid-2000s, protection had been granted based on an area's biological and ecological characteristics, with the intent of conserving biodiversity and protecting natural habitats. While these criteria still played an important role in allocating protection under the PPCDAm, protected territory was henceforth assigned with an additional explicit goal — block advancing deforestation. Current and future deforestation risks were to be taken into account when granting protection, such that protected territories in high-risk

of machinery, tools, and production goods — whose use essentially depends on law enforcers having access to seizable items and/or offenders' identities.

Figure 1: Extent of Protected Territory, 2004–2014



Notes: The graph presents total area under type-specific protection in the Amazon biome. Data sources: FUNAI and ISA (indigenous lands); MMA (protected areas).

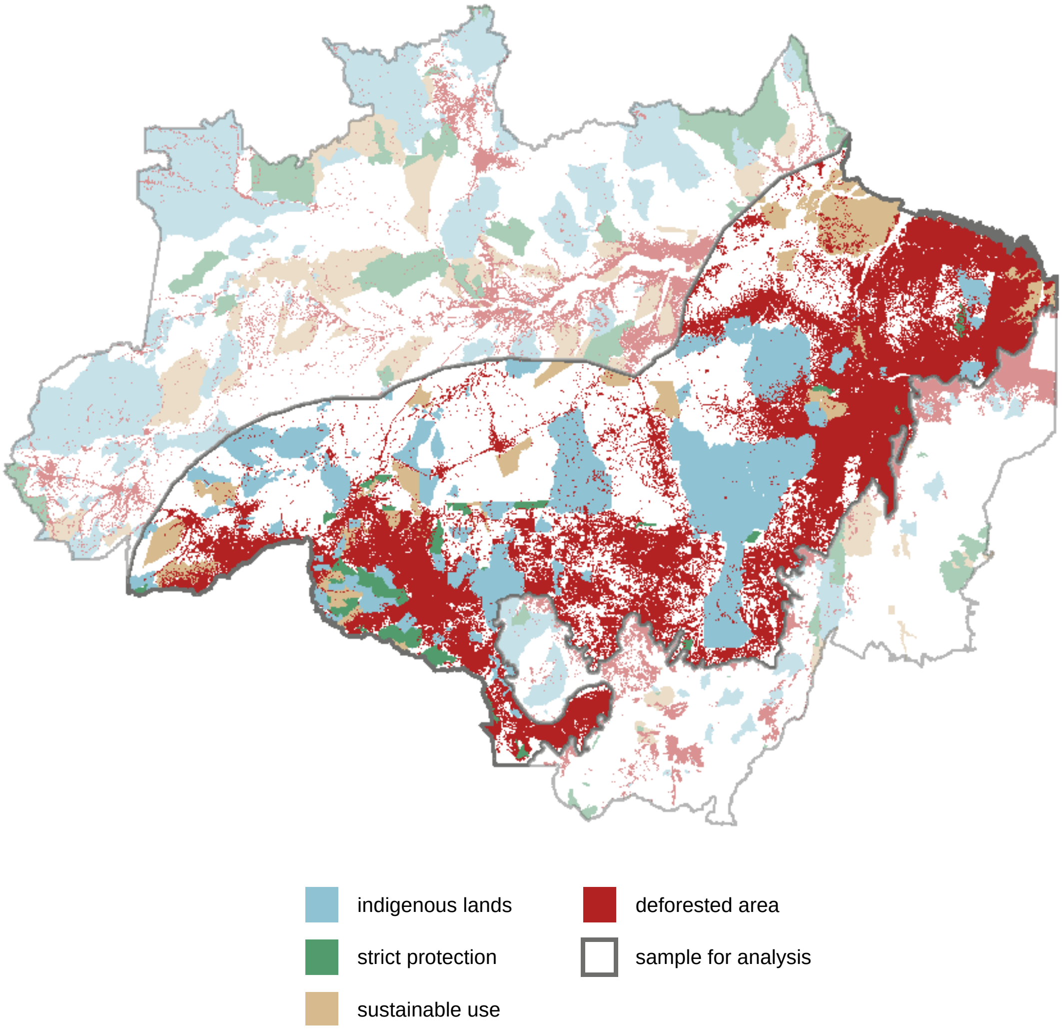
zones were meant to serve as shields against forest clearing pressures.

Prior to the PPCDAm, tropical clearings concentrated along the so-called Deforestation Arc, a region that historically captured the agricultural frontier pushing into the forest (see Figure 2). Protected territory spread throughout the Amazon, but much of it was located in the Amazon hinterland.[4] Yet, under the action plan, almost 35 million hectares of protected territory were allocated in regions under high risk of deforestation, as captured by their proximity to the Deforestation Arc (see Figure 3). Newly protected territory in these high-pressure zones largely consisted of protected areas for sustainable use and strictly protected areas, which could be more easily created by the government as compared to indigenous lands.

In practice, how is protection implemented? From a legal standpoint, an offender who engages in illegal forest clearing activity in protected territory is subject to harsher criminal and/or administrative penalties. Someone occupying territory in public domain, which includes both protected areas and indigenous lands, can be criminally charged and sentenced to three years of jail time (Brasil, 1966). Because Brazil's Federal Constitution assigned special preservation status to the Amazon biome, illegal deforestation in all public lands inside the biome is already subject to harsher penalties than outside it (Brasil, 1988, 1998). The

[4]Several studies empirically document that protection in tropical forests, including the Amazon, is often located in remote areas far from deforestation pressures (DeFries et al., 2005; Joppa et al., 2008; Joppa and Pfaff, 2011).

Figure 2: Deforestation and Protection Before the Action Plan



Notes: The map shows accumulated deforestation through 2004 and protected territory status in 2004, before the action plan was launched. Dimmed regions are non-sample areas (see Section 4.3 for sample definition). Data sources: PRODES/Inpe (deforestation); FUNAI and ISA (indigenous lands); MMA (protected areas); IBGE (Legal Amazon, Amazon biome).

country's Law of Environmental Crimes reinforces this by determining that illegal deforestation and/or degradation in all public areas of the Amazon biome are punishable with fines and two to four years of imprisonment (Brasil, 1998). Moreover, all direct and indirect harm caused to protected areas are further subject to one to five years of imprisonment (Brasil, 1998).[5]

Alongside criminal penalties, offenders also face administrative penalties. Illegal clearings in all public areas of the Amazon biome are subject to a fine of USD 3,000 per cleared hectare; in protected areas, this fine increases to USD 3,800 per cleared hectare.[6] Protection status also allows enforcers to apply an additional penalty

[5]Although protected areas for sustainable use are often mistakenly thought to be laxer in terms of environmental regulation, this view has no legal support; if not duly licensed/authorized, deforestation in these areas is legally equivalent to forest clearing in strictly protected areas.

[6]US dollar values calculated from Brazilian currency using the exchange rate from the period

that doubles the total amount offenders must pay (Brasil, 2008). In addition to the direct financial cost imposed by fines, criminal and administrative processes also carry large processing fees and legal costs. As such, even in a context of knowingly low collection rates for fines (Barreto et al., 2009; Börner et al., 2014; Schmitt, 2015), criminal and administrative charges carry a large financial burden. Fines are also typically accompanied by administrative measures aimed at further increasing this burden. These measures include, but are not limited to, seizure of illegally produced goods, seizure and/or destruction of machinery used for forest clearings, and production embargoes (Brasil, 2008). Combined, criminal and administrative penalties significantly increase the expected cost of clearing Amazon forest under protection.

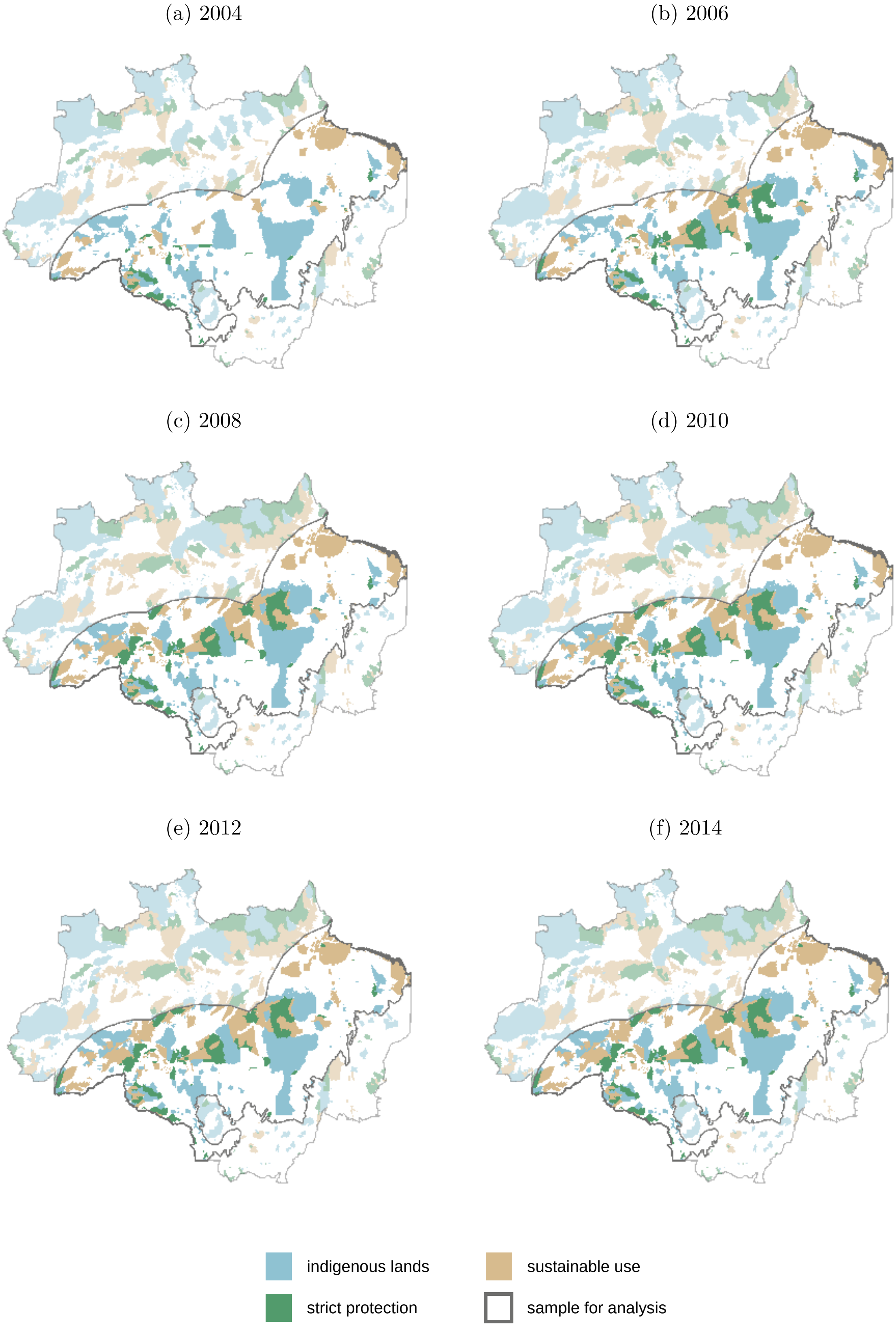
Beyond the existing legal framework for more severely punishing illegal deforestation inside protected territory, forest clearings in these areas are also subject to considerably greater public scrutiny. In addition to Ibama, which monitors the full extent of the Amazon, the Chico Mendes Institute for Biodiversity Conservation (ICMBio) and the Brazilian Native Peoples Foundation (FUNAI) also perform monitoring of federal protected areas and indigenous lands, respectively. Deforestation in protected territory also attracts much attention from both national and international medias, as well as from the civil society. Finally, native peoples in indigenous lands are anecdotally known to defend their territory from invasions and predatory use by third parties. Although this sort of dedicated monitoring by government agencies and local stakeholders cannot be directly quantified, it is likely that they, too, contribute to the overall sense that illegal clearings in protected territories are being more closely watched than those in their unprotected counterparts.

2.4. Rationale for Individual Land Use Decision

Since the seminal work of Becker (1968), an individual's decision to engage in an illegal activity has been modeled as an optimization problem in which the individual compares the expected gain of that activity with the expected cost of getting caught and punished. Bearing this in mind, consider an environmental offender who practices illegal deforestation in a given region that holds both protected and unprotected forests. When deciding where to deforest, the cost-minimizing offender will select the area perceived as less likely to result in his getting caught and punished. Because protected territory is under greater scrutiny, offenders clearing protected forests have a higher chance of getting caught. Moreover, when caught, these offenders face more severe criminal and administrative charges, including heavier financial penalties. It is therefore reasonable to posit that the expected cost of clearing forest in protected territory

during which the associated regulations were passed.

Figure 3: Targeted Expansion of Protected Territory



Notes: The maps show type-specific protection status in select years. Dimmed regions are non-sample areas (see Section 4.3 for sample definition). Data sources: FUNAI and ISA (indigenous lands); MMA (protected areas); IBGE (Legal Amazon, Amazon biome).

would be perceived as significantly higher, ultimately inhibiting offenders from operating in these territories. As such, legal protection would grant actual protection, serving as a shield against advancing deforestation.

3. Empirical Strategy

The proposed empirical strategy aims at assessing protected territory's capacity to shield against deforestation by comparing forest clearing outcomes in protected versus unprotected localities under equivalent deforestation pressures. Because deforestation exhibits spatial persistence, areas close to clearing activity are likely under greater risk of being themselves deforested. In light of this, the starting point for the analysis is a test of whether the intensity of alerts in a cell's neighborhood in a given year is associated with forest clearings inside that cell the following year. A positive association indicates that neighborhood alert intensity serves as a measure of cell-level deforestation pressure. The analysis then builds on this using variation in protection status both across cells and over time to evaluate if forest clearings advance over protected versus unprotected cells differently. The benchmark estimation equation is:

$$\begin{aligned} deforest_{i,t} = & \sum_{n \in \partial i} \{\alpha_n alerts_{n,i,t-1} + \beta_n (alerts_{n,i,t-1} * protect_{i,t-1})\} \\ & + X'_{i,t-1}\theta + \gamma_i + \delta_t + \varepsilon_{i,t} \end{aligned} \tag{1}$$

where $deforest_{i,t}$ is the deforested area in cell i and year t; for each of cell i's n neighborhoods, $alerts_{n,i,t-1}$ is a neighborhood-specific measure of deforestation pressure in year $t-1$, as measured by neighborhood alert intensity; $protect_{i,t-1}$ is an indicator that equals 1 when cell i is protected in year $t-1$, and 0 otherwise; $X_{i,t-1}$ is a vector of cell-level controls for geography (cloud-based satellite visibility, weather) and observed conservation policy (local law enforcement, priority municipality status); γ_i and δ_t are, respectively, cell and year fixed effects; and $\varepsilon_{i,t}$ is the cell-year idiosyncratic error. Estimates are robust to heteroskedasticity, and standard errors are clustered at the municipality level in all specifications, making them robust to intra-municipal serial correlation (Bertrand et al., 2004). For each cell, multiple neighborhoods are formed by concentric rings of increasing diameter around it. Dataset construction is such that each of the cell's neighborhood rings contains neither the cell itself nor any of the smaller concentric rings (see Appendix Appendix A.1). Coefficients α_n therefore capture whether forest clearings happening in a cell's neighboring region are associated with the risk of deforestation happening inside the cell; $\alpha_n > 0$ indicates that cells facing more intense clearing activity in their surroundings are under greater deforestation pressure. In turn, interaction coefficients β_n capture a differential effect for protected cells; $\beta_n < 0$ indicates that deforestation was effectively diverted from protected cells.

The identification of protected territory's shielding capacity fundamentally comes from the comparison of deforestation outcomes in protected versus unprotected cells exposed to equivalent deforestation pressures. This is particularly relevant in light of the discussion in the literature that the variation in deforestation pressures across the landscape have important implications for the evaluation of average protection effectiveness in the Amazon (Nepstad et al., 2006; Nolte et al., 2013; Pfaff et al., 2014, 2015). The use of cell fixed effects controls for potentially confounding time-invariant cell characteristics, such that coefficients are estimated using within-cell variation across time. Equation 1 also includes year fixed effects to recover impacts net of sample-wide annual shocks, as well as a host of cell-level controls to mitigate omitted variable bias. The first set of controls focuses on geographic variables. Remote sensing data are limited by visual obstructions that block the Earth's surface from view in imagery. Satellite visibility can affect not only recorded cell deforestation, but also alerts issued inside the cell (see Appendices Appendix B.2 and Appendix B.3). The benchmark specification accounts for these effects using information on unobservable areas in satellite imagery for both forest clearing and alert data. Local weather might also be correlated with local deforestation and neighborhood alert intensity. Certain weather conditions could favor clearings by facilitating access to forested areas, enabling the use of fires, or even influencing the expected productivity and thereby the expected value of deforested land. Rainfall and temperature could also correlate with cloud coverage limiting satellite visibility. All specifications therefore include controls for average annual temperature and total annual rainfall. The second set of controls accounts for other policies aimed at combating deforestation. These are admittedly more endogenous, but serve as a robustness test for the stability of estimated coefficients. Policy controls include the indicator for cell protection status $protect_i$, an indicator variable flagging whether the cell belong to a priority municipality, and a measure for the intensity of alerts issued inside the cell.

The timing of the deforestation response is also a relevant component of the identification strategy. When choosing where to deforest, an offender plausibly uses observational data collected in the past to inform his present decision. Moreover, moving across Amazon forest sites, where transport infrastructure is knowingly very poor (Weinhold and Reis, 2008; Börner et al., 2014, 2015), is a time-consuming process. As such, the response in deforestation is not expected to be concurrent, but rather lagged. Equation 1 sets a one-year lag for most independent variables, the only exception being satellite visibility for deforestation outcome data.

4. Data

The analysis is entirely based on spatial data that are publicly available from a variety of sources. This section provides a brief description of variables and presents descriptive statistics. The appendices contain detailed information on the empirical spatial setup (Appendix Appendix A) and data sources (Appendix Appendix B).

4.1. Main Variables

Cell-level deforestation is built from georeferenced data on Amazon-wide annual deforestation increments from PRODES/Inpe (see Appendix Appendix B.2). The outcome of interest is deforestation increment as a share of cell area. It is calculated using vector deforestation data rasterized at the 30m resolution and total minicell count for each cell.

Forest clearing alert data come from DETER/Inpe (see Appendix Appendix B.3). Monthly vector data on georeferenced alerts are rasterized at the 900m resolution, such that a cell will take on a value of 1 if it contains an alert and a value of 0 otherwise.[7,8] Neighborhood intensity is calculated as the annual number of alert cells in each neighborhood as a share of total neighborhood cell count.[9]

Spatial data on protection history for strictly protected areas and protected areas for sustainable use are provided by the MMA. Analogous data for indigenous lands are compiled from FUNAI and the non-governmental Socioenvironmental Institute (ISA) (see Appendix Appendix B.4). Annual protection status indicators are constructed from type-specific protected territory cover rasterized at the 900m resolution, which are then used to build a general protection indicator that annually flags whether a cell was under protection of any kind.

4.2. Controls

The benchmark specification in Equation 1 includes two sets of cell-level controls, in addition to cell and year fixed effects. First, geography controls account for natural phenomena. Clouds, shadows cast by clouds, and smoke from forest fires can all affect visibility in satellite imagery. Inpe releases spatial data on land areas blocked from view for both PRODES and DETER. Satellite visibility

[7] In practice, the rasterization algorithm assigns value 1 to a cell only if its centroid is contained within a polygon in the vector data. Because deforestation alerts can be as small as 25ha and the raster cells have an area of 81ha, running the algorithm on the raw vector resulted in the loss of a large amount of alerts. I therefore created a 1km buffer around all alerts and only then rasterized the alert-plus-buffer vector data, thereby ensuring that if a cell fell within 1km of an alert, it would be assigned value 1 during rasterization. For simplicity, I refer to this alert-plus-buffer area simply as the alert area throughout the analysis.

[8] There are a few occurrences of biweekly data, particularly in earlier DETER years. For a month with two deforestation alert datasets, I overlay the biweekly data to calculate total alert area for that month, as per Inpe's recommendation.

[9] Missing months in vector data indicate that no alerts were issued by DETER in that month.

controls for PRODES indicate the annual share of cell area suffering from visual obstructions, as captured by rasterizing vector data on unobservable areas at the 30m resolution. As DETER offers monthly data, its satellite visibility control is a cell-level measure of time spent blocked from view during one year.[10] Monthly data compiled by Matsuura and Willmott (2015) serve as the basis for building weather controls. The authors use multiple sources of global weather data and apply geographic extrapolations to calculate a regular georeferenced world grid of estimated temperature and rainfall over land.[11] Data points in the original dataset refer to grid nodes, not cells, such that average annual temperature and total annual rainfall are calculated from the monthly data for each Amazon grid node. Because the spatial resolution for this dataset is much lower than 900m, cell weather values are based on the average values for all grid node values within 180km of each cell to ensure all sample cells had non-missing weather data.

Second, observed policy controls address relevant conservation efforts that could affect deforestation pressures and local clearings. Two of these controls come from dataset that have already been described: the cell indicators for protection status and DETER alert area. The latter is an indicator variable if the cell itself contained a DETER alert in a given year. The last control refers to the cell being in a priority municipality. It is built from information contained in each of the MMA's annual listings of municipalities that were attributed priority status or removed from the blacklist. The 2007 Brazilian municipal division from the Brazilian Institute for Geography and Statistics (IBGE) is rasterized at the 900m resolution and is used to assign each cell to a single municipality.

4.3. Descriptive Statistics

At the 900m resolution, the Amazon biome raster contains 5.2 million cells. As this implies a very high number of observations, limited computational capacity for calculating cell-level fixed effects estimators imposed a sample restriction. Figure 4 illustrates the spatial sample, defined as the region inside the Amazon biome that is within 750km from its southeast border.[12]

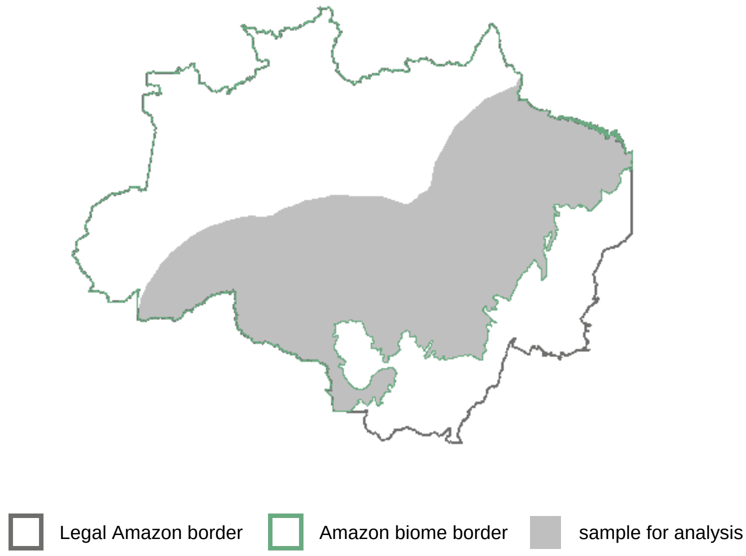
The spatial sample contains 2,880,663 cells. It extends over 55% of the Amazon biome, and captures 45% of its protected territory (see Figure 5). The distribution of protection inside the sample is broadly representative of the Amazon, with protected areas for sustainable use and indigenous lands each covering about a fifth of the

[10] As with DETER alerts, there are some months for which Inpe releases biweekly cloud coverage vector data. For these months, I intersect the biweekly data to identify areas that were blocked from view throughout the whole month. Note that this is different to the overlay method used for alerts — the procedure is performed as per Inpe's recommendation.

[11] This database has been extensively used in the economic literature both to evaluate the impact of climate variables on economic outcomes and to provide relevant rainfall and temperature controls (Dell et al., 2014).

[12] Although the PPCDAm applied to the entire Brazilian Legal Amazon, over 90% of tropical deforestation over the past two decades was located inside the biome.

Figure 4: Amazon Spatial Boundaries and Sample Definition



Notes: The map shows spatial boundaries for the Brazilian Legal Amazon and the Amazon biome, as well as for the analysis' spatial sample, which is defined as the area inside the Amazon biome that is within 750km from its southeast border. Data sources: IBGE (Legal Amazon, Amazon biome).

Table 1: Sample Protection and Deforestation by Year

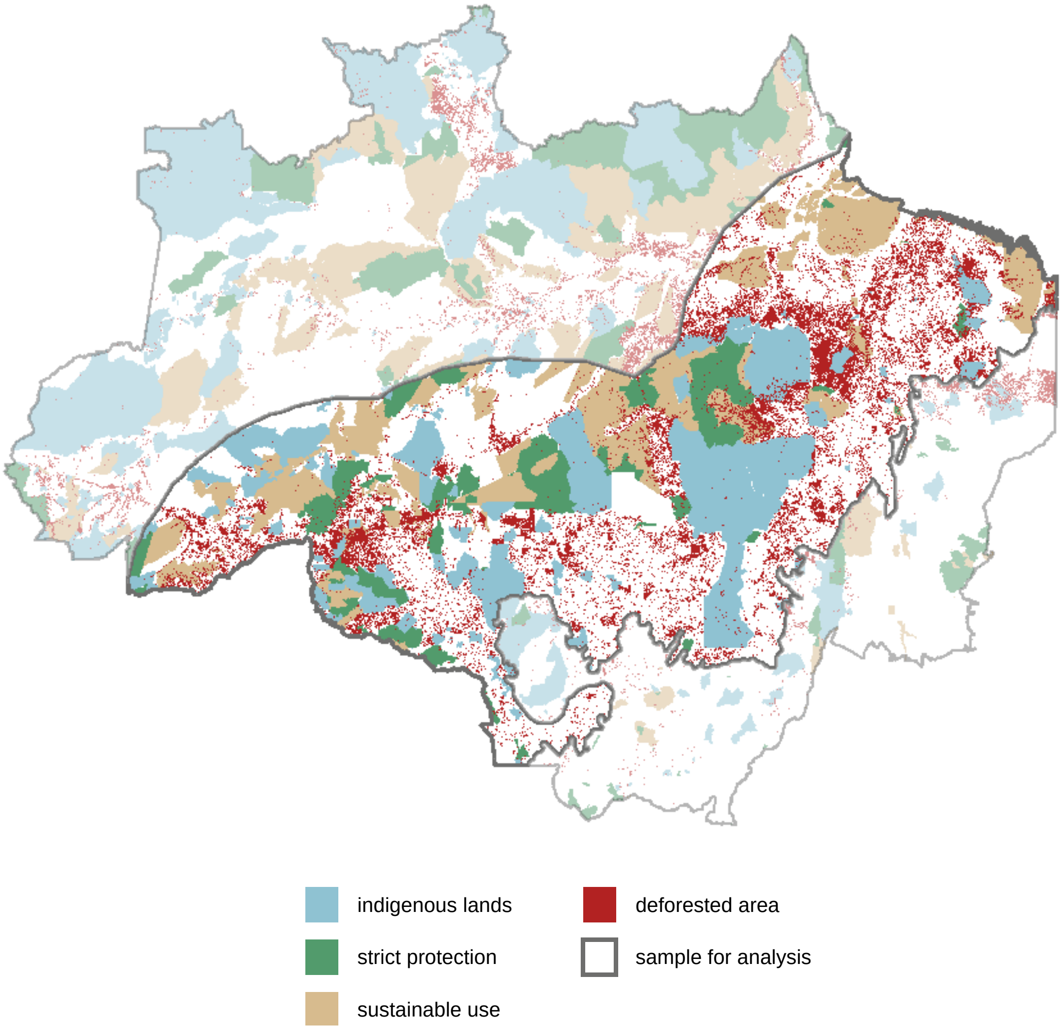
year	protected territory (ha)			deforestation (ha)	deforestation in protected territory (ha)		
	strict	sustainable	indigenous		strict	sustainable	indigenous
2006	14,390,361	29,187,312	43,760,741	957,654	9,845	33,993	16,925
2007	14,390,361	31,468,158	44,439,699	993,454	7,813	91,605	19,935
2008	16,908,733	34,646,834	44,602,169	1,082,954	11,311	65,311	30,395
2009	17,348,376	36,233,997	44,891,184	521,516	4,572	47,442	26,731
2010	17,354,740	36,235,850	44,912,771	481,134	3,144	38,771	12,718
2011	17,420,710	36,238,266	45,103,968	465,216	2,319	28,457	15,589
2012	17,420,710	36,238,347	45,104,613	359,672	2,793	27,550	11,302
2013	17,420,710	36,238,508	45,104,613	464,327	2,363	36,618	11,946
2014	17,420,710	36,238,508	45,120,562	409,924	1,364	38,156	5,743

Notes: The table reports annual protected territory coverage by protection type, deforestation increment, and deforestation increment inside protected territory for the sample region. Data sources: FUNAI and ISA (indigenous lands); MMA (protected areas); PRODES/Inpe (deforestation).

sample region, and strictly protected areas accounting for less than 10% of it. Table 1 presents protection coverage totals by type and year, showing that sample protected areas expanded by 20–25% from 2006 through 2014, while indigenous lands only grew by 3%. This is consistent with Brazil's institutional framework, which allows for the creation of protected areas, but not of indigenous lands.

In contrast, deforestation during the sample period was greatly concentrated inside the sample region (see Figure 5). It held more than 95% of total DETER alert area, and saw over 5.7 million hectares of cleared forest. As protection effectiveness crucially depends on local deforestation pressures, the sample region was intentionally designed to capture high-risk areas and, in doing so, assess

Figure 5: Sample Protection and Deforestation



Notes: The map shows protected territory status by protection type in 2014, and total area deforested from 2007 through 2014. Dimmed regions are non-sample areas (see Section 4.3 for sample definition). Data sources: FUNAI and ISA (indigenous lands); MMA (protected areas); PRODES/Inpe (deforestation); IBGE (Legal Amazon, Amazon biome).

protection's shielding capacity when faced with an actual threat. Table 1 provides annual areas cleared in the sample as a whole, as well as inside protected territory of each type.

Finally, Table 2 reports annual summary statistics for regression variables, showing that both the outcome of interest and key regressors exhibited cell-level variation across years.

5. Results

This section starts by empirically testing whether the intensity of neighborhood forest clearing alerts is associated with cell-level deforestation outcomes, and then builds on this to assess whether protection serves as a shield against forest loss. It follows with robustness checks, an investigation of heterogeneity across different

Table 2: Descriptive Statistics for Regression Variables

	sample years								
	2006	2007	2008	2009	2010	2011	2012	2013	2014
deforestation increment (% cell area)									
mean	0.0041	0.0043	0.0047	0.0022	0.0021	0.0020	0.0016	0.0020	0.0018
standard deviation	0.0378	0.0377	0.0377	0.0244	0.0215	0.0219	0.0202	0.0241	0.0228
alerts 50km ring (% ring area)									
mean	0.0196	0.0099	0.0198	0.0118	0.0076	0.0086	0.0062	0.0073	0.0085
standard deviation	0.0323	0.0153	0.0285	0.0173	0.0113	0.0139	0.0108	0.0130	0.0150
alerts 100km ring (% ring area)									
mean	0.0188	0.0098	0.0189	0.0117	0.0076	0.0086	0.0061	0.0072	0.0084
standard deviation	0.0234	0.0107	0.0214	0.0114	0.0077	0.0098	0.0078	0.0094	0.0109
d=1 if protected cell									
mean	0.3668	0.3796	0.4021	0.4120	0.4122	0.4124	0.4124	0.4124	0.4125
standard deviation	0.4819	0.4853	0.4903	0.4922	0.4922	0.4923	0.4923	0.4923	0.4923
unobservable PRODES (% cell area)									
mean	0.0362	0.0268	0.0221	0.0346	0.0364	0.0271	0.0285	0.0467	0.0470
standard deviation	0.1554	0.1259	0.1182	0.1506	0.1558	0.1318	0.1319	0.1727	0.1724
unobservable DETER (% cell area)									
mean	0.3601	0.5842	0.4614	0.5468	0.4336	0.4650	0.3191	0.3257	0.4270
standard deviation	0.0848	0.1317	0.2187	0.2106	0.2090	0.1687	0.1951	0.1972	0.2402
rainfall (mm)									
mean	2,254	2,135	2,162	2,223	2,015	2,157	2,080	2,215	2,181
standard deviation	426	447	402	383	309	349	418	423	398
temperature (Celsius)									
mean	26.05	26.22	25.90	26.14	26.73	26.45	26.22	26.24	26.07
standard deviation	1.04	1.04	1.21	1.20	1.33	1.23	1.22	1.16	1.26
d=1 if DETER alert in cell									
mean	0.0198	0.0100	0.0202	0.0118	0.0076	0.0087	0.0062	0.0073	0.0085
standard deviation	0.1394	0.0997	0.1407	0.1081	0.0870	0.0931	0.0785	0.0850	0.0917
d=1 if priority municipality									
mean	0.0000	0.0000	0.3142	0.3142	0.3479	0.3396	0.3506	0.3486	0.3294
standard deviation	0.0000	0.0000	0.4642	0.4642	0.4763	0.4736	0.4772	0.4765	0.4700

Notes: The table presents mean and standard deviations for variables used in the empirical analysis. Units are shown in parentheses; indicator variables are identified with “d=1”.

types of protection and proximity to transport infrastructure, and closes with counterfactual exercises that hypothetically revoke protection.

5.1. Main Results: Pressure and Protection

In the current empirical setting, if neighboring forest clearing activity serves as a measure of local deforestation pressures, alert intensity in a cell’s surroundings should have a non-null association with that cell’s deforestation outcome. Table 3 presents estimated coefficients that test for the existence and reach of this association. Columns 1 through 3 only control for cell and year fixed effects, but gradually increase maximum neighborhood size in 50km ring increments from 50km through 150km; columns 4 and 5 hold maximum neighborhood size fixed, but gradually include cell-level geography and observed policy controls. Coefficients remain positive, statistically significant, and largely stable across specifications for the 50km neighborhood, indicating that current clearing activity within 50km of a cell are associated with increased future clearings inside that cell. Deforestation activity happening further away, beyond the 50km neighborhood, does not appear to be associated with local clearing pressure. This is consistent

Table 3: Neighborhood Clearing Activity and Local Deforestation Outcomes

	deforestation increment in cell (t)				
	(1)	(2)	(3)	(4)	(5)
alerts 50km (t-1)	0.0338**	0.0339**	0.0332**	0.0334**	0.0306**
	(0.0133)	(0.0165)	(0.0162)	(0.0158)	(0.0154)
alerts 100km (t-1)		-0.0002	0.0098	0.0083	0.0071
		(0.0117)	(0.0102)	(0.0100)	(0.0098)
alerts 150km (t-1)			-0.0160	-0.0185	-0.0203*
			(0.0122)	(0.0121)	(0.0122)
R-squared	0.0024	0.0024	0.0024	0.0033	0.0036
number of observations	23,045,304	23,045,304	23,045,304	23,045,304	23,045,304
number of cells	2,880,663	2,880,663	2,880,663	2,880,663	2,880,663
controls					
cell fixed effects	yes	yes	yes	yes	yes
year fixed effects	yes	yes	yes	yes	yes
geography	no	no	no	yes	yes
observed policy	no	no	no	no	yes

Notes: The table reports fixed effects coefficients for Equation 1 (Section 3). The dependent variable is the cell-level deforestation increment (deforested area in cell i and year t as a share of total cell area). Reported independent variables are neighborhood alert intensities in year $t-1$ (total alert area as a share of total neighborhood area). Maximum neighborhood size increases from 50km (column 1) through 150km (columns 2 through 3), and controls are added gradually to the specification with the maximum neighborhood (columns 4 and 5). The no/yes markers in bottom rows indicate the inclusion of the following sets of cell-level controls: (i) cell and year fixed effects; (ii) geography: measuring and monitoring satellite visibility, precipitation, and temperature; and (iii) observed policy: alert intensity, protection status, and priority municipality status. The cell-by-year panel includes 2,880,663 cells located within 750km from the Brazilian Amazon biome southeast border and covers the 2006 through 2014 period. Standard errors are robust and clustered at the municipality level. Significance levels: *** p<0.01, ** p<0.05, * p<0.10.

with the idea that transportation within the Amazon is costly. As the region's vast dimensions are poorly connected by transport infrastructure, it is likely that deforestation operations are at least partially constrained by the feasibility of moving personnel, machinery, and goods across large distances. I therefore restrict the benchmark specification to a maximum ring distance of 100km, but only expect to see a shielding effect for protection through 50km. The negative, albeit less significant, coefficient for the 150km neighborhood suggests a different effect might be in place for distant clearing activities, but offers little information as to what this effect might be. Because I use deforestation pressure as a tool through which to asses protected territory's shielding capacity, I delve no further into this negative effect, but conduct robustness checks to test whether it affects the analysis' key findings.

Having shown that forest clearing alerts within 50km of a cell serve as a measure of local deforestation pressure, I now inspect whether protected and unprotected cells are equally affected by this pressure. If expected costs of engaging in forest clearing practices inside protected territory are higher, cell-level legal protection status should mitigate the positive relationship seen in Table 3. Unprotected territory is therefore expected to be more severely affected by advancing deforestation than protected territory. In light of this, Table 4 reports estimated coefficients for both neighborhood alert intensities and interaction terms between these intensities and cell protection status. Controls are included gradually to test the sensibility of results. The benchmark specification containing the full set of controls is presented in Table 4, column 3. Results show that, when exposed to the threat of deforestation, protected cells see significantly less forest clearings that similarly threatened unprotected ones. Again, estimated coefficients remain stable across the inclusion of controls, and clearing activity in the more distant neighborhood ring appears to have no significant effect on either protected or unprotected cells. Estimates indicate that the shielding effect is sizable. Under an increase of one standard deviation in the intensity of neighborhood alerts, the difference in clearings for unprotected and protected cells amounts to 3% of the sample standard deviation, or 26% of the sample mean.

Hence, at the cell level, legal protection seems to grant actual protection by serving as a shield against advancing forest clearings. This finding is consistent with Brazil's institutional framework, which implies a higher cost for clearing Amazon forest under protection due to both a greater chance of getting caught and heavier penalties. Moreover, the evidence lends support to the action plan's novel siting strategy — protection effectively blocked advancing deforestation from moving into protected forests.

5.2. Robustness: Extended Neighborhoods

Results from Table 3 revealed that the relationship between neighborhood forest clearing activities and local deforestation pressures is not stable across increasingly distant neighborhoods. As a robustness check, I test whether the main finding that protection serves as a shield against advancing deforestation holds when accounting for alert intensity through extended neighborhoods. Even columns in Table 5 report results for specifications that use 150km as the maximum neighborhood ring and gradually include the sets of controls. For comparison purposes, the table also reproduces coefficients from Table 3 in odd columns. Reassuringly, estimated coefficients remain largely robust both in magnitude and significance across specifications. Thus, accounting for clearing activities in more distant regions does not affect the finding that legal protection effectively protects territory within its domain from deforestation threats.

5.3. Heterogeneity: Protection Type and Transportation Infrastructure

This section individually explores two different dimensions of heterogeneity: protection type and proximity to transport infrastructure. So far, the analysis has treated protected territory as a single, uniform group. Yet, Amazon protected

Table 4: Protected Territory as a Shield to Advancing Deforestation

	deforestation increment in cell (t)		
	(1)	(2)	(3)
alerts 50km (t-1)	0.0376*	0.0376*	0.0347*
	(0.0204)	(0.0197)	(0.0191)
alerts 50km * protected (t-1)	-0.0385*	-0.0376*	-0.0371**
	(0.0201)	(0.0193)	(0.0185)
alerts 100km (t-1)	0.0039	0.0021	0.0003
	(0.0161)	(0.0150)	(0.0147)
alerts 100km * protected (t-1)	-0.0079	-0.0102	-0.0117
	(0.0179)	(0.0170)	(0.0170)
R-squared	0.0025	0.0034	0.0036
number of observations	23,045,304	23,045,304	23,045,304
number of cells	2,880,663	2,880,663	2,880,663
controls			
cell fixed effects	yes	yes	yes
year fixed effects	yes	yes	yes
geography	no	yes	yes
observed policy	no	no	yes

Notes: The table reports fixed effects coefficients for Equation 1 (Section 3). The dependent variable is the cell-level deforestation increment (deforested area in cell i and year t as a share of total cell area). Reported independent variables are neighborhood alert intensities in year $t-1$ (total alert area as a share of total neighborhood area), and interaction terms between neighborhood alert intensities and cell protection status in year $t-1$ (d=1 if cell i protected). All specifications contain both 50km and 100km neighborhood rings. The no/yes markers in bottom rows indicate the inclusion of the following sets of cell-level controls: (i) cell and year fixed effects; (ii) geography: measuring and monitoring satellite visibility, precipitation, and temperature; and (iii) observed policy: alert intensity, protection status, and priority municipality status. The cell-by-year panel includes 2,880,663 cells located within 750km from the Brazilian Amazon biome southeast border and covers the 2006 through 2014 period. Standard errors are robust and clustered at the municipality level. Significance levels: *** p<0.01, ** p<0.05, * p<0.10.

territory is divided into three distinct categories: indigenous lands, strictly protected areas, and protected areas for sustainable use. These categories have been found to differ in terms of their impact on local deforestation outcomes, arguably due to their being allocated in regions under systematically lower or greater deforestation pressures (Nepstad et al., 2006; Nolte et al., 2013; Pfaff et al., 2014, 2015). If a specific type of protected territory is located in a less risky area, its actual contribution to avoid deforestation in that area might be relatively smaller. Moreover, because each protection type has its own set of regulations regarding illegal forest conversion and associated punishments (see Section 2.3), the estimated shielding capacity for the full set of protected cells need not be homogeneous across protection types.

In light of this, I re-estimate protection shielding capacity, but now distinguish between the type of protection in each cell. Table 6 presents estimated coefficients under the gradual inclusion of controls. Shielding capacity varies across protection

Table 5: Robustness – Extended Neighborhoods

	deforestation increment in cell (t)					
	(1)	(2)	(3)	(4)	(5)	(6)
alerts 50km (t-1)	0.0376*	0.0373*	0.0376*	0.0372*	0.0347*	0.0343*
	(0.0204)	(0.0202)	(0.0197)	(0.0195)	(0.0191)	(0.0189)
alerts 50km * protected (t-1)	-0.0385*	-0.0401**	-0.0376*	-0.0395**	-0.0371**	-0.0393**
	(0.0201)	(0.0201)	(0.0193)	(0.0194)	(0.0185)	(0.0187)
alerts 100km (t-1)	0.0039	0.0120	0.0021	0.0112	0.0003	0.0098
	(0.0161)	(0.0148)	(0.0150)	(0.0142)	(0.0147)	(0.0140)
alerts 100km * protected (t-1)	-0.0079	-0.0022	-0.0102	-0.0043	-0.0117	-0.0035
	(0.0179)	(0.0179)	(0.0170)	(0.0178)	(0.0170)	(0.0179)
alerts 150km (t-1)		-0.0142		-0.0164		-0.0172
		(0.0182)		(0.0176)		(0.0172)
alerts 150km * protected (t-1)		-0.0050		-0.0049		-0.0078
		(0.0168)		(0.0161)		(0.0148)
R-squared	0.0025	0.0025	0.0034	0.0034	0.0036	0.0036
number of observations	23,045,304	23,045,304	23,045,304	23,045,304	23,045,304	23,045,304
number of cells	2,880,663	2,880,663	2,880,663	2,880,663	2,880,663	2,880,663
controls						
cell fixed effects	yes	yes	yes	yes	yes	yes
year fixed effects	yes	yes	yes	yes	yes	yes
geography	no	no	yes	yes	yes	yes
observed policy	no	no	no	no	yes	yes

Notes: The table reports fixed effects coefficients for Equation 1 (Section 3). The dependent variable is the cell-level deforestation increment (deforested area in cell i and year t as a share of total cell area). Reported independent variables are neighborhood alert intensities in year $t-1$ (total alert area as a share of total neighborhood area), and interaction terms between neighborhood alert intensities and cell protection status in year $t-1$ (d=1 if cell i protected). Odd columns replicate the gradual inclusion of controls in the benchmark specification from Table 4; even columns perform the same gradual inclusion of controls with an extended maximum neighborhood ring of 150km. The no/yes markers in bottom rows indicate the inclusion of the following sets of cell-level controls: (i) cell and year fixed effects; (ii) geography: measuring and monitoring satellite visibility, precipitation, and temperature; and (iii) observed policy: alert intensity, protection status, and priority municipality status. The cell-by-year panel includes 2,880,663 cells located within 750km from the Brazilian Amazon biome southeast border and covers the 2006 through 2014 period. Standard errors are robust and clustered at the municipality level. Significance levels: *** p<0.01, ** p<0.05, * p<0.10.

types. Although point estimates for this neighborhood's interaction coefficients are all negative, the shielding effect is stronger in magnitude and significance in protected areas for sustainable use. Strict protection provides some shielding, albeit at lower statistical significance, and indigenous lands do not appear to significantly block advancing clearings. Differences in regulation might explain the variation in shielding capacity across protection types, but the actual details of how different institutional settings influence shielding are yet to be understood. Finally, the significantly negative coefficient for the interaction between enforcement intensity in the outer 100km ring and indigenous lands is a clear deviation from the pattern observed thus far. There is no evidence to suggest that a specific protection type was systematically assigned to more or less risky regions in the sample, so potential underlying reasons for this are still under investigation.

The second set of heterogeneity exercises assesses if shielding capacity varies according to the cell-level distance to transport infrastructure. As transportation

Table 6: Heterogeneity – Protection Types

	deforestation increment in cell (t)		
	(1)	(2)	(3)
alerts 50km (t-1)	0.0368*	0.0369*	0.0341*
	(0.0200)	(0.0193)	(0.0187)
alerts 50km * protected indigenous (t-1)	-0.0239	-0.0222	-0.0207
	(0.0205)	(0.0198)	(0.0189)
alerts 50km * protected strict (t-1)	-0.0328*	-0.0299	-0.0331*
	(0.0197)	(0.0193)	(0.0190)
alerts 50km * protected sustainable (t-1)	-0.0622***	-0.0655***	-0.0660***
	(0.0196)	(0.0186)	(0.0184)
alerts 100km (t-1)	0.0049	0.0030	0.0009
	(0.0155)	(0.0145)	(0.0142)
alerts 100km * protected indigenous (t-1)	-0.0258*	-0.0303**	-0.0333**
	(0.0140)	(0.0132)	(0.0136)
alerts 100km * protected strict (t-1)	-0.0048	-0.0044	0.0017
	(0.0138)	(0.0136)	(0.0139)
alerts 100km * protected sustainable (t-1)	0.0417	0.0470	0.0491
	(0.0369)	(0.0363)	(0.0347)
R-squared	0.0025	0.0034	0.0037
number of observations	23,045,304	23,045,304	23,045,304
number of cells	2,880,663	2,880,663	2,880,663
controls			
cell fixed effects	yes	yes	yes
year fixed effects	yes	yes	yes
geography	no	yes	yes
observed policy	no	no	yes

Notes: The table reports fixed effects coefficients for Equation 1 (Section 3). The dependent variable is the cell-level deforestation increment (deforested area in cell i and year t as a share of total cell area). Reported independent variables are neighborhood alert intensities in year $t-1$ (total alert area as a share of total neighborhood area), and interaction terms between neighborhood alert intensities and type-specific cell protection status in year $t-1$ (d=1 if cell i protected). Protection types are indigenous lands (indigenous), strictly protected areas (strict), and protected areas for sustainable use (sustainable). The no/yes markers in bottom rows indicate the inclusion of the following sets of cell-level controls: (i) cell and year fixed effects; (ii) geography: measuring and monitoring satellite visibility, precipitation, and temperature; and (iii) observed policy: alert intensity, protection status, and priority municipality status. The cell-by-year panel includes 2,880,663 cells located within 750km from the Brazilian Amazon biome southeast border and covers the 2006 through 2014 period. Standard errors are robust and clustered at the municipality level. Significance levels: *** p<0.01, ** p<0.05, * p<0.10.

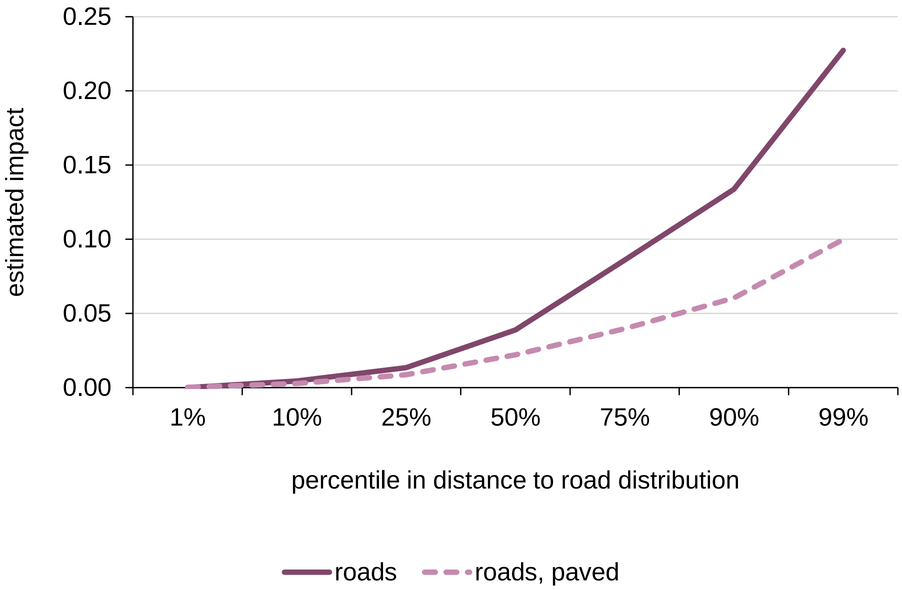
within the Amazon is predominantly terrestrial, proximity to roads has been shown to be strongly correlated with deforestation outcomes and to drive relevant heterogeneity across the landscape (Angelsen and Kaimowitz, 1999; Chomitz and Thomas, 2003; Pfaff et al., 2007; Herrera, 2015; Pfaff et al., 2015; Busch and Ferretti-Gallon, 2017). Data on road networks in the Brazilian Amazon come from the Brazilian National Department for Transport Infrastructure (DNIT) and are only available as a 2010 spatial cross-section. Table 7 presents estimated coefficients for specifications that include double and triple interactions with the

Table 7: Heterogeneity – Distance to Transport Infrastructure

	deforestation increment in cell (t)	
	(1) roads, all	(2) roads, paved
alerts 50km (t-1)	-0.0097	0.0260
	(0.0148)	(0.0210)
alerts 50km * protected (t-1)	-0.0106	-0.0099
	(0.0202)	(0.0226)
alerts 50km * distance to road (t-1)	0.1548***	0.0099
	(0.0435)	(0.0110)
alerts 50km * protected * distance to road (t-1)	-0.1211**	-0.0239*
	(0.0508)	(0.0127)
alerts 100km (t-1)	0.0164	0.0274
	(0.0144)	(0.0209)
alerts 100km * protected (t-1)	-0.0028	-0.0302
	(0.0245)	(0.0318)
alerts 100km * distance to road (t-1)	-0.0304	-0.0357**
	(0.0276)	(0.0158)
alerts 100km * protected * distance to road (t-1)	-0.0108	0.0276
	(0.0351)	(0.0202)
d=1 if protected * distance to road (t-1)	0.0021**	-0.0024**
	(0.0009)	(0.0011)
d=1 if alert issued (t-1)	0.0004	0.0005
	(0.0007)	(0.0007)
d=1 if priority (t-1)	-0.0016**	-0.0017**
	(0.0006)	(0.0007)
d=1 if protected (t-1)	-0.0005	0.0034***
	(0.0010)	(0.0009)
R-squared	0.0040	0.0037
number of observations	23,045,304	23,045,304
number of cells	2,880,663	2,880,663
controls		
cell fixed effects	yes	yes
year fixed effects	yes	yes
geography	yes	yes
observed policy	yes	yes

Notes: The table reports fixed effects coefficients for Equation 1 (Section 3). The dependent variable is the cell-level deforestation increment (deforested area in cell i and year t as a share of total cell area). Reported independent variables are neighborhood alert intensities in year $t-1$ (total alert area as a share of total neighborhood area), and double and triple interaction terms between neighborhood alert intensities, cell protection status in year $t-1$ (d=1 if cell i protected) and cell-level distance to nearest road (in 100km). Column headers indicate if specification refers to all roads (column 1) or only paved roads (column 2) The no/yes markers in bottom rows indicate the inclusion of the following sets of cell-level controls: (i) cell and year fixed effects; (ii) geography: measuring and monitoring satellite visibility, precipitation, and temperature; and (iii) observed policy: alert intensity, protection status, and priority municipality status. The cell-by-year panel includes 2,880,663 cells located within 750km from the Brazilian Amazon biome southeast border and covers the 2006 through 2014 period. Standard errors are robust and clustered at the municipality level. Significance levels: *** p<0.01, ** p<0.05, * p<0.10.

Figure 6: Impact Accounting for Distance to Transport Infrastructure



Notes: The graph plots the difference in forest clearing outcomes between protected and unprotected cells under the same level of deforestation pressure along select percentiles of the distance to roads distribution.

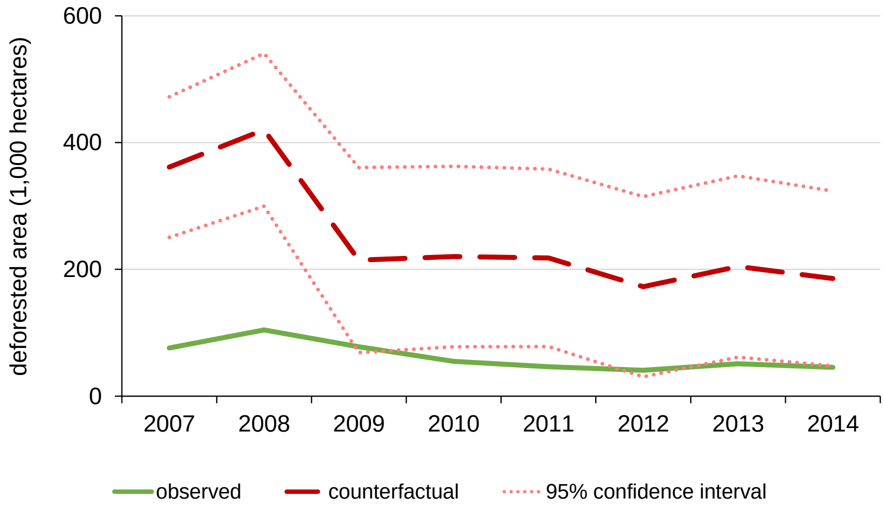
cell-level distance to the nearest road. Results indicate that proximity to roads tends to nullify protection's shielding effect. This is more easily seen in Figure 6, which plots the difference in forest clearing outcomes between protected and unprotected cells under the same level of deforestation pressure along select percentiles of the distance to roads distribution. For cells that are very close to roads, protection seems to be incapable of holding back deforestation; as cells become more isolated from transport infrastructure, protection's shielding effect becomes increasingly more accentuated. This is an intuitive result considering that roads facilitate access to forest areas and might thereby increase deforestation risk. Figure 6 also shows that the influence of roads is not restricted solely to paved ones, corroborating the perception that the network of unpaved roads in the Amazon plays a relevant role in regional mobility.

5.4. Counterfactual Exercises: Aggregate Deforested Area

The cell-level analysis provides empirical evidence that protected territory serves as a local shield against deforestation pressures. Yet, to gain insight into the economic relevance of these cell-level effects, I conduct counterfactual exercises that explore deforestation trends under hypothetical scenarios that revoke protection. These exercises build on the benchmark specification (Table 4, column 3) to estimate cell-level forest clearing outcomes had protection never been assigned. In practice, this is performed by setting protection status variables to 0 across cells and years.

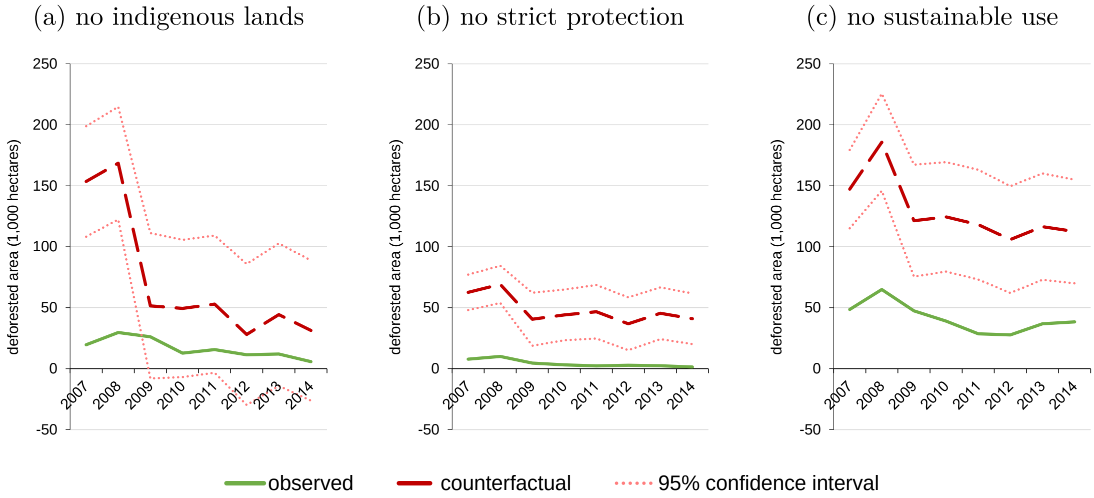
Figure 7 compares the total deforestation increment observed in sample protected territory with that estimated in the counterfactual scenario that revokes all Amazon

Figure 7: Counterfactual Exercise – No Protection



Notes: The graph plots annual deforestation in counterfactual and observed scenarios. The counterfactual scenario revokes all protected territory. Totals are calculated by adding the cell-level deforestation increment across sample cells that were under protection during part or all of the sample period.

Figure 8: Counterfactual Exercise – No Protection, by Type



Notes: The graph plots annual deforestation in counterfactual and observed scenarios. The counterfactual scenarios revoke type-specific protected territory. Totals are calculated by adding the cell-level deforestation increment across sample cells that were under type-specific protection during part or all of the sample period.

protection. Counterfactual deforestation is systematically larger, indicating that these regions would have seen more forest clearings in the absence of protection's shielding effect. The difference between observed and counterfactual deforestation is most significant in years of more intense deforestation activity, a finding that is consistent with the idea that protection serves as an effective shield insofar as areas under its domain face an actual threat.

To explore heterogeneity, this exercise is repeated for type-specific protection. Plots in Figure 8 are analogous to that of Figure 7, but each refers to a separate hypothetical scenario in which only type-specific protection is revoked. Again, protected areas exhibit stronger shielding capacity than indigenous lands, with

Table 8: Counterfactual Exercise – No Protection, Full Sample Impact

year	deforested area (in hectares)	
	observed	counterfactual: no protection
2007	1,001,963	1,010,052
2008	1,088,463	1,083,634
2009	524,428	535,353
2010	483,821	481,643
2011	467,814	454,895
2012	361,680	351,589
2013	466,920	447,774
2014	412,213	398,559
total	4,807,300	4,763,499

Notes: The table reports annual deforestation in observed and counterfactual scenarios. The counterfactual scenario revokes all protected territory. Totals are calculated by adding the cell-level deforestation increment across all sample cells.

counterfactual deforestation being systematically and significantly larger than that observed across sample years. Thus, forests within the domain of strictly protected areas or protected areas for sustainable use would have suffered greater losses had it not been for legal protection. Indigenous lands, in contrast, appear to have benefited from shielding only in the very high-pressure years following the adoption of the PPCDAm. Although counterfactual deforestation under revoked indigenous lands is larger than observed, the difference between them is not statistically significant for most of the sample period.

Thus far, results corroborate protected territory's capacity to locally shield forest areas from deforestation pressures. Moreover, they serve as evidence that assigning protection to a given area influences the spatial dynamics of forest clearings in that area. This does not imply, however, that protection reduces aggregate deforestation levels. Table 8 reports annual deforested area in the sample, totaling deforestation outcomes in both protected and unprotected territories. There is remarkably little difference in forest loss between observed and hypothetical scenarios. As such, protection does not appear to reduce deforestation. Rather, it stands in the way of advancing clearings, which, instead of pushing forward into protected forest, then relocate to unprotected territory. Overall, these findings suggest that protection effectively deflects harm and thereby conserves the integrity of whatever lies under its domain — deflected deforestation, however, seems to finds its way to unshielded territory.

6. Final Remarks

This analysis yields important policy implications that can potentially contribute to Brazil's goal of further reducing Amazon deforestation. The evidence that protected territories effectively shield forests within their domain from forest clearings attests to protection's effectiveness, and corroborates the action plan's use of these territories as a means of blocking advancing deforestation. Additionally, protected territories have been shown to influence regional deforestation dynamics. However, the finding that protection deflects clearings elsewhere points towards the need for policy interaction, as the strategic targeting of protected territory should be accompanied by complementary conservation efforts that effectively reduce deforestation. Exploring potential interactions could improve policy design, allowing policymakers to strengthen conservation by building on complementarities across interventions, eliminating redundancies, and mitigating potentially harmful impacts (Robalino et al., 2015; Pfaff and Robalino, 2017; Sims and Alix-Garcia, 2017).

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Appendices

Appendix A. Spatial Setup

Appendix A.1. Georeferenced Raster Structure

A raster is a matrix data structure that represents a regular grid of cells. For a given variable of interest taking on a range of possible values, each raster cell can hold one, and only one, value. Georeferenced rasters contain spatial information that associate it with a well defined region of the world's surface: (i) the coordinate reference system, which determines the origin and set of spatial axes to be used with geographical coordinates; (ii) the spatial extent, which defines the minimum and maximum limits of the area covered by the raster; and (iii) the spatial resolution, which sets raster cell size and thereby, given (i) and (ii), determines the number of rows/columns in a raster. In georeferenced rasters, each cell holds a specific position in space, as marked by the coordinates of that cell's centroid. This enables the recovery of spatial relationships, such as the distance between two cells. Moreover, it allows for the tracking of the same cell across different rasters, as long as all share the same coordinate reference system, extent, and spatial resolution.

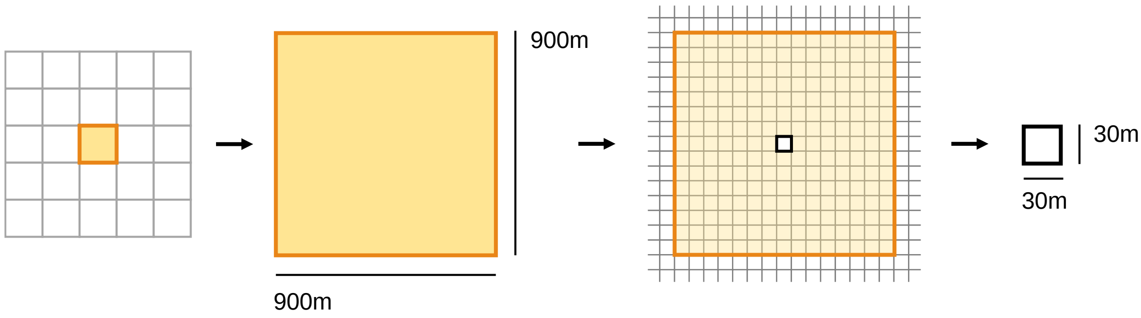
The coordinate reference system used for dataset construction is the unprojected 1969 South American Datum (SAD69). All mentions of metric distances are metric equivalences of measures actually in degrees. The spatial resolution is set at 900m, such that the raster unit is a square raster cell with an area of 81ha. Construction of variables stated as shares of cell area are based on georeferenced rasters with the higher 30m resolution. Typically, each of the 900m cells contains 900 of the 30m minicells, though the existence of spatial boundaries may result in lower minicell count in frontier cells. Shares are always calculated in terms of total cell-specific minicell count. Each minicell is associated with its respective parent cell using an indexation algorithm. Figure A.9 depicts cells, minicells, and the relationship between them.

Cell neighborhoods refer to the areas covered by concentric rings of increasing diameter around the cell. Larger neighborhoods do not contain smaller ones, and the cell itself is excluded from the smallest neighborhood. Figure A.10 illustrates raster cell neighborhoods. All cells within a given neighborhood are weighed equally, despite variation in distance to and direction from the central cell.

Appendix A.2. Geographical Regions

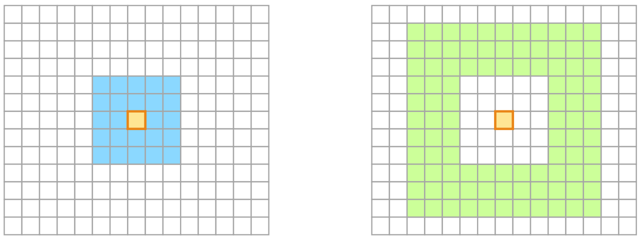
The Brazilian Legal Amazon is a geopolitical administrative subdivision that encompasses Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, and

Figure A.9: Raster Grid, Cell, and Minicell



Notes: The figure illustrates the basic structure of the raster data used in the empirical analyses. The grid is composed of 900m by 900m square cells, which, in turn, subdivides into 30m by 30m square minicells. The cells and minicells in the figure are not drawn to scale.

Figure A.10: Raster Cell Neighborhoods



Notes: The figure illustrates raster cell neighborhoods, as determined by concentric rings of increasing diameter around the cell. Larger neighborhoods do not contain smaller ones, and the cell itself is excluded from the smallest neighborhood.

Tocantins states, as well as the western part of Maranhão state. The Amazon biome is entirely contained within the Legal Amazon, but is defined based on biophysical and ecological criteria. Figure 4 maps the Brazilian Legal Amazon and Amazon biome. IBGE provides vector data indicating spatial boundaries for both. When rasterized at the 900m resolution, the Brazilian Legal Amazon and Amazon biome territories contain about 6.3 and 5.2 million cells, respectively.

Appendix B. Data Sources and Descriptions

Appendix B.1. Land Cover and Land Use

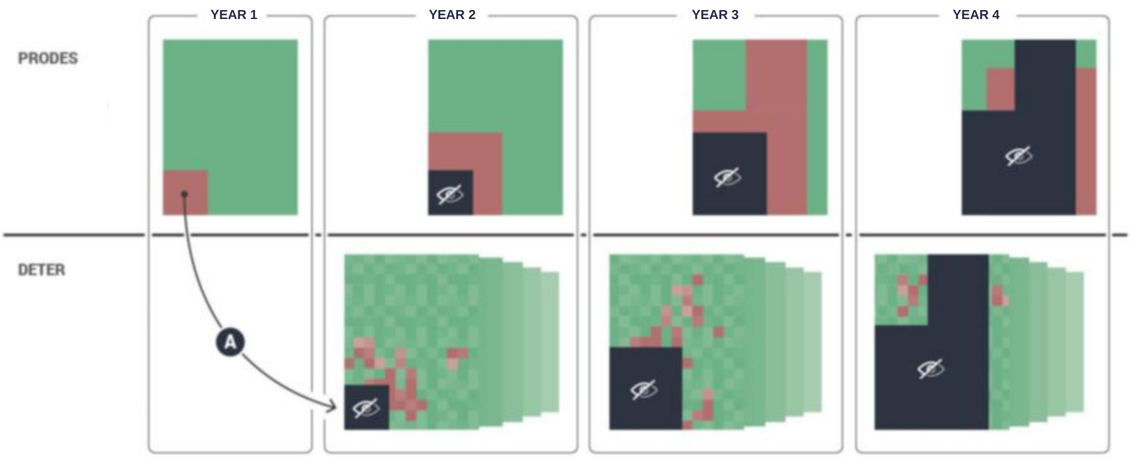
Brazil's systems for detecting tropical forest loss are widely recognized as being at the forefront of national efforts to combat deforestation (Tyukavina et al., 2017). The country has used satellite imagery to map and quantify Amazon deforested area since the late 1980s. Today, it operates two different remote sensing-based programs: one that measures annual tropical deforestation, another one that monitors tropical forest disturbance.

Appendix B.2. Measuring Deforestation

The Project for Monitoring Deforestation in the Legal Amazon (PRODES), established by Inpe in 1988, provides georeferenced data on annual tropical deforested area. The system detects forest clearings by comparing, for any given area, satellite imagery from years $t - 1$ and t to detect changes in land cover. When an area is identified as deforested in satellite imagery, it is classified as part of that year's deforestation increment; as of the following year, it is taken as accumulated deforestation and is not revisited. Accumulated deforestation is known as the "PRODES mask". The top panel in Figure B.11 presents a conceptual illustration of how PRODES works: in year 1, the system maps and records deforested area; in year 2, the system no longer looks for clearings inside this area, but maps and records new patches of cleared forest outside it; in year 3 and beyond, this process repeats itself, with total deforested area through the previous year being incorporated into the PRODES mask and the system looking for new deforestation outside this mask. This setup has two important consequences. First, PRODES only detects the clearing of primary vegetation (forest that has never been cut down). Second, and relatedly, it is an incremental system, such that, for each year of data, it provides information on newly deforested areas, but never reclassifies previously cleared areas. This implies that the PRODES mask is, by construction, non-decreasing in area.

The system classifies land cover throughout the full extent of the Brazilian Legal Amazon into five categories of mutually-exclusive classes: forest (standing primary vegetation), deforestation, bodies of water, non-forest (areas that have never been covered by tropical vegetation), and residue (a minor residual category). Only tropical forest areas can ever be deforested, as PRODES is not technically fit to compute the clearing of other types of vegetation. Although the Brazilian Legal Amazon is mostly covered by tropical forest, some areas, particularly those outside the Amazon biome, are naturally covered by savanna-like *cerrado* vegetation — these areas are classified as non-forest in PRODES and are not accounted for in official Amazon deforestation statistics. Because clouds, shadows cast by clouds, and smoke from fires obstruct visibility in satellite

Figure B.11: Satellite Systems for Detecting Forest Disturbances



Notes: The figure presents a conceptual illustration of how satellite-based PRODES and DETER systems operate at an annual basis. The top panel refers to PRODES: in year 1, the system maps and records deforested area; in year 2, the system no longer looks for clearings inside this area, but maps and records new patches of cleared forest outside it; as of year 3, the process repeats itself. PRODES data is annual. The bottom panel refers to DETER: in year 1, the system takes input from PRODES (region A); in year 2, the system looks for signs of disturbance in forest areas outside the PRODES mask and issues deforestation hot spot alerts accordingly; at the end of year 2, PRODES will either confirm or reject deforested status for these areas, and only those that are confirmed are incorporated into the PRODES mask; in year 3 and beyond, the process repeats itself, with DETER always looking for signs of forest disturbance in forest areas outside the mask. DETER alerts are forwarded to law enforcement daily, but data is made publicly available in monthly aggregates. Both PRODES and DETER are built to only capture loss of primary tropical vegetation.

imagery, some areas might be classified into a sixth category: non-observable areas. Actual land cover in these areas is only classified once the visual obstruction clears.

PRODES was created, and is still used, to calculate the Amazon-wide deforestation rate. While the deforestation increment measures total visible deforested area, the deforestation rate accounts for an estimate of cleared forest areas that were partially or entirely blocked from view during remote sensing. The rate thereby attempts to more closely capture the speed at which the Amazon was cleared, while the increment reflects when the cleared area became known to authorities.[13] Only the deforestation increment is made available as spatial data.

PRODES uses imagery from Landsat class satellites with a spatial resolution of 20 to 30m. When the system was implemented, technical limitations restricted detection to deforestation patches larger than 6.25ha. Today, although smaller patches are detected, processed, and forwarded to environmental authorities, public data are restricted to patches larger than 6.25ha to preserve comparability across the time series. In addition, the system only detects areas that have been clear-cut, so selective logging and forest degradation are not included. Deforested area measured by PRODES has been validated both internally, via Inpe-led field-based accuracy evaluations (Adami et al., 2017), and externally, via

[13]See Inpe (2013) for a detailed account of PRODES methodology and deforestation rate estimation details.

third-party independent interpretation of satellite imagery (Souza Jr. et al., 2013; Turubanova et al., 2018). Cross-validations only refer to clear-cut deforestation, as PRODES does not detect tropical degradation. As expected, analyses that account for degradation estimate larger areas of affected forest (Souza Jr. et al., 2013; Tyukavina et al., 2017).

Inpe annually releases updates to the PRODES series in vector format, such that year t data contain a spatial history of all areas deforested through that year and their associated year of deforestation. However, deforestation years do not refer to calendar years. To minimize cloud cover and thereby maximize visibility of the Earth's surface, satellite images from the Amazon dry season are typically used. Hence, for a given year t, PRODES measures deforestation that happened from August of the previous year $(t-1)$ through July of that year (t). The datasets in this dissertation are built to fit this August-through-July window. For simplicity, I refer to this time frame simply as "year" throughout the analyses.

Figure B.12a plots total deforested area for the 2006 through 2014 sample period. PRODES vector data are currently available through 2016, but the historical spatial series is only comparable through 2014. This is because, in 2015, Inpe implemented a mask shift — a non-linear spatial displacement to adjust for inaccuracies that accumulated over time. Unfortunately, during this procedure, the full history of clearings prior to 2013 was collapsed and all areas cleared until then became aggregated under the 2012 year reference. As restricting the sample to the post-2012 period would result in the loss of seven years of law enforcement data, the analyses use pre-shift PRODES data. This sets 2014 as the sample's final year.

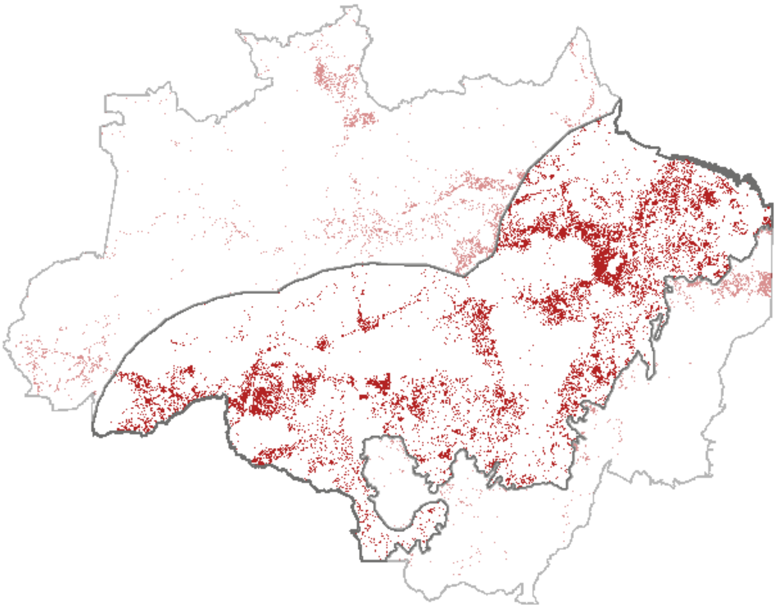
Appendix B.3. Monitoring Deforestation and Degradation

DETER is a satellite-based system, developed and operated by Inpe, that provides near real-time identification of forest clearing activity. Like PRODES, DETER compares current satellite images with earlier ones, scanning for changes in forest land cover. Upon detection, potential forest disturbances map onto georeferenced alerts signaling areas of forest clearing activity. These alerts are sent to the environmental law enforcement authority and serve as the basis for targeting Amazon law enforcement.

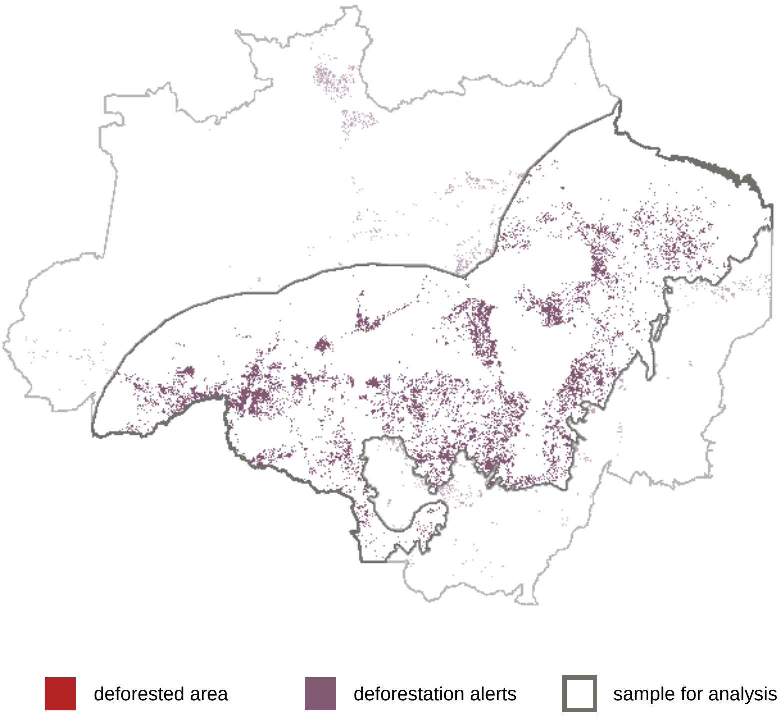
DETER builds on the PRODES system to the extent that it only scans for forest disturbances outside the PRODES mask. The bottom panel in Figure B.11 illustrates the procedure: DETER needs year 1 input from PRODES (deforested area in year 1, labeled A in the figure); in year 2, the system looks for signs of disturbance in forest areas outside the PRODES mask and issues deforestation hot spot alerts accordingly; at the end of year 2, PRODES will either confirm or reject deforested status for these areas, and only those that are confirmed are incorporated into the PRODES mask; in year 3 and beyond, the process repeats itself, with DETER always looking for signs of forest disturbance in forest areas outside the

Figure B.12: Detected Forest Disturbances

(a) measuring deforestation: deforested area, 2006–2014



(b) monitoring deforestation: alert area, 2006–2014



Notes: The maps plot forest disturbances detected by PRODES and DETER in the 2006 through 2014 period. Sub-figure (a) shows deforested area captured in PRODES, which detects clearings larger than 6.25ha; sub-figure (b) shows forest clearing alert area captured in DETER, which detects clearings and degraded areas larger than 25ha. Dimmed regions are non-sample areas (see Section 4.3 for sample definition). Data sources: PRODES/Inpe (deforestation); DETER/Inpe (alerts); IBGE (Legal Amazon, Amazon biome).

mask.

DETER covers the full extent of the Brazilian Legal Amazon, but only detects signs of disturbance in areas classified as forest in PRODES; again, *cerrado* areas are not included. It originally used images from the MODIS sensor on the Terra satellite, which has a spatial resolution of 250m. The system can therefore only detect forest clearings larger than 25ha. This relatively poor spatial resolution was compensated by both increased temporal frequency (the satellite revisits any given area within the Brazilian Legal Amazon daily) and the ability to detect not only clear-cut deforestation, but also forest degradation. Since 2015, Inpe has operated DETER alongside DETER-B. The new system also serves to issue georeferenced alerts for recent forest degradation and deforestation activity, but it detects changes in land cover in patches larger than 1ha, albeit at lower temporal frequency (Diniz et al., 2015).

Despite its high frequency, DETER data is aggregated at a monthly basis for public release in vector format. DETER was implemented in 2004, but remained in experimental mode through mid-2005. Thus, although a few months of data are available for 2004 and early 2005, consistent remote sensing data on DETER alerts only starts in the second half of 2005. The first year of DETER data is therefore set at 2006 throughout the empirical analyses. Figure B.12b plots total alert area during the sample period.

Appendix B.4. Protected Territory

FUNAI publicly releases spatial vector data for indigenous lands throughout the country. This dataset contains date variables for each of the indigenous territory recognition stages (see Section 2.3), enabling the construction of a georeferenced annual panel. Despite being the official source for information on indigenous lands in Brazil, the FUNAI dataset contains several occurrences of missing data for date variables. I address these gaps using information from ISA, which compiles its own historical record of the many recognition stages for indigenous territories. ISA data are publicly available online and were collected using a data-scrapping algorithm. The ISA-based dates fill in the gaps in FUNAI data, but never replace them. Throughout this dissertation, an indigenous land is only regarded as protected when it has completed the declaration stage, at which point its spatial boundaries have been published via ordinance.[14]

Spatial vector data on protected areas come from the Brazilian Ministry of the Environment (MMA). The georeferenced dataset contains information on each area's date of creation and protection type (strictly protected areas or protected areas for sustainable use).

[14]Chiavari et al. (2016) support this cutoff stage, stating that indigenous territories are only protected once they have been declared.