Protected or Postponed? Dynamics of Deforestation in Protected and Non-Protected Areas

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Abstract

This paper studies the effectiveness of forest protected areas (PAs) in a dynamic setting. I investigate whether the establishment of PAs in the Brazilian Amazon immediately accelerates deforestation in the neighborhoods, and logging activities gradually shift back to PAs over time. This dynamic displacement stems from the fact that trees in the Amazon are treated as a nonrenewable resource. Exploiting variations in the proximity to PA boundaries and in the timing of PA establishment, I identify the dynamic effects of new PAs on deforestation in non-protected areas (NPAs) and PAs, respectively. The establishment of PAs dramatically increases the size of newly deforested areas in the neighborhoods for the first 6 years, while the incremental effect suddenly disappears or the deforestation rate even decreases 7-10 years after the establishment. In the interior of PAs close to their boundaries, the rate of deforestation gradually increases from the beginning of the establishment. Deforestation is particularly severe inside PAs in the second phase of deforestation in NPAs (i.e., 7-10 years after the establishment). This phenomenon suggests that logging activities repeatedly shift in response to the dynamics of logging costs in NPAs and PAs.

Keywords: Deforestation, Protected areas, Nonrenewable Resource, Dynamic optimization

JEL Classification: Q32, Q38, Q57

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1 Introduction

Forest protected areas (PAs) have been regarded as one of the most effective environmental policies to reduce deforestation, preserve biodiversity, and protect local residents' property rights. Various studies provide evidence that PAs achieve these objectives (Oliveira et al., 2007; Nelson and Chomitz, 2011; Sims, 2014; Brandt et al., 2015; OECD, 2015; Walker et al., 2020). However, several studies highlight that the positive effects can be offset to some extent because of a *leakage effect*: i.e., an increase in deforestation in the neighborhoods of PAs due to the displacement of logging activities from PAs to non-protected areas (NPAs) (Robalino, 2007; Alix-Garcia, Shapiro, and Sims, 2012; Robalino, Pfaff, and Villalobos, 2017; Moffette and Gibbs, 2021). Does combining these two contradicting impacts fully determine the effectiveness of PAs?

If trees are treated as a nonrenewable resource, the effectiveness of PAs must be assessed in a dynamic setting. Establishing PAs would give rise to a discrepancy in the costs of logging between PAs and NPAs since loggers should make additional efforts not to be caught in PAs. This cost gap would cause the *leakage effect* and logging activities would increase in the neighborhoods of PAs at the beginning. However, if trees are not replanted after logging activities, loggers should move further away from the neighborhoods as they continue logging. Accordingly, transport costs would gradually increase and the cost gap between PAs and NPAs would shrink over time. In theory, loggers eventually invade PAs for logging when the costs of logging in the two areas become identical (or the cost in NPAs goes beyond the one in PAs).

The presence of this dynamic displacement of logging implies a failure of full protection. Though PAs may seem to succeed in curbing deforestation inside the areas, creating those areas would accelerate deforestation in the neighborhoods in the short term and logging activities would shift back to PAs gradually. In the Brazilian Amazon, loggers indeed treat trees as a nonrenewable resource. They use cleared lands for agricultural purposes due to their higher profitability (Margulis, 2004; Andrade de Sá, Palmer, and Di Falco, 2013; Skidmore et al., 2021). Human Rights Watch (2019) highlights a gradual increase in violence against indigenous peoples residing in Brazilian PAs. This phenomenon might be attributed to the dynamic displacement of logging induced by the establishment of PAs and the nonrenewable characteristics of trees in the Amazon.

This paper aims to clarify the presence of the dynamic displacement effects caused by PA establishment. First, I investigate how establishing PAs affects deforestation in the neighborhoods of the areas over time. The second part focuses on the dynamic effects of PAs on deforestation inside the areas. Combining the two studies of dynamic displacement effects, I find out what kind of dynamic transition in deforestation is formed by the establishment of PAs.

To conduct an empirical analysis, I employ a large set of satellite data on deforestation and geospatial data on PAs in the Brazilian Amazon. The deforestation data from Global Land Analysis and Discovery (GLAD) record the year of deforestation between 2001 and 2020 in each pixel whose spatial resolution is 30 meters (Hansen et al., 2013). I aggregate original pixels to 1.2km $\times$ 1.2km cells and create a cell-level panel data set. The main outcome variable of deforestation is defined as the number of original pixels deforested in a given year. In addition, the Brazilian PA data from the

Amazon Network of Georeferenced Socio-Environmental Information (RAISG) are used to identify cells *treated* by the establishment of PAs. I split the cells in the data set into two subsamples; one only includes the cells outside PAs, whereas the other only includes the cells inside PAs. For the former, the treated cells are defined as the ones located in the 0-30 kilometers neighborhoods of PAs. For the latter, the cells located within PAs and less than 10 kilometers away from the boundaries are defined as the treated cells. These treated cells in the two subsamples are likely to be affected by the establishment of new PAs due to their proximity to past logging areas and the lower risk of being caught specifically for the treated areas within PAs.[1]

I identify the dynamic displacement effects through a difference-in-difference event study design with the Poisson quasi-maximum likelihood (QML) estimator. I exploit variation in the proximity to PA boundaries and variation in the timing of PA establishment. The closeness to a boundary explains whether cells are influenced by PA establishment since the costs of logging in both PAs and NPAs increase in proportion to the distance from the boundary. The different timings of PA establishment in Brazil allow me to distinguish the pre- and the post-treatment periods. Combining these two variations, I estimate the effects of PA establishment on deforestation over time in NPAs and PAs, respectively.

The event study for the effects in NPAs shows that the establishment of PAs triggers the dynamic displacement of logging activities between NPAs and PAs. New PAs dramatically and progressively increase the size of newly deforested areas in the neighborhoods for the first 6 years since the establishment. However, these treatment effects suddenly disappear or the size of newly deforested areas even shrinks 7-10 years after the establishment. From the 11th year, the treatment effects fluctuate over time.

The first phase of increasing deforestation suggests that logging activities are displaced from PAs to the neighborhoods since additional efforts for logging in PAs increase the cost of economic activities in the areas. However, this first displacement effect does not remain in the medium or long term. Given that trees in the Brazilian Amazon are treated as a nonrenewable resource, loggers should move further as they continue logging activities. Accordingly, the transport cost in the neighborhoods constantly increases, leading the cost of logging in the neighborhoods to go beyond the costs outside the neighborhoods. Due to the dynamic transition of logging cost, the rate of deforestation in the neighborhoods decreases in the second phase. This implies that logging activities shift again to other areas where the costs of logging are relatively low. After the second phase of displacement, logging activities increase and decrease repeatedly in the neighborhoods in response to the spatial gap of logging costs.

The event study for the dynamic displacement effects in PAs highlights that logging activities gradually shift back from NPAs to PAs. The establishment of PAs gradually increases the size of newly deforested areas inside those PAs 0-10 kilometers away from the boundaries (i.e., sufficiently close to the boundaries). In particular, the increment of deforestation in the areas is relatively large

[1]When logging activities shift from PAs to NPAs, they would shift to the neighborhoods of PAs because loggers would be willing to reduce moving costs. Likewise, when loggers invade PAs, they would invade the areas close to the boundaries to save moving costs and reduce the risk of being caught.

in the period of decreasing logging activities in the PA neighborhoods (i.e., 7-10 years after the establishment). This deforestation pattern implies that logging activities previously displaced to NPAs flow back to PAs more and more. This phenomenon is attributed to the gradually increasing logging cost in NPAs.

Interestingly, this gradual increase in the rate of deforestation inside PAs does not remain 12-15 years after the establishment. The incremental impact of new PAs on deforestation diminishes over time in this period. The continuous inflow of logging activities gradually raises the cost of logging in PAs because loggers should go further into the interior of the areas. In response to this increasing cost, loggers would move back to NPAs again to benefit from the relatively low logging cost in NPAs.

To my best knowledge, this study is the first empirical work to explore the dynamic displacement effects of PA establishment in the long term. Expanding the main strand of literature on the positive consequences of PAs observed inside the areas (Oliveira et al., 2007; Nelson and Chomitz, 2011; Sims, 2014; Brandt et al., 2015; OECD, 2015; Walker et al., 2020), various studies have focused on the *leakage effect* of PAs to explain the increasing rate of deforestation in NPAs (Robalino, 2007; Alix-Garcia, Shapiro, and Sims, 2012; Robalino, Pfaff, and Villalobos, 2017; Moffette and Gibbs, 2021). This study analyzes the displacement effect further in a dynamic setting, uncovering that the current PA policy does not prevent but just postpones illegal logging. This boomerang effect fundamentally stems from the nonrenewable characteristics of trees in the Brazilian Amazon.

This paper also highlights the unexpected role of the PA policy as a crucial determinant of different deforestation patterns. Current literature has documented that different dynamics in deforestation are generated by Cournot competition among local officials (Burgess et al., 2012), highway upgrades (Asher, Garg, and Novosad, 2020), accessibility to rural credits (Assunção et al., 2020), and firms' incentives to avoid externalities (Balboni, Burgess, and Olken, 2021). I underline a discrepancy in logging costs induced by PAs as another driver of spatial and temporal variations in deforestation. Understanding this mechanism is essential because the dynamic transition of logging costs directly undermines the effectiveness of PAs. It is crucial to design the PA policy in light of the fundamental notion of increasing extraction costs in response to the depletion of nonrenewable resources (Heal, 1976; Pindyck, 1978; Livernois and Uhler, 1987).

The rest of the paper is organized as follows. Section 2 describes the background of the Brazilian PA policy and the motivation of this study. Section 3 presents the data on PAs and deforestation. Section 4 describes the identification strategy to study the dynamic displacement effects of PA establishment. Section 5 presents the results of the empirical analysis, and Section 6 provides concluding remarks.

2 Background and Motivation

2.1 Protected Areas in the Brazilian Amazon

Forest PA is one of the salient environmental policies to slow down deforestation and protect biodiversity. After rigorous discussions and scrutiny by the government and the public, Brazil established the National System of Protected Areas (SNUC) in 2000 (OECD, 2015). The legislation aimed to boost the creation of PAs, enhance the management of existing PAs, and consolidate the roles of government institutions and the public in the national PA system. The PA policy has been supported by regularizing land tenure, adopting new monitoring technologies, and strengthening legal enforcement (Pfaff et al., 2014).

The priority is given to biological importance and the risk of environmental degradation for selecting new PAs under the SNUC (Silva, 2005). However, the process also requires consideration of social and economic interests conflicting with environmental gains (OECD, 2015). To harmonize all these conflicting factors reasonably, the SNUC legalizes a system in which local communities and other stakeholders as well as government institutions are involved in the selection process.

PAs are broadly categorized into conservation areas and indigenous territories. The main objective of conservation areas is to protect biodiversity and natural resources. Conservation areas are divided further into two categories depending on the possibility of economic activities. The first one is strict protection areas where any type of natural resource extraction is prohibited. The second category is sustainable use areas, permitting certain degrees of exploitation in agreement with sustainable use of resources.[2] Although indigenous territories have the same objective of environmental conservation, they mainly aim to protect indigenous peoples' land ownership and their right to use natural resources in the areas. The SNUC did not directly recognize indigenous territories as PAs. They were officially included in the category of PAs under the National Protected Areas Plan in 2006 (OECD, 2015).

2.2 Illegal Logging in the Brazilian Amazon

The Brazilian Amazon, the largest tropical forest in the world, has been a lucrative area for logging due to its ample amount of trees and vast land for agricultural activities. To achieve sustainability in timber extraction, the Brazilian government uses multiple regulatory policies such as forest concessions and legal enforcement. Although the government achieved a decrease in deforestation in the Amazon by 83% between 2004 and 2012 through such efforts, deforestation has gradually increased after the curbing period (Human Rights Watch, 2019). The main cause of the rebound is pervasive illegal logging. Brancalion et al. (2018) find the discrepancy between the volumes of approved logging permits and the estimated timber volumes. Even though the number of illegal

[2] Strict protection areas include ecological station, biological reserve, national park, natural monument, and wildlife refuge area. Sustainable use areas include environmental protection area, area of relevant ecological interest, national forest, extractive reserve, sustainable development reserve, fauna reserve, and private natural heritage reserve. OECD (2015) shows key features of each of the 12 conservation areas.

loggers' invasions into PAs has been increasing, investigations and punishments are inadequate to restrict those illegal activities (Human Rights Watch, 2019).

2.3 Motivation

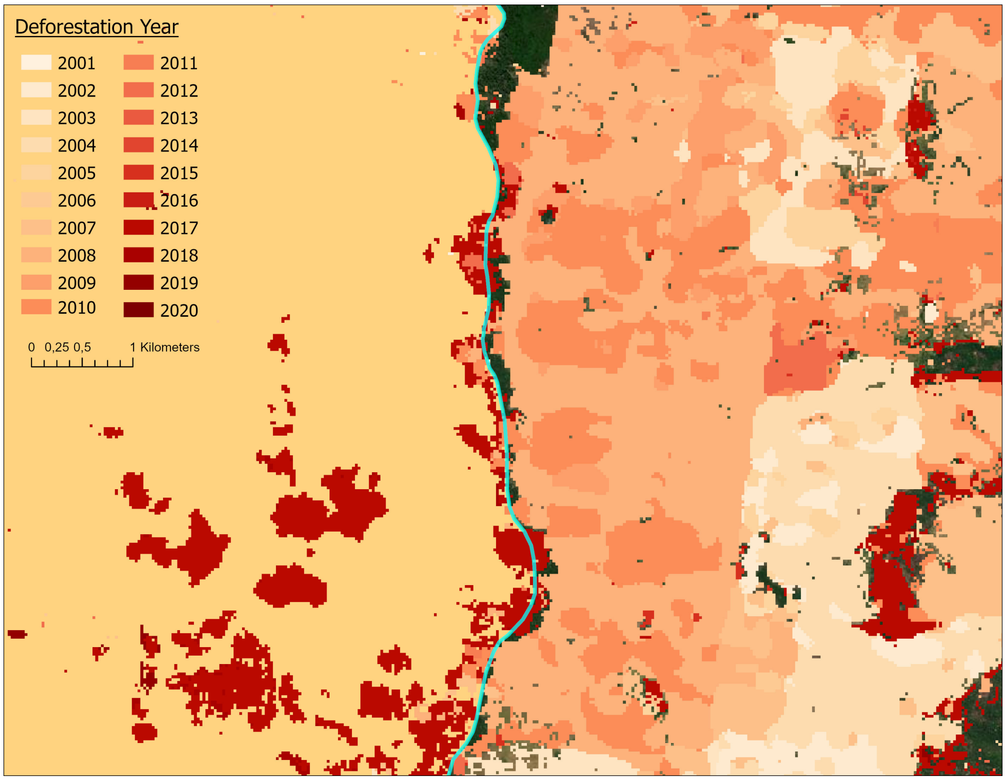


Figure 1: Indigenous Territory (Badjonkore) and the Pattern of Deforestation

Are Invasions by illegal loggers into PAs fully attributed to weak legal enforcement? What if they seek trees in PAs simply because there are no trees left uncut in the neighborhoods of PAs? The map in figure 1 depicts a pattern of deforestation supposedly driven by the establishment of a PA. The orange area on the left side is an indigenous territory called Badjonkore. The blue line in the middle is the boundary of the indigenous territory. The red colors indicate the years when deforestation occurred, ranging from 2001 to 2020. The darker the red color is, the more recently the area was deforested.

The Badjonkore territory was officially declared in 2001 and registered in 2003. Interestingly, the rate of deforestation immediately increased outside the indigenous territory at the moment of declaration and registration. Deforestation then gradually spread in the neighborhood of the indigenous territory (i.e., on the right side of the territory's boundary). This increase in forest clearing in the neighborhood is presumably caused by the displacement of logging activities from the PA to NPA. The establishment of the PA raised the cost of logging in the area, and the higher cost might eventually have pushed out logging activities to the neighborhood.

An important feature of the Brazilian Amazon is that trees are regarded as a non-renewable resource. That is, logging firms do not replant trees after they cut them down. Instead, they usually use cleared lands for agricultural purposes since this land conversion has higher returns (Margulis, 2004; Skidmore et al., 2021). Then, the number of trees left uncut in the neighborhood would gradually decrease. Accordingly, the cost of logging in the NPA would gradually increase because the transport cost of logs would increase when loggers move further to cut trees. Thus, in theory, there must be a moment at which the cost of logging in the NPA goes beyond the one in the PA. That is the occasion in which logging firms invade the PA for illegal exploitation. This phenomenon could explain the recent deforestation inside the Badjonkore territory adjacent to its boundary.

3 Data

To estimate the dynamic effects of establishing PAs on deforestation, I employ a large set of satellite data on deforestation and geospatial data on PAs. I describe below the properties of these data sets and the details of data processing for the empirical analysis.

3.1 Deforestation

Processing time-series Landsat images, Global Land Analysis and Discovery (GLAD) provides annual forest change data at a 30-meter spatial resolution (Hansen et al., 2013). To identify deforested areas in the Brazilian Amazon, I use pixel-level forest loss data between 2001 and 2020. Hansen et al. (2013) define forest loss as a stand-replacing disturbance or the complete clearing of tree cover canopy. The data allow me to observe the occurrence of deforestation in a specific pixel and the exact year it happened between 2001 and 2020. Additionally, I collect pixel-level data on the percentage of tree cover in 2000. The data are used to control for any time trends of deforestation driven by differential rates of forest cover in the initial year. I reshape these satellite data to construct a panel data set where the unit of observation is at the level of a cell in a given year.

3.2 Protected Areas

The main data on PAs in the Brazilian Amazon come from the Amazon Network of Georeferenced Socio-Environmental Information (RAISG). RAISG provides detailed geospatial data on PAs in the Amazon rainforest. PAs in the data set are classified into conservation areas and indigenous territories. The former is divided further into national and state-level PAs, and I observe whether these conservation areas allow for sustainable use or prohibit any extraction of natural resources. The location and the creation year of each PA are particularly important information since I use them to exploit spatial variation in the proximity to a PA and temporal variation in the year of establishment for the identification strategy.

The data set also includes information on the current demarcation status of indigenous territories. To complement the data, I scrape the full history of the demarcation process of each indigenous territory from an online platform managed by Instituto Socioambiental (ISA).[3]. I manually match the indigenous territories from the two different sources by their names.

3.3 Data Processing for Identification Strategy

The pixels of the original data are at a spatial resolution of 30 meters. To ease data-intensive processes, I aggregate original pixels to 1.2km $\times$ 1.2km cells. Thus, a new composite cell, which is the spatial unit of observation for the empirical analysis, consists of 1600 original pixels. The outcome variable of deforestation is defined as the number of original pixels deforested. The forest cover in 2000 for a composite cell is computed as the average of the forest cover percentages of 1600 original pixels.

I overlap the forest data with the PA data where there exist records on 385 conservation areas and 390 indigenous territories. I remove the cells whose centroids are located outside the Brazilian Amazon or in water areas such as rivers, lakes, and reservoirs. Then, I split the sample of cells into two subsamples containing the cells outside and inside the PAs, respectively. The former is used to investigate the dynamic effects of establishing PAs on deforestation in the neighborhoods, whereas the latter is used to explore the dynamic effects identified within PAs.

A variation exploited is in proximity to the PA boundaries for the identification strategy. In the case of the displacement effects in NPAs, if a PA is established, logging activities that originally occurred inside the area would shift to the neighborhood, but not too far from the boundary given the increasing moving and transport cost. To define these *treated* neighborhoods in NPAs, I create 30-kilometer outward buffer zones of PA boundaries and identify the cells overlapped with the buffer zones as the treated.[4] Accordingly, the cells outside the buffer zones are considered as the untreated.

I also use proximity to boundaries to identify the displacement effects within PAs. As loggers invade PAs, they would start logging activities in the areas close to the boundaries to reduce moving and transport costs. This strategy would also help them cut trees in PAs without being noticed. The closer illegal loggers move to the center of a PA, the higher risk of being caught it would entail. Therefore, I define the treated cells in the PA sample as the ones located within 10 kilometers away from PA boundaries.

Another variation for identification stems from different timings of PA establishment. Though the legislation of SNUC in 2000 was a milestone for the expansion of the PA program, not all PAs were established right after the legal reform. There is sufficient variation in the timing of PA creation between 2001 and 2020. This environment allows me to identify the pre- and the post-intervention periods.

A challenge in estimating the displacement effects in NPAs is the presence of overlapping treat-

[3]The information is available at https://terrasindigenas.org.br/en

[4]The 30-kilometer distance is an arbitrary threshold to define the treated and the untreated areas by the establishment of PAs. The treated areas are to be the ones sufficiently close to new PAs from which logging activities supposedly shift to the neighborhoods. One can adjust the threshold, but it should be defined carefully based on the spatial differentials of logging cost.

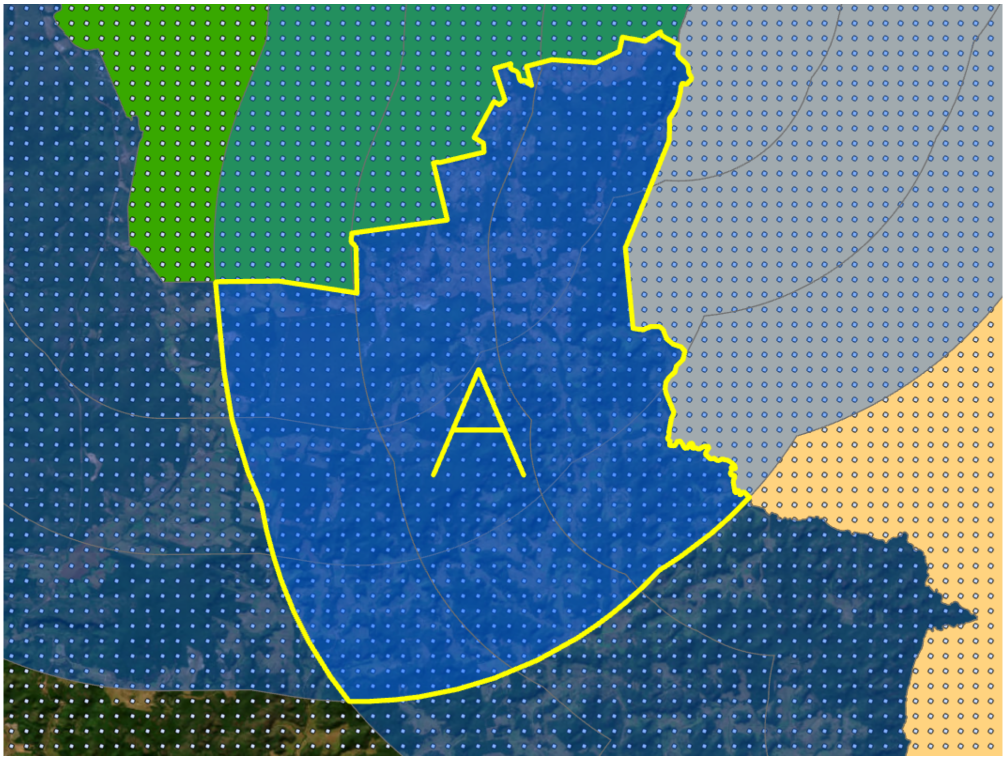


Figure 2: Example of Overlapping Treatments

ments. Numerous PAs in the Brazilian Amazon are adjacent to each other. If a cell in the neighborhood of a PA is affected by another PA due to the proximity of the two PAs, the treatment effect on deforestation in the cell can be overestimated. To limit this bias, I exclude the cells falling into multiple outward buffer zones of PAs in the same year. If a cell is treated for the first time in a specific year and treated again by another PA later, I remove the observations corresponding to the year of the second treatment and the years onward.

For example, in figure 2, the green area is a conservation area established in 2005 and the orange area is an indigenous territory created in 2008. The blue areas are outward buffer zones covering the space of 0 to 30 kilometers away from the boundaries. The cells in A area are located in both buffer zones of the conservation area and the indigenous territory. I exclude the observations of these cells corresponding to the years of 2008-2020. In the end, the cells in A area are identified in the NPA sample as the not-yet treated in 2001-2004 and as the treated in 2005-2007. Through this process, I eventually keep in the sample the cells never treated (i.e., not falling into any buffer zones) or treated only once by a PA.

As I do with the NPA sample, I should also cope with a similar issue of overlapping areas in the PA sample. First, some PAs are completely surrounded by other PAs established later. I remove all cells located in the inner PAs to construct a clean treatment-control structure. Second, since many PAs are adjacent to each other, cells inside some PAs are affected by other PAs established nearby. To avoid the confounding effects caused by the proximity of PAs, I use the 30-kilometer outward buffer zones, restricting the sample to a group of cells located inside PAs but not falling into any outward buffer zones of other PAs.

I report in table 1 the summary statistics of the variables used in the empirical analysis. The table shows that the main outcome variable of deforestation varies to a large extent across cells and years in both NPAs and PAs. The average size of newly deforested areas is roughly 10 times larger in NPAs than in PAs, providing suggestive evidence of the success of PA policy from the myopic perspective. However, within PAs, the gap in the size of deforested areas between the treated and the untreated areas is significant (approximately 3 times higher in the treated areas). Clarifying whether it is simply because of the proximity to NPAs or a gradual increase in invasions due to the dynamic displacement of logging requires an in-depth analysis. In the next section, I study whether any spatial and temporal transitions of deforestation are created by the establishment of PAs.

Table 1: Summary Statistics

Variables	Mean	Std dev	Min	Max	Obs
NPA sample:					
0-30km neighborhood (treatment)	0.29	0.45	0	1	25,778,112
Tree cover in 2000 (%)	62.27	37.20	0.0006	100	25,778,112
Deforestation	11.43	63.64	0	1600	25,778,112
Defo. for the treated	10.02	58.30	0	1600	7,384,402
Defo. for the untreated	11.99	65.65	0	1600	18,393,710
PA sample:					
Inside PA 0-10km away from boundary (treatment)	0.37	0.48	0	1	5,909,000
Tree cover in 2000 (%)	93.49	20.76	0.0006	100	5,909,000
Deforestation	1.85	26.20	0	1600	5,909,000
Defo. for the treated	3.09	33.17	0	1600	2,157,640
Defo. for the untreated	1.13	21.13	0	1600	3,751,360

Notes: Deforestation is defined as the number of original pixels deforested in a given year between 2001 and 2020. For the NPA sample, cells are identified as the treated if they are located in the 0-30km neighborhoods of PAs. For the PA sample, cells are identified as the treated if they are located in areas 0-10km away from the boundaries toward the interior of PAs.

4 Empirical Strategy

The empirical analysis is to uncover how establishing PAs affects the rates of deforestation over time both outside and inside those PAs. I construct difference-in-difference models and conduct event studies to estimate the dynamic displacement effects in NPAs and PAs separately.

4.1 Impact of Protected Areas on Deforestation in Non-protected Area

The first interest is in the displacement of logging activities in NPAs. Using the sample of cells located in NPAs, I estimate the effects of establishing PAs on deforestation in NPAs (i.e., in the neighborhoods of PAs).

The properties of the outcome variable in the study are to be addressed properly. The outcome variable is the number of original pixels deforested in a specific year. To cope with this count variable having many zero values, I estimate the following equation by the fixed-effects Poisson quasi-maximum likelihood (QML) estimator (Silva and Tenreyro, 2006).

$$\begin{aligned}\mathbb{E}[Defo_{cst}] = \gamma_c \exp\Big(\sum_{k=-10}^{-2} \beta_k^{pre} NPA_c \times Pre_{t,k} \\ + \sum_{k=0}^{15} \beta_k^{post} NPA_c \times Post_{t,k} + \mu_{st} + Z_c \cdot \delta_t \Big)\end{aligned} \tag{1}$$

$Defo_{cst}$ is the number of original pixels deforested in year t within cell c located in state s. NPA_c is an indicator for whether cell c falls into an outward buffer zone covering the neighborhood of a PA. The baseline buffer zones cover the neighborhoods of 0 to 30 kilometers. Thus, the group of cells more than 30 kilometers away from any PA is considered as a control group. The dummy variable of $Pre_{t,k}$ indicates the period k years earlier than the year of treatment as cell c is treated in t. $Post_{t,k}$ is defined analogously for the periods ahead of the treatment year. γ_c and μ_{st} are cell and state-year fixed effects, respectively. To control for any time trends of deforestation induced by the degrees of forest cover in the initial period, I also interact the percentage of tree cover in 2000 Z_c with a vector of year fixed effects δ_t. Standard errors are clustered at the cell level.

The estimated coefficients of β_k^{post} will measure the effects of establishing a PA on the rates of deforestation in NPA over time in the form of semi-elasticity (i.e., the percentage change in deforestation with respect to the PA creation).[5] If new PAs push out logging activities to NPAs, the rates of deforestation in the neighborhoods would increase for a while (compared to the rates in the untreated NPAs). However, if the nonrenewable characteristics of trees play a role in the selection of logging areas, the deforestation rates in the treated areas would decrease in the medium or long term since logging activities would shift to somewhere else.

4.2 Impact of Protected Areas on Deforestation in Protected Area

If logging activities in the outward buffer zones (i.e., the neighborhoods of PAs) gradually move to different areas, where do they go? It depends on spatial differentials in logging costs in a given year (under the assumption that the values of all trees in the Amazon are homogeneous). They may shift to originally untreated NPAs. They may also move to other NPAs within the outward buffer zones if there exist trees that remain intact yet.[6] A more problematic case is in which logging activities shift back to PAs. The presence of this boomerang effect implies that the PA policy does not fully prevent invasions for illegal logging but just postpones them.

To examine this displacement of logging into PAs, I use the PA sample where all cells are located inside PAs. I estimate the effects of establishing PAs on deforestation inside those PAs through the

[5] In general, estimating average treatment effects on the treated in level is not possible through a fixed-effects Poisson model (Wooldridge, 2022).

[6] In this case, the decline in the treatment effects on deforestation in NPA would be delayed.

following Poisson QML model event study.

$$\mathbb{E}[Defo_{cst}] = \gamma_c \exp\Big(\sum_{k=-10}^{-2} \beta_k^{pre} PA_c \times Pre_{t,k} + \sum_{k=0}^{15} \beta_k^{post} PA_c \times Post_{t,k} + \mu_{st} + Z_c \cdot \delta_t \Big) \tag{2}$$

The specification is identical to the one in the NPA analysis except for the treatment indicator PA_c. PA_c is equal to one if cell c is less than 10 kilometers away from the boundary of a PA. Accordingly, the control group includes the cells more than 10 kilometers away from the boundary toward the interior.

If PAs succeed in *full* protection at the beginning of creation, the estimated coefficients of β_k^{post} would equal zero for the first few ks. However, if logging activities shift back to PAs due to the clearing in NPAs, $\hat{\beta}_k^{post}$ would gradually increase. This hypothesis relies on the assumption that the cost of logging inside PAs is proportional to the distance toward the interiors of the areas from their boundaries. Loggers would cut trees in the areas close to the boundaries first since illegal logging in the inner areas would be spotted more easily. In addition, they could reduce transport costs by logging near the boundaries first given the short moving distance and accessibility to roads or sawmills in NPAs.

5 Results

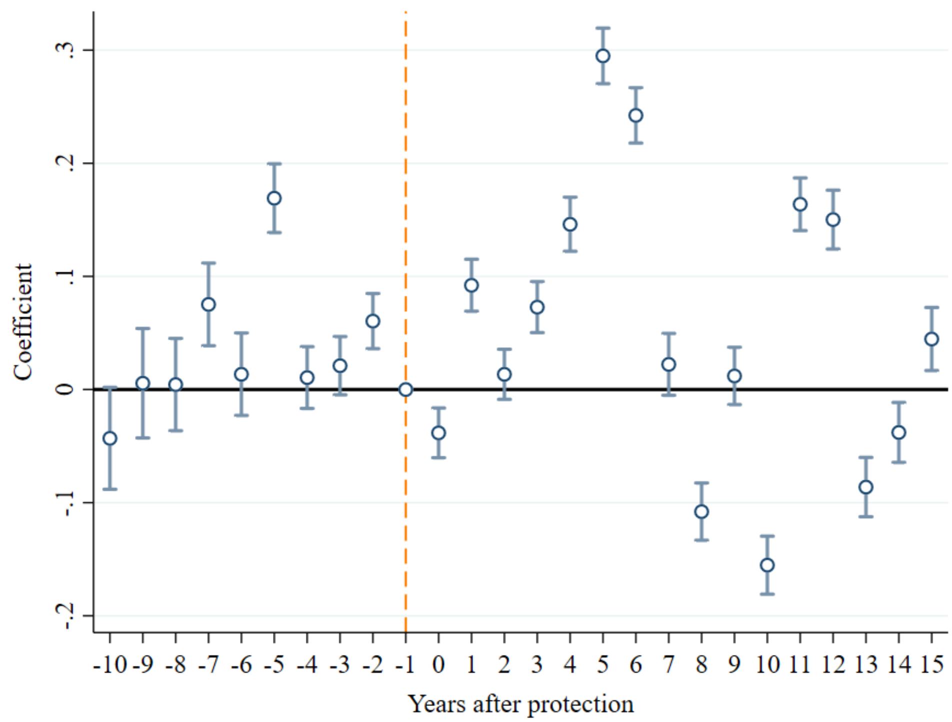
5.1 Deforestation in Non-protected Area

Figure 3 shows the event study result where I plot the estimated effects of PA establishment on deforestation in NPA (i.e., β_k^{pre} and β_k^{post} in equation (1)). One notes that establishing PAs impacts deforestation in the neighborhoods of the areas and the effects are not temporary ones. Roughly speaking, there are three dynamic patterns in the treatment effect.

The first striking phenomenon is a sharp increase in deforestation in the neighborhoods at the beginning of PA establishment. For the first 6 years, new PAs dramatically increase deforestation in the 0-30 kilometers neighborhoods, compared to the outside of the neighborhoods in NPAs. For example, PAs approximately raise the rate of deforestation in the neighborhoods by 34% 5 years after their establishment. This suggests that logging activities previously implemented in not-yet-protected areas shift to their neighborhoods once the areas are protected. This displacement is supposedly caused by the discrepancy in logging costs between PAs and NPAs.

The *leakage effect* faces a new phase 7-10 years after the establishment. In this period, establishing PAs has no impact on the size of newly deforested areas in the neighborhoods or even reduces the size. This sudden change implies that logging activities shift to other areas from the neighborhoods due to the nonrenewable features of trees in the Amazon. Given that not all areas of the PA neighborhoods have roads or sawmills nearby, loggers might have considered transport

Figure 3: Event Study – Impacts of PA Establishment on Deforestation in NPA (0-30km neighborhoods)



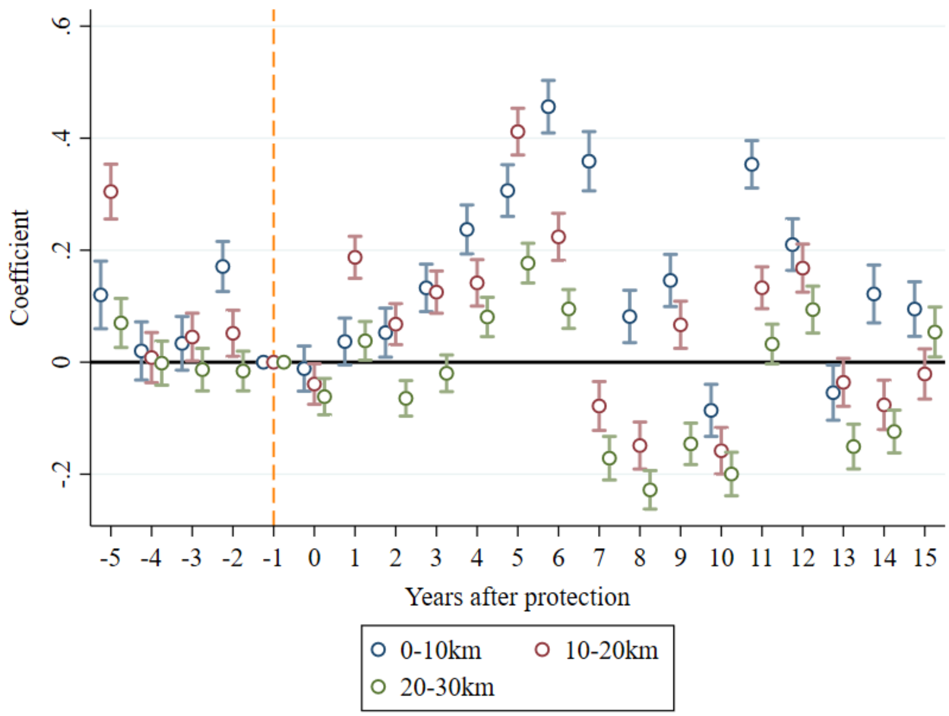
Notes: The figure depicts the effects of PA establishment on deforestation in NPA. The effects are estimated by the Poisson QML estimator using a difference-in-difference structure. The outcome variable is the number of original pixels deforested in a given year. The treated areas are the neighborhoods of PAs covering 0-30 kilometers from the boundaries, whereas the control areas are the rest of NPAs. The baseline year is one year before the years of PA establishment. Standard errors are clustered at the cell level. The vertical lines indicate 95% confidence intervals.

costs and moved to other areas (i.e., untreated areas in NPA, insides of PAs, or both) although there still exist trees left uncut in the treated areas.

After the second displacement phase, the treatment effect fluctuates (11-15 years after the establishment). This provides evidence that logging activities shift constantly in response to the change in logging costs. Loggers would come back to the neighborhoods if the costs of logging in other areas go beyond the cost in the neighborhoods. If the cost in the neighborhoods exceeds the costs in other areas, they would move to the outside of the treated neighborhoods again.

I also split the 0-30 kilometers treated area into three 10-kilometer-interval bands, estimating

Figure 4: Event Study − Impacts of PA Establishment on Deforestation in NPA (0-10, 10-20, and 20-30km neighborhoods)



Notes: The figure depicts the effects of PA establishment on deforestation in NPA. The effects are estimated by the Poisson QML estimator using a difference-in-difference structure. The outcome variable is the number of original pixels deforested in a given year. The treated areas are the neighborhoods of PAs covering 0-10, 10-20, and 20-30 kilometers from the boundaries, whereas the control areas are the rest of NPAs. The baseline year is one year before the years of PA establishment. Standard errors are clustered at the cell level. The vertical lines indicate 95% confidence intervals.

the displacement effect in each neighborhood band.[7] Figure 4 presents the result.

In the 0-10 kilometers neighborhoods, the rapid increase in the deforestation rate by the establishment of PAs is conspicuous. By contrast, the displacement effect at the beginning of PA establishment is smaller in the 20-30 kilometers neighborhoods. This suggests that logging activities pushed out from PAs shift more to the neighborhoods closer to the PA boundaries because the cost of displacement increases as loggers move further from their previous logging areas.

In the second displacement phase, new PAs generally increases the size of areas newly deforested

[7]The Poisson QML model in equation (1) is modified as:

$$\mathbb{E}[Defo_{cst}] = \gamma_c \exp\Big(\sum_{b=1}^{3}\sum_{k=-5}^{-2} \beta_{k,b}^{pre} NPA_{c,b} \times Pre_{t,k} + \sum_{b=1}^{3}\sum_{k=0}^{15} \beta_{k,b}^{post} NPA_{c,b} \times Post_{t,k} + \mu_{st} + Z_c \cdot \delta_t\Big) \tag{3}$$

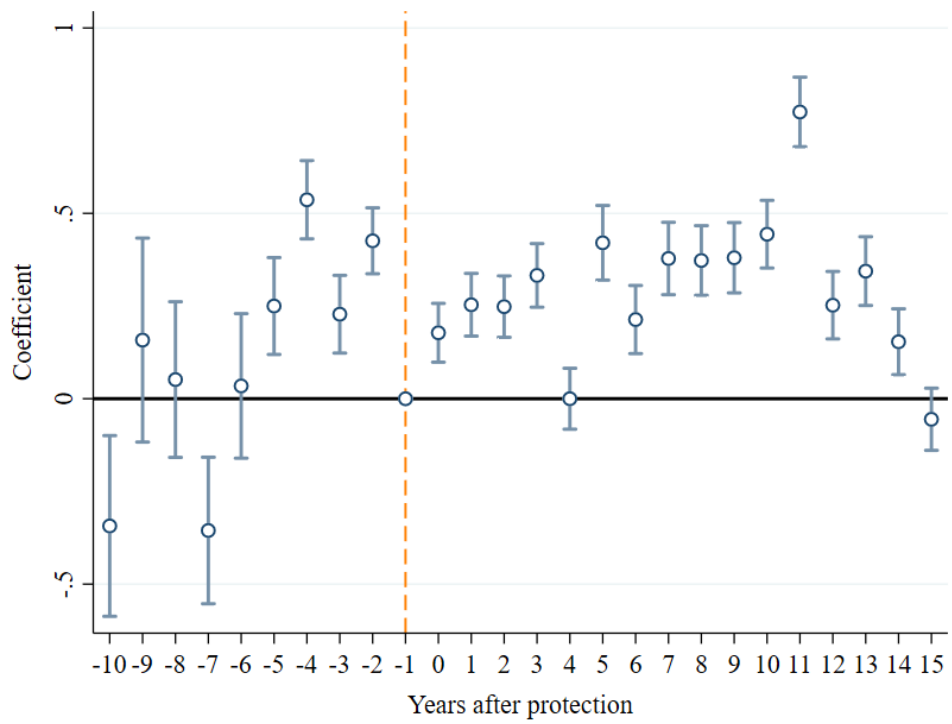
where the band numbers $b = 1, 2, 3$ indicate the 0-10, 10-20, and 20-30 kilometers neighborhoods, respectively.

in the 0-10 kilometers neighborhoods although the treatment effects are lower than the ones in the first displacement phase. The opposite displacement effect (shown in figure 3) is mainly driven by the change in the 10-30 kilometers neighborhoods. One can anticipate that logging activities in these neighborhoods shift to the outside of the neighborhoods or to the 0-10 kilometers neighborhoods.

5.2 Deforestation in Protected Area

In this section, I show event study results highlighting the dynamic displacement effects on the interior of PAs. Figure 5 depicts the effects of PA establishment on deforestation in PA.

Figure 5: Event Study – Impacts of PA Establishment on Deforestation in PA (areas 0-10km away from boundaries)



Notes: The figure depicts the effects of PA establishment on deforestation in PA. The effects are estimated by the Poisson QML estimator using a difference-in-difference structure. The outcome variable is the number of original pixels deforested in a given year. The treated areas are the inner areas of PAs 0-10 kilometers away from the boundaries, whereas the control areas are the rest of PAs. The baseline year is one year before the years of PA establishment. Standard errors are clustered at the cell level. The vertical lines indicate 95% confidence intervals.

The first noticeable feature is the increase in deforestation in the 0-10 kilometers inner areas before the establishment of PAs (i.e., the period of -5 to -2). The process of PA establishment is time-consuming. It often takes multiple years to legalize protection due to conflicting interests (OECD, 2015). If loggers are informed of future protection for a certain area, they may strategically increase logging activities in the area close to the future boundary of the PA. This strategic behavior will allow them to save the displacement cost when the PA becomes legally binding because they can easily move to NPA for the next logging activities.

Surprisingly, compared to the untreated areas of PAs (i.e., inner areas more than 10 kilometers away from the boundaries), creating PAs increases deforestation in the treated areas (i.e., inner areas 0-10 kilometers away from the boundaries) even at the beginning of establishment. It can be explained by the spillover effect of increasing deforestation in the PA neighborhoods. Establishing PAs pushes out logging activities to their neighborhoods, but the difficulty of full protection presumably allows for some spillovers of deforestation toward the inside of PAs. That is, the instantaneous increase in the rate of deforestation in figure 5 indicates that the inside of PAs close to the boundaries always faces a high risk of invasion compared to the rest of the interior.

The main evidence of the dynamic displacement of logging is the gradual increase in the treatment effect. The size of newly deforested areas induced by new PAs increases over time. This finding implies that logging activities previously displaced to NPAs gradually shift back to PAs. The more trees loggers cut in NPAs, the higher the transport cost they should pay. Due to the increasing cost in NPAs, loggers have more incentives to invade PAs where the cost of logging is relatively low. In particular, the treatment effects are relatively large and stable 7-10 years after the PA establishment. This is the second displacement period in which logging activities in the PA neighborhoods are expected to shift to somewhere else (see figure 3). The two displacement effects in NPAs and PAs in this period suggest that logging activities flow into PAs from the neighborhoods.

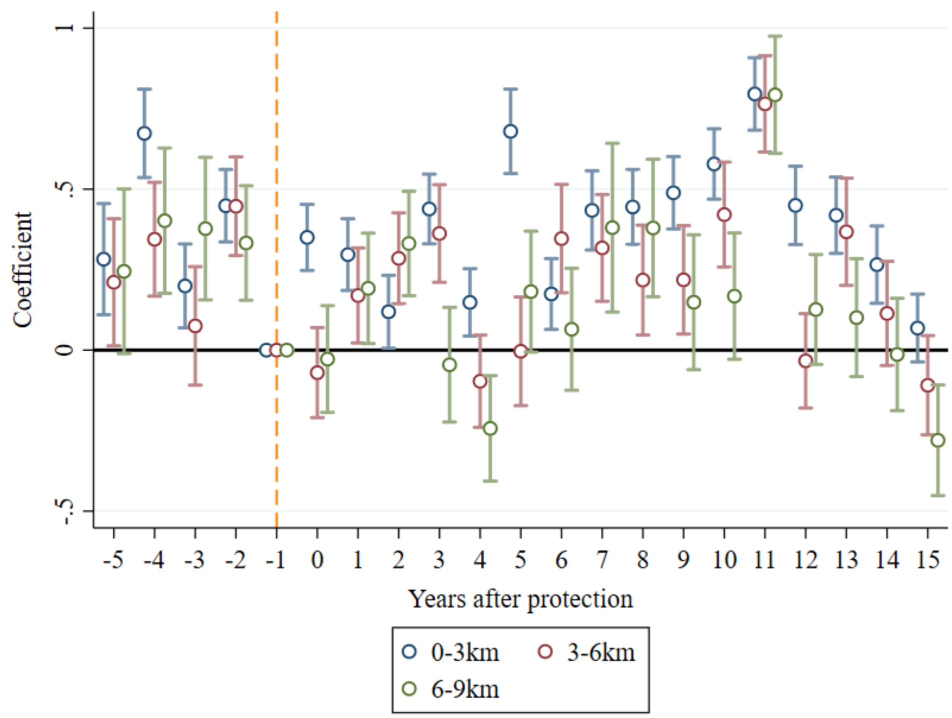
I also find that cutting and transporting a tree is more costly in PAs than in NPAs. The growth rate of the displacement effect in PAs is lower than in NPAs for the first 6 years. It is attributed to the fact that logging in PAs requires extra costs of efforts not to be caught. Thus, it is very costly to go further into the interior of PAs, and it is more likely that logging activities shift back to NPAs again after the 0-10 kilometers PAs are cleared to some extent. The decreasing trend in the increment of deforestation in the long term (i.e., 12-15 years after the establishment) supposedly accounts for this phenomenon.

To delve into spatial differentials in the treatment effect, I also create 0-3, 3-6, and 6-9 kilometers bands and estimate the dynamic displacement effect on deforestation in each band. I plot the estimated coefficients in figure 6. In general, the dynamic displacement effect is relatively large in the 0-3 kilometers treated areas. This finding highlights that loggers make decisions on the location of illegal logging strategically in light of transport costs and the risk of being caught.

5.3 Caveats

To examine the dynamic impacts of PAs on deforestation, I exploit variation in proximity to PA boundaries and variation in establishment timing. A current body of the difference-in-difference estimator literature rigorously discusses potential bias in treatment effects if the effects are not free from heterogeneity across groups or over time (de Chaisemartin and D'Haultfœuille, 2020; Callaway and Sant'Anna, 2021; Goodman-Bacon, 2021; de Chaisemartin and D'Haultfœuille, 2022). Given

Figure 6: Event Study − Impacts of PA Establishment on Deforestation in PA (areas 0-3, 3-6, and 6-9km away from boundaries)



Notes: The figure depicts the effects of PA establishment on deforestation in PA. The effects are estimated by the Poisson QML estimator using a difference-in-difference structure. The outcome variable is the number of original pixels deforested in a given year. The treated areas are the inner areas of PAs 0-3, 3-6, and 6-9 kilometers away from the boundaries, whereas the control areas are the rest of PAs. The baseline year is one year before the years of PA establishment. Standard errors are clustered at the cell level. The vertical lines indicate 95% confidence intervals.

the potential presence of heterogeneous treatment effects in PA establishment and the nonlinearity of the difference-in-difference structure in the empirical model, interpreting the magnitudes of the treatment effects requires more caution. However, the event studies evidently show that the dynamic patterns of the rate of deforestation are driven by the establishment of PAs. This finding spotlights the fundamental reason for invasions into PAs.

Another concern is the placement of PAs responsive to the rate of deforestation. If PAs are created in places where past deforestation rates are high, this reverse causality can cause an overestimation of the dynamic displacement effect. To disentangle this channel with the treatment effect (at least partially), I introduce in the regressions the interaction of tree cover in 2000 and year fixed effects ($Z_c \cdot \delta_t$ in equations (1) and (2)). If the tree cover status in 2000 (i.e., the stock of deforested areas until 2000) is persistently correlated with the rate of deforestation in the following years, this variable should sufficiently account for the role of past deforestation rates as a determinant of PA establishment.

6 Conclusion

This paper examines how establishing PAs affects the rate of deforestation in different areas at different times. I find that new PAs dramatically increase the rate of deforestation in the neighborhoods of the areas in the short term, whereas the rate decreases or fluctuates in the medium or long term. Logging activities are displaced from the inside of PAs to their neighborhoods at the beginning of establishment due to the gap in logging costs. However, the logging cost in the neighborhoods increases as the number of trees left uncut decreases. Eventually, logging activities shift again from the PA neighborhoods to other areas where the costs of logging are relatively low.

This dynamic displacement of logging gradually raises the rate of deforestation in PAs. I find that establishing PAs gradually increases the size of newly deforested areas in the interior of PAs close to the boundaries. This implies, in response to the dynamic transition of logging costs in PAs and NPAs, logging activities previously displaced to the neighborhoods of PAs shift back to the inside of PAs. However, since continuous logging activities in PAs also increase the cost of logging in the areas, the increasing rate of deforestation gradually dissipates in the long term when logging activities flow out to NPAs again. This dynamic displacement of logging will repeatedly occur over time because of the continuous change in the costs of logging in PAs and NPAs.

These findings deliver a strong message that PAs do not prevent but just postpone illegal logging as long as trees are treated as a nonrenewable resource. If the cost of logging in NPAs continues to increase as NPAs are cleared more and more, invasions into PAs are unavoidable. The dynamic displacement of logging will constantly happen whenever the cost in NPAs overtakes the cost in PAs.

Designing a PA policy has been challenging due to the complexity of conflicting interests such as climate change adaptation and mitigation, firms' profit maximization, and protection of local residents' property rights. This study uncovers that decision-making for PA establishment is indeed more difficult due to the presence of the dynamic displacement effect. To find the optimal policy design, this study is to be developed further. It is important to understand how the types of protected areas, political stability, and accessibility to local markets affect the dynamic displacement of logging activities. The next study should also explore what roles the incentives of land use and local market conditions play in the dynamic consequences of PA establishment.

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