Impacts of Paraguay's zero-deforestation law

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Abstract

Countries are increasingly banning deforestation on private lands. While this policy represents an ambitious commitment to forest conservation, its lack of flexibility has drawn criticism. However, relatively little research details whether such bans have been effective. Here, we study the impacts of Paraguay's zero-deforestation law, a ban on deforestation across the Eastern half of the country that was adopted in 2004. We estimate the impact of the law by comparing deforestation trends in Eastern Paraguay against deforestation in other South American sub-national jurisdictions using a synthetic difference-in-differences approach. We find a precisely estimated null result, which is robust to a wide variety of alternate model specifications. To explore why the law failed to reduce deforestation, we draw upon a review of the law's implementation, and novel, remotely sensed data detailing the drivers of deforestation. We demonstrate that weak enforcement and conflicts with agrarian reform policies likely undermined the zero-deforestation law.

Keywords: deforestation, conservation policies, law enforcement

1 Introduction

Agriculture, forestry, and other land use (AFOLU) activities contributed 23% to the total net anthropogenic greenhouse gas emissions between 2007 and 2016 (IPCC, 2019). The most significant economic opportunities for AFOLU emissions reduction lie in conservation and forest management programs, with reducing deforestation in tropical regions having the highest mitigation potential (IPCC, 2022). Therefore, the trajectory of global emissions highly relies on the capacity of developing countries to implement and enforce forest conservation policies (Greenstone and Jack, 2015), and research in this setting can help explain the potential gap between *de jure* design and *de facto* policy implementation (Balboni et al., 2023).

This paper estimates the impact of Paraguay's zero-deforestation law (hereafter referred to as ZDL) on deforestation and agricultural land use. Approved in 2004, the law aimed to protect the remaining areas of the Atlantic forest, a severely threatened tropical biome. The policy banned deforestation in Eastern Paraguay - which holds almost 98% of the population and nearly half of the country's territory - and forbade deforestation for any potential land use. This setting allows us to assess the effectiveness of the ZDL and the drivers of ongoing deforestation clearly. We assess the policy effectiveness with a synthetic control approach and analyze the contribution of smallholder and large-scale agriculture to deforestation. We highlight the conflicts between government jurisdictions and, specifically, the contribution of agrarian reform programs to deforestation.

Increasingly, forest conservation initiatives rely on economic incentives for preservation, e.g., payment for environmental services (PES) schemes (Alix-Garcia and Wolff, 2014), eco-certifications (Blackman et al. (2018), Blackman and Naranjo (2012)) and private supply chain initiatives (Heilmayr et al. (2020), Gibbs et al. (2016), Carlson et al. (2018)). Nonetheless, governments in developing countries still rely on the designation of protected areas (Watson et al., 2014) and command-and-control policies as the dominant interventions for forest conservation (Börner et al., 2020).

Strict deforestation bans on private lands have been implemented in Costa Rica (Fagan et al., 2013) and Queensland, Australia (Simmons et al., 2018). While these policies hold significant potential for conservation, their strict land-use restrictions may impact economic outcomes and raise equity concerns by hindering smallholders' access to agricultural land. Furthermore, research pointing to the effectiveness of strict forest management policies demonstrates how they hinge heavily on monitoring and enforcement capacity, a result of the detection technology (Assunção et al. (2023), Moffette et al. (2021)), and also political economy factors, such as cross-jurisdiction interactions (Burgess et al., 2012). We argue and provide empirical evidence demonstrating that the zero-deforestation commitment had a non-significant impact due to a combination of (i) a lack of detection technology and (ii) issues in cross-jurisdiction interactions and conflicting interests.

Our discussion of policy effectiveness is twofold. First, we employ a synthetic difference-in-differences approach to assess the policy impact on deforestation. Estimating the impacts of ZDL is empirically challenging since the policy targeted East Paraguay - which encompasses nearly half of Paraguay's territory - and, therefore, potentially led to deforestation leakage in the non-affected area. Due to the likely spillovers, West Paraguay cannot be used to identify the counterfactual deforestation trajectory in the absence of ZDL. Considering this setting, we follow Arkhangelsky et al. (2021) synthetic difference-in-differences approach to construct a synthetic counterfactual time-series scenario for Paraguay's deforestation trajectory. We leverage an extended panel of forest cover data from MapBiomas, spanning from 1986 to 2020, and consider the deforestation trajectory of other regions within South America to construct the synthetic control. Second, we leverage our novel remotely sensed land-use data, focused on mapping small-scale agriculture, to characterize policy compliance and deforestation drivers.

Initial results indicate that the policy had no statistically significant effect on Eastern Paraguay's deforestation trajectory post-2004 relative to the constructed counterfactual. Our results are robust to variations in the donor pool regions, pre-treatment periods, and placebo tests. A combination of factors explains the lack of an effect on deforestation. First, the agency responsible for enforcing the policy, Paraguay's National Forest Institute (INFONA), had no system to consistently monitor forest cover until 2020. Secondly, even when violations were detected, the judiciary system faced multiple challenges in prosecuting violators. We argue these two factors severely lowered the potential cost of a policy violation to the offenders. In tandem, agrarian reform policies also contributed to ongoing deforestation in the post-2004 period.

Our paper contributes to the literature on the effects of forest conservation mandates on private lands (Alston and Mueller (2007), Fagan et al. (2013), Simmons et al. (2018)). Our results suggest that a lack of enforcement capacity and conflicts with other government institutions can harm policy effectiveness in protecting forests. Our analysis contributes to the extensive literature discussing the drivers of the gap between *de jure* and *de facto* environmental rules in a developing country setting (Balboni et al. (2023), Burgess et al. (2012), Harstad and Mideksa (2017), Robinson et al. (2010)). We also speak to the literature discussing the contribution of small and large-scale agriculture to deforestation in the developing world (Pendrill et al. (2022), Song et al. (2021)), Curtis et al. (2018), Austin et al. (2017), H. K. Gibbs et al. (2010)). Finally, our work adds to the literature on land use change in Paraguay (Huang and Yao (2023), Da Ponte et al. (2017a), Da Ponte et al. (2017b)), a country that has experienced some of Latin America's highest deforestation rates (Hansen et al., 2008). Our work adds to Fenton (2023) discussion of the ZDL impacts and can inform the potential implications of similar bans in the developing world.

2 Background

In this section, we present a contextual overview of the zero-deforestation law. We also raise two important aspects to guide the discussion of policy implications: (i) the role of agrarian reform colonies in Paraguay's rural colonization and (ii) the contribution of agriculture to deforestation in the last decades.

2.1 The Zero-deforestation Law

Spanning Brazil, Argentina, and Paraguay, the Atlantic Forest is one of the most important biodiversity hotspots on the planet. Five centuries of urbanization and agricultural expansion led to substantial forest loss and fragmentation, and today, most of the Atlantic forest landscape consists of small forest fragments (<50 hectares) (Joly et al. (2014), Vancine et al. (2024)). Starting in the 1970s, the academic community and international organizations (e.g., Conservation International and World Wildlife Fund (WWF)) began recognizing the Atlantic Forest as a priority region for biodiversity conservation (Marques and Grelle, 2021). In this context, in Paraguay in mid-2004, after decades of persistent deforestation, WWF and the country's vice president Luis Castiglione proposed a commitment to a 'Social pact for Paraguay's Upper Paraná Atlantic Forest'. The commitment would be signed by private and public institutions and establish limitations to the conversion of forest in the Atlantic biome (WWF, 2004). The initial idea of a pact shifted to 'Ley de Deforestación Cero' (Zero-Deforestation Law), approved by Paraguay's congress in December

2004.

At first, the ZDL established a two-year ban on deforestation for any land use in Eastern Paraguay, including agricultural land and urban areas. Figure 1 shows the territorial divide between East and West Paraguay. The 2-year ban had the objective of hampering deforestation rates. It included the suspension of previous land-use plans[1] in which deforestation was authorized and forbade the issuance of new land-use plans that included any deforestation. Before this policy, rural property owners in East Paraguay were required to submit a land-use plan to INFONA (Paraguay's National Forest Institute) with the necessity of keeping 25% of the property area as forest cover. The Law was extended in 2006, 2008, 2013, and 2018; in 2020, it was last extended for 10 additional years.

Figure 1: East Paraguay and Atlantic forest coverage

To the best of our knowledge, the ZDL was the world's first national-level policy to ban deforestation completely. Although Costa Rica had a similar country-wide ban on deforestation established in 1996, the policy still allowed for regulated logging (Fagan et al., 2013). Further, it was implemented in a different context relative to Paraguay since the ban was accompanied

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[1] A land-use plan (*Planes de uso de la tierra*) was required for any rural property of 20 hectares or larger. The document, to be submitted to INFONA (Paraguay's National Forest Institute) for approval, contained the land-use plan, including a forest inventory.

by a nationwide payment for environmental services program and following decades of increasing conservation-focused policies (Morse et al., 2009).

Overall, the legal regiment changed very little through each law interaction, but a few modifications in the text are worth highlighting. The 2008 version of the policy (Law 3663/2008) specifically highlighted that forest areas could not be used in agrarian reform. In 2018, Law 6256/2018 created the National System of Forest Monitoring (English for *Sistema Nacional de Monitoreo Forestal (SNMF)*), which would release monthly maps of forest cover in the Eastern area. The update also highlighted the capacity of INFONA and MADES (Ministry of the Environment and Sustainable Development) to sanction law violators at the administrative level, in addition to the previously established judicial sphere.

In all of its versions, the ZDL defined forest cover as an area with a minimum surface of two hectares, with a tree-cover canopy of at least 50%, and where there are more than 60 trees per hectare with more than 15 centimeters of diameter. The Law demanded that an inventory of the forest be made, which would be used to verify the law's effectiveness. However, it was not until 2011 that INFONA constructed the first forest-cover inventory of the region, tracing forest loss that took place between 2004-2011.

Considering INFONA's 2004 forest cover mapping, Table 1 shows the distribution of forest within Eastern Paraguay at the time. When the policy was established, almost 84% of forest cover was located outside protected areas or indigenous territories - Figure A.3 shows the distribution of these areas in the country. Hence, the ZDL could potentially affect a large share of the existing forest not managed by Paraguay's government[2]. Further, almost 2.5 million hectares of forest were located within the Atlantic forest biome area. The area is significant considering that recent estimates from Rezende et al. (2018) show that in Brazil, the country that held most of the biome area, only 32 million hectares remain. Hence, despite the substantial deforestation of the Atlantic forest since the 1970s, in 2004, Paraguay still held a considerable area of the biome to be potentially protected by the ZDL.

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[2] For reference, the total forest area represents approximately 17% of the eastern territory, which covers a total area of 16 million hectares.

Table 1: Eastern Paraguay forest-cover: 2004

Territory	INFONA Mapping (ha)
Indigenous lands and conservation units	555,483
Outside indigenous lands and conservation units	2,865,740
Within Atlantic biome	2,447,339
Total area	3,421,223

Note: We consider the geographical limits of the Atlantic forest biome within Paraguay as in MapBiomas (2024).

Using Mapbiomas data (more details on the data are presented in Section 4), Table 2 provides a breakdown of the forest cover distribution within Paraguay's departments (Figure A.4) and the forest loss pre and post-ZDL. The table highlights that departments in the eastern border of the country - Alto Paraná, Caaguazú, and Itapuá - had some of the highest rates of forest loss pre-treatment and mostly kept the highest rate of forest loss post-2005. Overall, the table shows a reduction in the deforested area and rates post-policy; however, the share of forest loss in the post-treatment period is still high, considering the ZDL introduced a strict prohibition on forest clearing.

Table 2: Variation in forest cover (ha) - Pre and post ZDL

Department	Forest 1985 (ha)	Dif. 1985-2004*	Loss (%) 1985-2004	Forest 2005	Dif.2005-2020*	Loss (%) 2005-2020
Alto Paraná	774,053	459,807	59	344,828	86,083	25
Amambay	605,740	237,225	39	383,983	79,588	21
Caaguazú	537,954	239,781	45	369,773	116,871	32
Caazapá	409,905	155,503	38	264,195	46,184	17
Canindeyú	1,095,149	554,816	51	545,466	162,806	30
Central	26,592	3,317	12	23,610	1,947	8
Concepción	817,988	144,229	18	682,039	59,315	9
Cordillera	84,671	5,637	7	80,792	4,592	6
Guairá	133,306	41,256	31	99,581	13,748	14
Itapúa	631,592	303,153	48	349,606	42,129	12
Misiones	49,394	3,744	8	49,298	2,374	5
Ñeembucú	57,234	7,055	12	59,975	6,158	10
Paraguarí	134,998	12,041	9	128,904	4,827	4
San Pedro	949,628	377,072	40	599,157	191,883	32

* Forest cover reductions relative to 1985 and 2005 forest cover baselines.

To the best of our knowledge, this is one of the first papers providing a direct assessment of the impacts of Paraguay's zero-deforestation law. Fenton (2023) shows that the policy did not significantly reduce overall deforestation rates but impacted large-scale agriculture-driven forest loss. While Fenton (2023) conducts a comparative analysis only within eastern Paraguay, we complement it by estimating the policy impacts using a synthetic differences-in-differences approach, which allows us to construct a counterfactual scenario for the deforestation trajectory. Further, we use our unique remotely sensed data to qualify the contribution of different deforestation actors, e.g., farmers in government colonies and large-scale agriculture.

2.2 Atlantic forest degradation, land reform and agricultural expansion

In 2005, Paraguay stood out as the nation experiencing the most significant rate of tropical forest clearance relative to the year 2000 forest cover baseline (Hansen et al., 2008). Most deforestation in Eastern Paraguay in the last decades has occurred to clear land for agricultural use. The massive colonization of rural areas of Eastern Paraguay and the consequential degradation of forest cover starting in the second half of the 20th century can be partially attributed to (i) the establishment of colonies from government-led agrarian reform in the region and (ii) the expansion of large scale agriculture.

Alfredo Stroessner's dictatorship (1954 - 1989) created *Instituto de Bienestar Rural* (IBR) and the new *Estatuto Agrario* in 1963 with the objective of promoting agrarian reform by creating colonies in public lands. To reduce the population concentration around the capital and to contain the increasing pressure from settlers on the border with Brazil, the new statute led to a 'march to the east', in which massive peasant populations were allocated in colonies in Alto Paraná and Caaguazú departments (Riquelme and Kretschmer (2016), Setrini (2011)). Furthermore, with the implementation of these policies, the distribution of large agricultural plots became one of the most important forms of rewarding the regime allies, especially within the military. Through IBR, 12.2 million hectares of land were allocated during the dictatorship period, and two-thirds (representing 19.3% of Paraguay's territory) are associated with irregularities (González et al., 2022).

With democratization, the 1992 constitution gave legal support for agrarian reform, and the end of the dictatorship allowed peasant organizations to become more active, carrying out occupations more frequently (Rojas Villagra and Areco, Abel, 2017). According to Riquelme (2015) in Rojas Villagra and Areco, Abel (2017), this pressure resulted in around 500 thousand hectares of land distributed in East Paraguay since the democratization. In 2004, IBR was replaced by INDERT (*Instituto Nacional de Desarrollo Rural y de la Tierra*), which carried out the same objectives of promoting agrarian land reform. Between 2005 and 2020, INDERT titled 17,127 land plots in Eastern Paraguay, covering an area of roughly 172 thousand hectares. Figure A.5 shows the evolution of land distribution in eastern Paraguay since the ZDL was implemented.

Although agrarian reform colonies have been responsible for distributing forested land in eastern Paraguay since the 1960s, the development of large-scale agriculture has contributed significantly to deforestation. According to MapBiomas (2024), the area occupied by agriculture and ranching in eastern Paraguay jumped from 2.5 million hectares in 1985 to 5.3 million in 2020. Even more striking, the area occupied by agriculture went from 0.9 million to 3 million in 2020.

The threefold expansion in agriculture was mostly driven by soybean and maize production. According to INBIO (2020), the maize and soy cultivation areas in eastern Paraguay in 2020 covered 865 thousand and 515 thousand hectares, respectively. The departments on the border with Argentina and Brazil and within the Atlantic biome area - Canindeyú, Alto Paraná, and Itapuá - were responsible for at least 60% of the total production of both commodities in the country in 2019-2021. Figure A.6 shows the regional distribution of production.

3 Empirical Strategy

We follow the synthetic difference-in-differences (SDID) approach from Arkhangelsky et al. (2021) to estimate ZDL's impacts on deforestation. The method combines features of difference-in-differences (DID) and Synthetic Control (SC) methods. In a DID approach, the empiricist selects the comparison units based on arguments about the affinity with the treated unit(s) and assumes the parallel trends assumption holds after controlling for time and unit fixed effects. In our setting, where we have a highly aggregated treated unit - Eastern Paraguay region - it is unclear which non-treated area should be used as a valid counterfactual. Due to potential SUTVA violations from deforestation spillovers, Western Paraguay is not a valid comparison group in the traditional difference-in-differences setting. Additionally, it is questionable whether other geographical regions outside the country would have sufficient affinity to be compared with Eastern Paraguay (Abadie, 2021). SDID approach overcomes these issues by constructing a valid counterfactual while controlling for unit-level time-invariant characteristics.

Following the notation from Arkhangelsky et al. (2021), consider a balanced panel of N units and T time periods. Let N_{tr} be the number of treated units. There are N_{co} units never exposed to treatment, which will form the donor pool used to construct the counterfactual. The sample size of $N = N_{co} + N_{tr}$ in our setting consists of $N = 929$ sub-national regions of South America[3], where $N_{tr} = 13$ since we consider the departments within Eastern Paraguay[4] as treated units. Figure A.1 shows the geographic units considered in our sample.

To illustrate how we estimate the average causal effect of exposure (denoted by τ) to the zero-deforestation law using SDID approach, consider a basic two-way fixed effects regression:

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[3] The sub-national geographical divisions considered are governments' administrative segmentation of their territories. We used either state-level or second-level administrative divisions, which are below the state level but above the municipal level. We use this division across all South American countries to roughly match the geographical dimension of the 14 administrative departments within Paraguay's Eastern region (affected by the policy). Our sample contains 1,300 sub-national regions from Brazil, Argentina, Uruguay, Paraguay, Bolivia, Peru, Ecuador, Colombia, Venezuela, Guyana, Suriname, and French Guyana. Our final sample has $N = 929$ since we are only considering areas that had non-zero forest cover at the beginning of our sample in 1986.

[4] We drop Asunción district, which is within Eastern Paraguay, from our sample since it is a capital district and occupies a small territory.

$$Y_{it} = \mu + \alpha_i + \beta_t + W_{it}\tau \tag{1}$$

where Y_{it} is the deforestation percentage in region i in year t. $W_{it} \in \{0, 1\}$ indicates treatment exposure of area i in period t to the law. α_i is a unit-level fixed effect and β_t the time fixed effect. In a DID setting the effect of treatment exposure is estimated by solving the two-way regression problem:

$$\left(\hat{\tau}^{\text{sdid}}, \hat{\mu}, \hat{\alpha}, \hat{\beta}\right) = \underset{\tau,\mu,\alpha,\beta}{\arg\min} \left\{ \sum_{i=1}^{N} \sum_{t=1}^{\mathrm{T}} \left(Y_{it} - \mu - \alpha_i - \beta_t - W_{it}\tau\right)^2 \right\} \tag{2}$$

The SDID approach estimates the average causal effect of exposure τ by estimating a weighted DID regression. This is implemented by solving the following:

$$\left(\hat{\tau}^{\text{sdid}}, \hat{\mu}, \hat{\alpha}, \hat{\beta}\right) = \underset{\tau,\mu,\alpha,\beta}{\arg\min} \left\{ \sum_{i=1}^{N} \sum_{t=1}^{\mathrm{T}} \left(Y_{it} - \mu - \alpha_i - \beta_t - W_{it}\tau\right)^2 \hat{\omega}_i^{\text{sdid}}\, \hat{\lambda}_t^{\text{sdid}} \right\} \tag{3}$$

where $\hat{\omega}_i^{\text{sdid}}$ and $\hat{\lambda}_t^{\text{sdid}}$, are estimated unit and time weights, respectively. The estimator can be interpreted as a DID of weighted averages of observations, where more weight is placed in units and time periods more similar (on average) to the treated units and periods.

We omit the optimization process used to obtain $\hat{\omega}_i^{\text{sdid}}$ and $\hat{\lambda}_t^{\text{sdid}}$, which is presented in detail in Arkhangelsky et al. (2021). To introduce the general idea behind the weighting scheme, it is worth noting that, similarly to the standard SC method, $\hat{\omega}_i^{\text{sdid}}$ roughly matches the pre-treatment deforestation trajectory of non-treated units with treated ones such that:

$$\sum_{i=1}^{N_{CO}} \hat{\omega}_i^{\text{sdid}}\, Y_{it} \approx N_{tr}^{-1} \sum_{i=N_{CO}+1}^{N} Y_{it} \text{ for all } t = 1, ..., T_{pre} \tag{4}$$

where we have N_{CO} units never exposed to the treatment, and $N - N_{CO}$ which are exposed. Forest cover data from MapBiomas allows us to have $T = 35$ time periods between 1986 and 2020. Since the zero-deforestation policy became valid in 2005 (the policy was approved in December 2004), we have $T_{pre} = 19$ pre-treatment periods.

The main difference between SDID and the traditional synthetic control method is that SDID allows for an intercept, implying that the weights no longer lead to a perfect match with the level of the treated unit. Instead, the weights make the weighted average outcome for control units approximately parallel to the average outcome of treated units. SDID's flexibility, relative to SC, is possible because the unit fixed effects will absorb the time-invariant differences between units.

The time weights $\hat{\lambda}_t^{\text{sdid}}$ are introduced to balance pre-treatment periods with post-treatment periods, reducing the role of periods that are very different from post-treatment and reducing bias. Additionally, the time-fixed effects help explain the variation in the outcome of interest, improving precision.

Finally, it is worth highlighting why we follow the SDID approach relative to the traditional SC method. As discussed by Arkhangelsky et al. (2021), adding unit fixed effects usually contributes to explaining much of the variation in the outcome, improving precision. Also, the unit fixed effect only requires the non-treated pre-trends to be parallel rather than exactly matching the outcome level, making the model more flexible. Overall, Arkhangelsky et al. (2021) demonstrates that SDID compares to, or dominates, the SC approach.

3.1 Approach validity

The credibility of the synthetic difference-in-differences estimation hinges on creating a credible synthetic control. This section briefly discusses the contextual requirements for this and how our empirical strategy intends to meet them.

Selection of comparison group: We select the sub-national regions of South America as control units since the region shares common aspects driving deforestation, i.e., demand for pasture land and commercial cropland cultivation (Sy et al., 2015). One relevant concern is that units in the control group have adopted similar conservation policies to Paraguay's zero-deforestation law, which will impact the deforestation outcome similarly to the treated unit (Abadie, 2021). Due to this, we removed regions within the Brazilian Amazon from the donor pool sample in our main specification. Rigorous public environmental policies and supply-chain mandates were introduced in the region starting in the mid-2000s and are associated with a substantial decrease in deforestation (Assunção et al. (2023), Assunção and Rocha (2019), Heilmayr et al. (2020)). As a robustness exercise, we show how the results are affected by this exclusion.

Sufficient pre-intervention information and adequate post-intervention window: Trust in aligning pre-exposure deforestation trends relies on an adequate pre-intervention window (Abadie, 2021). While an extensive pre-intervention period opens the possibility of structural breaks, a small number of pre-intervention periods can lead to a perfect fit of the predictor values, failing to reproduce the trend in the absence of treatment. To deal with this trade-off, as a robustness check, we vary the pre-intervention period, considering other time frames of analysis. Results also can vary according to the post-intervention window, so as a robustness exercise we show how our results vary according to different time frames.

No interference assumption: The SDID approach implicitly assumes the stable unit treatment value assumption. Considering this, we removed regions in western Paraguay from our donor pool due to likely policy spillovers. Nevertheless, we cannot rule out international spillovers arising from the law. That is, deforestation potentially pushed to other regions in our donor pool due to the policy. As a robustness check, we show how our results vary when dropping neighboring countries. This implicitly assumes that countries closest to Paraguay would most likely suffer from deforestation leakages.

4 Data

We combined multiple MapBiomas products to calculate the yearly deforestation rate at each geographical unit in our sample. MapBiomas (2023) presents country and biome-level land-cover products, covering most of South America's territory at a 30-meter resolution. To the best of our knowledge, it is the only product available that simultaneously allows us to map forest cover since the mid-80s at a high resolution and has adequate regional coverage for our empirical approach.

In our forest cover classification, used to generate the yearly deforestation rates between 1986 and 2020, we calculate the deforestation rate of unit i in year t by dividing the number of forest cover pixels lost at the end of period t by the number of pixels covered by forest at the beginning of period t. Figure A.7 shows the evolution of deforestation rates within Paraguay's departments. We provide more details on our MapBiomas data processing in Section A.1.1.

5 Results

Table 3 presents our main SDID estimate and compares it to classic SC and DID estimates. In our main specification - considering the 1986-2020 period and excluding regions within the Brazilian Amazon - we find that the average effect of exposure to ZDL within Paraguay's eastern region is small (-0.083 percentage point) and statistically insignificant. Table A.2 displays the weights of the main contributors from the donor pool sample. The weights attributed to the main donors are small, which ensures that a few control units do not drive the comparative trajectory. Table A.3 displays the time weights used in the main specification.

The classic DID estimate, which gives equal weights to all observations in the control group, is also small and statistically insignificant. The synthetic control method, which constructs a control matching the deforestation trajectory and trend of Eastern Paraguay and does not assume different time weights, points to a slighter higher reduction post-treatment (-0.546 percentage point of deforestation) but is also statistically insignificant at a 5% significance level.

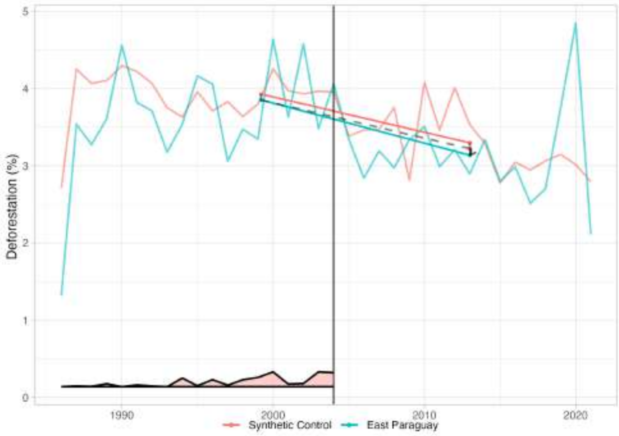
Table 3: Estimates for the average effect of Paraguay's zero-deforestation law on deforestation rates

	Outcome variable: Deforestation Rate		
	SDID	DID	SC
Estimate	-0.083	0.303	-0.546
Standard error	(0.376)	(0.291)	(0.315)
FE: region and year	Yes	Yes	No
Regions	929	929	929
Observations	33,444	33,444	33,444

Note: We use the clustered bootstrap standard error estimation as suggested in Arkhangelsky et al. (2021).

Figure 2 displays the deforestation trajectory in Eastern Paraguay and the synthetic counterfactual, created with SDID time and unit weights, and plots the treatment estimate. Note that SDID re-weighted the unexposed units to make their deforestation trend parallel to Eastern Paraguay pre-intervention, but not identical. Figure A.8 compares the trajectory of East Paraguay's deforestation and the counterfactual considered in the SDID, DID and SC estimations.

Figure 2: SDID estimates for the effect on deforestation rates



Note: Figure shows deforestation trends in Eastern Paraguay *versus* the constructed counterfactual. The small black arrow displays the estimated effect.

Our findings are robust to different specifications. As an alternative to the regional-level deforestation rate, we normalize the deforestation outcome variable due to the large variation in forest area within each region. We follow the benchmark normalization, which uses the inverse hyperbolic sine transformation [5]. We also show how our results vary using an alternative normalization using the log of deforestation [6] as in Assunção et al. (2023). We also demonstrate how the estimates vary considering an alternative forest cover classification. Section A.1.1 provides details on the forest-cover variables constructed.

Table 4 presents the results considering these alternative outcomes. Results considering the IHS and log transformations using the SDID point to similar magnitude of effects and indicate a lack of statistically significant difference in eastern Paraguay's deforestation post-treatment.

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[5] The IHS transformation is implemented as $IHS(D)_{it} = ln(Dit + (Dit^2 + 1)^{1/2})$, where Dit is the deforestation increment in hectares at region i in time t.

[6] The transformation is given by $ln(D_{it} + 0.01)$, where Dit is the deforestation increment in hectares at region i in time t. Note that all non-zero deforestation records are greater than 0.01 ha, and the minimum of our sample is 0.1 ha deforested in a given year.

Table 4: Estimates for the average effect of Paraguay's zero-deforestation law

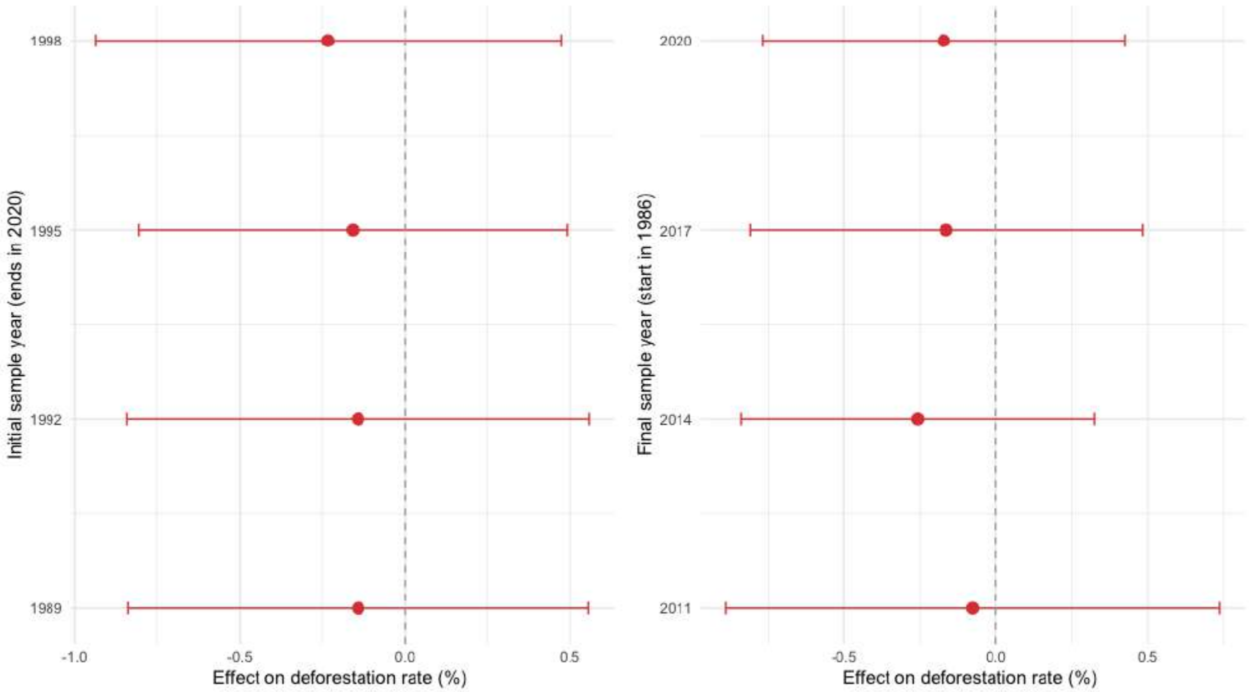
	IHP(deforestation)			log(deforestation)			Deforestation - Alternative specification		
	SDID	DID	SC	SDID	DID	SC	SDID	DID	SC
Estimate	-0.104	-0.262	0.013	-0.119	-0.379	0.04	0.478	0.926	0.898
Standard error	(0.108)	(0.113)	(0.119)	(0.111)	(0.116)	(0.125)	(0.424)	(0.376)	(0.473)
FE: region and year	Yes	Yes	No	Yes	Yes	No	Yes	Yes	No
Regions	929	929	929	929	929	929	929	929	929
Observations	33,444	33,444	33,444	33,444	33,444	33444	33,444	33,444	33444

Note: We use the clustered bootstrap standard error estimation as suggested in Arkhangelsky et al. (2021).

5.1 Robustness Checks

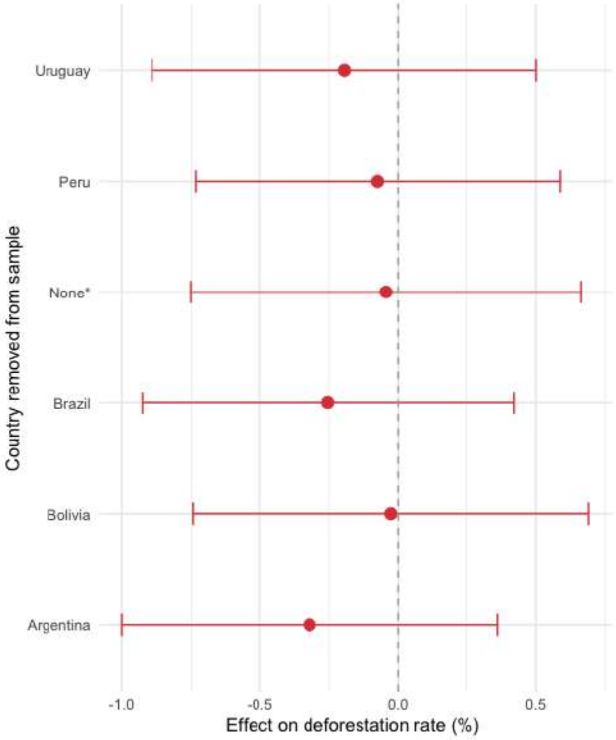
Variations in pre and post-intervention information: Figure 3 displays how our estimates for the policy effect change by altering the pre-intervention time frame considered to construct the counterfactual. The results remain stable regardless of the time frame analysis. The figure also displays how the post-intervention window considered affects the estimated treatment. Again, we find no statistically significant policy treatment.

Figure 3: Variation in pre and post-intervention window



Variations in donor pool: Due to potential policy spillovers to neighboring countries, we check how the estimates vary according to excluding such countries from the donor pool. We also show our estimate when considering the entire sample since, in our main specification, we exclude the areas within the Brazilian Amazon. The lack of statistically significant results persists. It is worth highlighting that this does not rule out policy spillovers to other areas within our sample. Villoria et al. (2022) shows that cross-border leakage from Brazil's Soy Moratorium (a zero-deforestation supply chain mandate) is small relative to the impacts in geographically distant regions that share common destination markets. Still, in this scenario, where the policy effects are not significant due to multiple factors to be discussed in the next section, it is likely that there were no substantial policy spillovers since the policy had very little *de facto* impact within Paraguay.

Figure 4: Variation in donor pool sample



Treatment backdating and anticipation: To detect any pre-treatment differences in deforestation rates between Eastern Paraguay and the synthetic control, we estimate a placebo treatment in the pre-treatment period. Figure A.9 displays this exercise. We consider the placebo treatment period proportionally the same as in the real treatment scenario. The placebo backdating points to a statistically non-significant difference ($\hat{\tau} = 0.747$, s.e. 0.450), which gives us additional confidence in a lack of pre-treatment differences in the deforestation trajectory.

We also estimate the ZDL impacts considering treatment anticipation. Da Ponte et al. (2017a) presents anecdotal evidence of anticipation by landowners of the ZDL restriction before its approval, which could cause 'panic clearing' (Simmons et al., 2018). According to the forest law in place at the pre-intervention period, landowners had to comply with their land-use plans which included their intended deforestation. Therefore, the potential future restrictions could drive illegal deforestation (not predicted in the land-use plans) or simply accelerate landowners' plans of using forest areas. Considering this, we show how the results change in Table 5, assuming that the treatment could have been potentially anticipated in 2003 and 2004. Even assuming treatment anticipation, we find no statistically significant impact of the ZDL.

Table 5: Estimates considering treatment anticipation

	SDID - 1st year of treatment: 2004	SDID - 1st year of treatment: 2003
Estimate	-0.049	-0.139
Standard error	(0.354)	(0.321)
FE: region and year	Yes	Yes
Regions	929	929
Observations	33,444	33,444

Note: We use the clustered bootstrap standard error estimation as suggested in Arkhangelsky et al. (2021).

6 Discussion

Provided the empirical evidence that the zero-deforestation law did not have a statistically significant impact on East Paraguay deforestation, in this section, we discuss the potential drivers of the persistent deforestation post-2004. We first demonstrate how policy enforcement was problematic despite the shift in environmental legislation of the ZDL. Second, we explore our remotely sensed data to qualify the contribution of (i) agricultural settlements and (ii) large-scale agriculture to the ongoing deforestation.

6.1 Issues with policy enforcement

The implementation of the ZDL was not accompanied by a substantial change in Paraguay's environmental monitoring and enforcement. We discuss the deficiencies in policy enforcement mechanisms that may have contributed to the lack of substantial changes in deforestation trends following 2004.

Lack of a consistent deforestation mapping and detection system: Although the ZDL established that an inventory of forest cover would be made immediately following its approval, monitoring of land use change by INFONA began only in 2011. Before 2011, there was no systematic detection of forest cover by the institution, and any investigation of potential law violation was done case-by-case (Instituto Forestal Nacional (INFONA), 2022).

According to conversations with INFONA staff, between the implementation period and 2018, policy monitoring predominantly depended on anonymous reports of forest-clearing activities. Despite the existence of 17 regional offices of the institution in the Eastern area, there was a lack of directives for conducting in-loco monitoring until 2020 [7]. Consequently, there was an absence of active regional-level participation in environmental monitoring efforts. In 2018, Law 6256/18 (*Sistema Nacional de Monitoreo Forestal*) implemented a national monitoring system under INFONA and MADES (Ministry of the Environment and Sustainable Development)[8]. In 2020, INFONA implemented an early deforestation detection system that generates weekly reports. The deforestation reports are then forwarded to its regional offices, which use them to guide in-person monitoring.

The poor capacity to detect deforestation is potentially one of the causes driving the lackluster policy results. This is not surprising in light of work from Assunção et al. (2023) showing that Brazil's near-real-time deforestation alerts system was fundamental to target environmental enforcement. Even though we don't have data on staff from INFONA to qualify if the institution had a capacity issue, the challenge of conducting in-loco environmental monitoring in Paraguay was frequently raised in conversations. Therefore, the recently established near-real-time monitoring system can potentially provide more information for the institution to better target its efforts.

Notwithstanding the flawed monitoring system, the ongoing deforestation post-2004 cannot be fully attributed to the lack of detection capacity. Following the law's approval, WWF started private deforestation monitoring within the Atlantic forest biome in eastern Paraguay (month-to-month and later every quarter). The institution detected deforestation at a property level, and documentation was forwarded to legal institutions (WWF, 2008). According to the organization, despite the evidence of deforestation of large areas, very few cases were prosecuted or resulted in insignificant financial punishment (EFEverde, 2014).

Weak legal institutions and punishment: The legal sanctions for breaking the zero-deforestation law are dictated by Law 716/96 (*Que sanciona los delitos ambientales*). The legislation established a penalty of 3 to 8 years in jail and a vague system of fines, with payments

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[7] Resolución INFONA n 094/2020 defined clear guidelines on the roles and duties of regional offices. The resolution stated clearly that offices were obligated to report any information about potential law violations to the legal team (Articles 6, 7 and 8).

[8] The system becomes INFONA's responsibility with Law 6676/20

ranging from 500 to 2000 of the daily minimum stipend ('jornales mínimos legales'). The law is vague about how the financial punishment for a deforestation violation will vary according to the deforested area and in conversations with local actors in Paraguay, the consensus is that the fine is perceived as low. The minimum daily stipend was equivalent to roughly 14 dollars in April 2024, meaning that the fine stipulates a punishment between 7,000 - 28,000 US dollars. Therefore, especially among big land landowners practicing large-scale agriculture, there is a huge gap between the revenue generated from illegal deforestation - e.g., agricultural practices, wood extraction, or urban expansion - and the symbolic reparation applied.

In addition to the meager financial punishment, prosecution and legal punishment of infractions is rare, partially due to the weak legal apparatus (Aguayo et al., 2016). Paraguay's Prosecution Office is responsible, at the judiciary level, for prosecuting individuals breaking environmental legislation. Within the Prosecution Office, Paraguay has a unit dedicated to environmental issues (known as *Unidad Especializada de Delitos Ambientales*). The unit was created in 2007, and by 2014, there were 19 specialized legal unit offices in the country (versus 424 units dedicated to all subjects). Within the specialized units, in 2016, there were only 27 technical specialists for the entire country to conduct technical assessments of environmental law misconduct (Aguayo et al., 2016). According to Aguayo et al. (2016), between 2012 and 2013, the offices specialized in environmental causes received 2,997 complaints of violations of Ley N 716/96 (which comprehends multiple environmental-law infractions, including the ZDL), making the available infrastructure incompatible for proper assessment and prosecution of the environmental-law violations. Consequently, prosecutors of cases of environmental policy violation often fail to comply with procedural due process, resulting in effectively no legal sanction.

Finally, even more striking is the lack of recognition of the ZDL by the judiciary in cases studied by Aguayo et al. (2016). In some legal cases, deforestation was considered insignificant due to the number of hectares affected, even though the ZDL makes no exception as to the size of the area deforested. In other judicial cases studied, judges failed to even recognize that the law had been violated and to dictate punishment accordingly.

6.2 Deforestation drivers

In this part, we explore our unique remotely sensed dataset, constructed to map smallholder agriculture at a 10-meter resolution, to qualify the ongoing deforestation drivers post-2004. Using a map of land cover for 2022 (the only year we have available thus far), we present the land-use changes that took place in the post-ZDL period relative to INFONA's 2004 forest cover baseline - the mapping is displayed in Figure A.10.

Contribution of large-scale and small-scale agriculture: Table 6 presents the land-use change that took place in Eastern Paraguay's forest cover post-2004, which, according to the ZDL, could not be deforested. Overall, between 2004-2022, 38% of the vegetation cover was converted to other land uses. Conversion to soybeans and grassland (which includes pasture areas) were the main sources of change, representing 57% of the total converted area. Smallholder mix contributed 10% to the total forest loss area.

We also display the change within the Atlantic biome since the policy was originally designed to protect it. According to our maps, 42% of the vegetation was lost despite the policy—equivalent to 1,021 thousand hectares. The expansion of soy and pastures was responsible for 57% of the expansion, which is not surprising given that the area within the biome had a developed large-scale agricultural sector pre-ZDL.

Table 6: Change in forest cover 2004- 2022

Category	East (ha)	Share (%)	Atlantic Biome (ha)	Share (%)	ITs and PAs (ha)	Share (%)
Crop (non-soy)	40,637	1	35,862	1	3,827	1
Grassland	459,012	13	298,491	12	75,949	14
Natural shrubs / Regrowth	233,615	7	168,605	7	41,135	7
No vegetation	87,884	3	74,248	3	18,933	3
Smallholder mix	133,230	4	111,847	5	17,928	3
Soybeans	299,765	9	291,622	12	17,888	3
Tree Plantation	49,233	1	40,349	2	8,683	2
Vegetation	2,117,847	62	1,426,314	58	371,141	67
Total	3,421,223	100	2,447,339	100	555,483	100

Note: Change relative to INFONA's 2004 forest cover baseline using our remotely sensed data.

Contribution of agrarian reform colonies: According to public data from INDERT and Rojas Villagra and Areco, Abel (2017), between 2004 and 2020, Paraguay titled 17,127 land plots in Eastern Paraguay, covering an area of roughly 172 thousand hectares. Until the present moment, we were not able to access the fraction of such colonies that were established in forest land post-2004. Future work will link information on the colonies created by INDERT and the georeferenced information on the colony's boundaries to further discuss the conflicts between government jurisdictions. That is, we seek to directly answer if INDERTs work on agrarian reform post-2004 was directly in conflict with the ZDL deforestation ban.

Table 7 shows the land use change within georeferenced INDERT colonies (2023 data), which includes colonies created pre and post-ZDL[9]. Figure A.11 shows the distribution of the agrarian reform colonies in the eastern area. The table shows that there were 480 thousand hectares of forest cover in 2004 in areas that are now INDERT colonies. Since our dataset on INDERT agrarian reform colonies does not contain the entire sample of colonies within Eastern Paraguay, this is a lower bound of the forest area. Considering that there were 2.865 million hectares of forest cover outside indigenous lands and protected areas in 2004 (Table 6), the area within colonies represents almost 17% of the 2004 forest cover in private lands.

Even though we don't have information on the location of the colonies created post-2004, Table 7 indicates that at some moment, the institute allocated land plots to agrarian reform colonies in areas with forest cover. Although this does not directly reveal that the two agencies' objectives were directly in conflict post-ZDL, it demonstrates how the zero-deforestation policy design was not careful to consider the potential conflicts with agrarian reform colonies and the associated equity implications. In other words, the policy design overlooked the implications on smallholders, given that the areas distributed by INDERT were often within forest areas.

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[9] So far, we only have a list of the colonies created, but the list does not allow a direct match with the colonies shapefiles from INDERT.

Table 7: Change in forest cover 2004- 2022 within INDERT Colonies

Category	Area (ha)	Share (%) of 2004 Area
Crop (non-soy)	12,583.5	2.6
Grassland	96,257.4	20.0
Natural shrubs / Regrowth	51,265.3	10.7
No vegetation	16,154.4	3.4
Smallholder mix	58,924.6	12.3
Soybeans	48,513.7	10.1
Tree Plantation	4,759.7	1.0
Vegetation	191,708.0	39.9
Total	480,166.5	100.0

Note: Change relative to INFONA's 2004 forest cover baseline.

7 Conclusion

We combined data from MapBiomas (2023) and a synthetic difference-in-differences approach to investigate the impacts of Paraguay's zero-deforestation policy on deforestation. Our results show that the policy had no statistically significant impact on the deforestation trajectory post-2004. We argue that this is likely due to a combination of (i) poor monitoring capacity, (ii) issues with legal enforcement and prosecution, and (iii) conflict with agrarian reform policy. Our work informs policymakers on the potential issues with strict deforestation bans, especially the potential difficulties in their *de facto* implementation and the unintended conflicts with policies promoting agricultural development.

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A.1 Appendix

A.1.1 Data

To map annual deforestation for the years 1986-2020, we combined multiple MapBiomas products covering different countries and biomes in South America. The products share a common land-use classification, which divides the landscape into five broad classes: forest, non-forest natural formations, agricultural areas (including ranching), non-vegetated areas, and water bodies. Some products present a more detailed classification into sub-classes, e.g., Brazil Collection 8 splits Agriculture into Temporary Crops, Soybean, Sugar cane, Rice, Cotton, and Other Temporary Crops. However, other products, e.g., Paraguay Collection 1, exhibit fewer land classes, with only one class for agriculture, for example. Still, the common forest classification and methodology allowed us to combine the products and uniformly classify the different maps, reducing potential inconsistencies. Table A.1 provides more details on each MapBiomas product used and the geographic area covered.

Table A.1: MapBiomas Products

Geographical Area	MapBiomas Product
Argentina	Chaco Collection 4 and Atlantic Collection 3
Bolivia	Bolivia Collection 1
Brazil	Brazil Collection 8
Colombia	Colombia Collection 1
Ecuador	Ecuador Collection 1
French Guiana	Amazon Collection 5
Guyana	Amazon Collection 5
Paraguay	Paraguay Collection 1
Peru	Peru Collection 1
Suriname	Amazon Collection 5
Uruguay	Uruguay Collection 1
Venezuela	Venezuela Collection 1

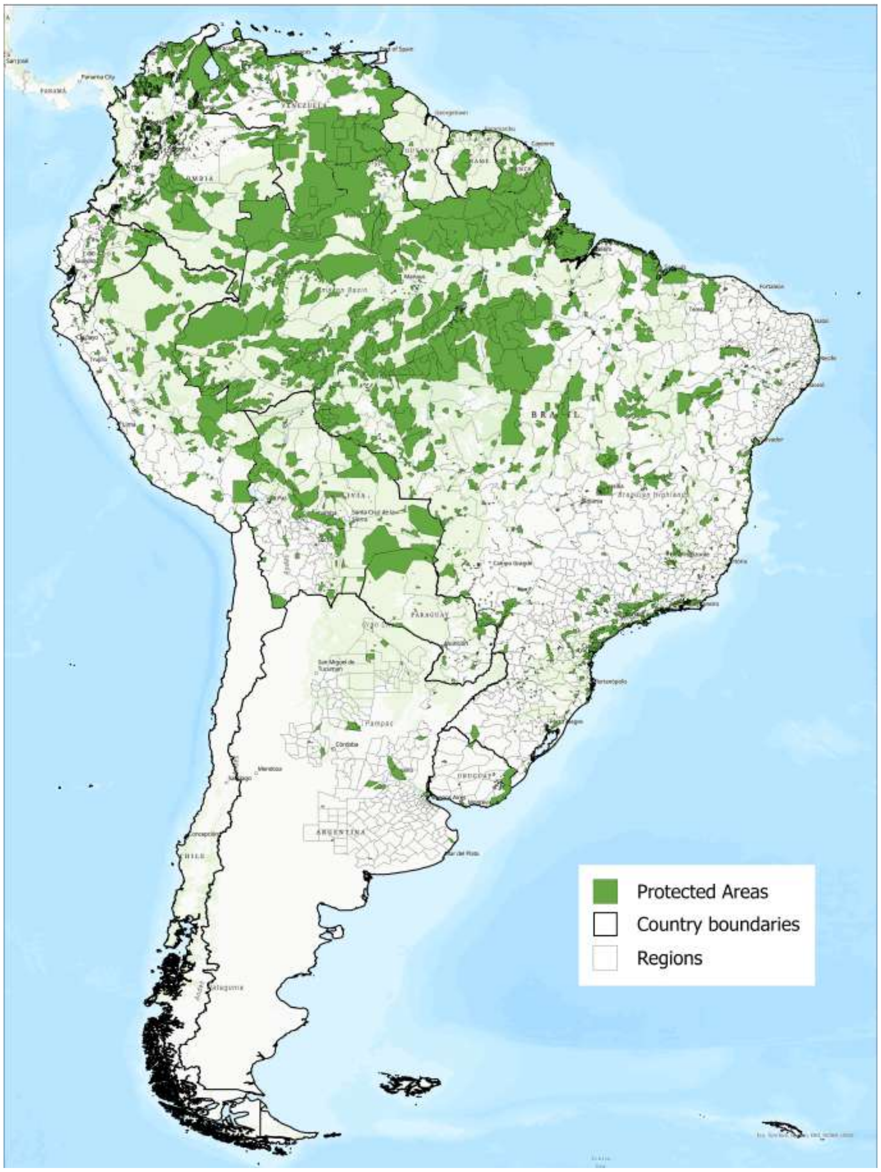
Note: Argentina is not entirely covered by the two products. Hence, we only consider the territory overlapping with MapBioma's mapping.

We present two different aggregations of the Mapbiomas forest cover classification classes to construct our data. For our main estimates, we consider the classes 'Forest Formation' and 'Savanna Formation' as forest cover. In our alternative specification, we include the 'Mangrove' and "Floodable Forest' classes. In both classifications, we calculate the deforestation rate for each of the sub-national geographic units. Figure A.1 shows the distribution of the political boundaries of the areas considered. For each area, we calculate the yearly deforestation rate by dividing the number of observed grids that lost forest cover in the period t by the number of pixels that started the period t.

Figure A.1: South American second-level administrative divisions

As an additional robustness exercise, in future versions of this paper, we will present our estimates considering the deforestation rates outside protected areas within each region. We will use data from UNEP-WCMC and IUCN (2024) on global protected areas to exclude the fractions of land within protected areas in the MapBiomas data. Figure A.2 shows the distribution of protected areas in our countries of interest in South America.

Figure A.2: Protected areas within study area



A.1.2 Tables

Table A.2: Top 20 donor pool contributors

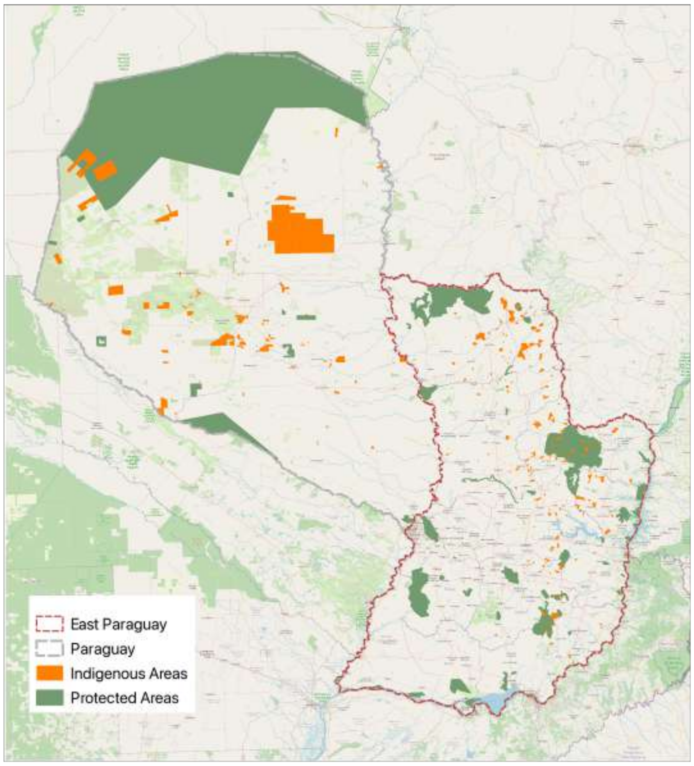
Region-Country	Synthetic control weight ($\hat{\omega}_i$)
Mayor Luis J. Fontana - Argentina	0.0047
Mburucuyá - Argentina	0.0046
Aguirre - Argentina	0.0045
Belgrano - Argentina	0.0038
Mitre - Argentina	0.0034
Luján - Argentina	0.0033
Mercedes - Argentina	0.0033
Unión - Argentina	0.0032
Gualeguay - Argentina	0.0031
Guatraché - Argentina	0.0029
Eduardo Avaroa - Bolivia	0.0028
Obispo Santistevan - Bolivia	0.0027
Sapé - Brazil	0.0026
Carira - Brazil	0.0026
Sucre - Colombia	0.0025
Durazno - Uruguay	0.0025
Maldonado - Uruguay	0.0025
Rivera - Uruguay	0.0023
Rocha - Uruguay	0.0023
Tacuarembó - Uruguay	0.0023

Table A.3: Time weights used in main SDID estimation

Year	Time weight ($\hat{\lambda}_t$)
2000	0.16
2003	0.16
2004	0.16
1999	0.10
1994	0.10
1996	0.08
1998	0.08
2002	0.03
1989	0.03
2001	0.03
1991	0.02
1997	0.02
1995	0.01
1987	0.01
1992	0.01
1988	0.00

A.1.3 Figures

Figure A.3: Paraguay's Indigenous Territories and Protected Areas



A.1.4 Figures

Figure A.4: Paraguay's Departments

Figure A.5: INDERT's land distribution: 2005-2020

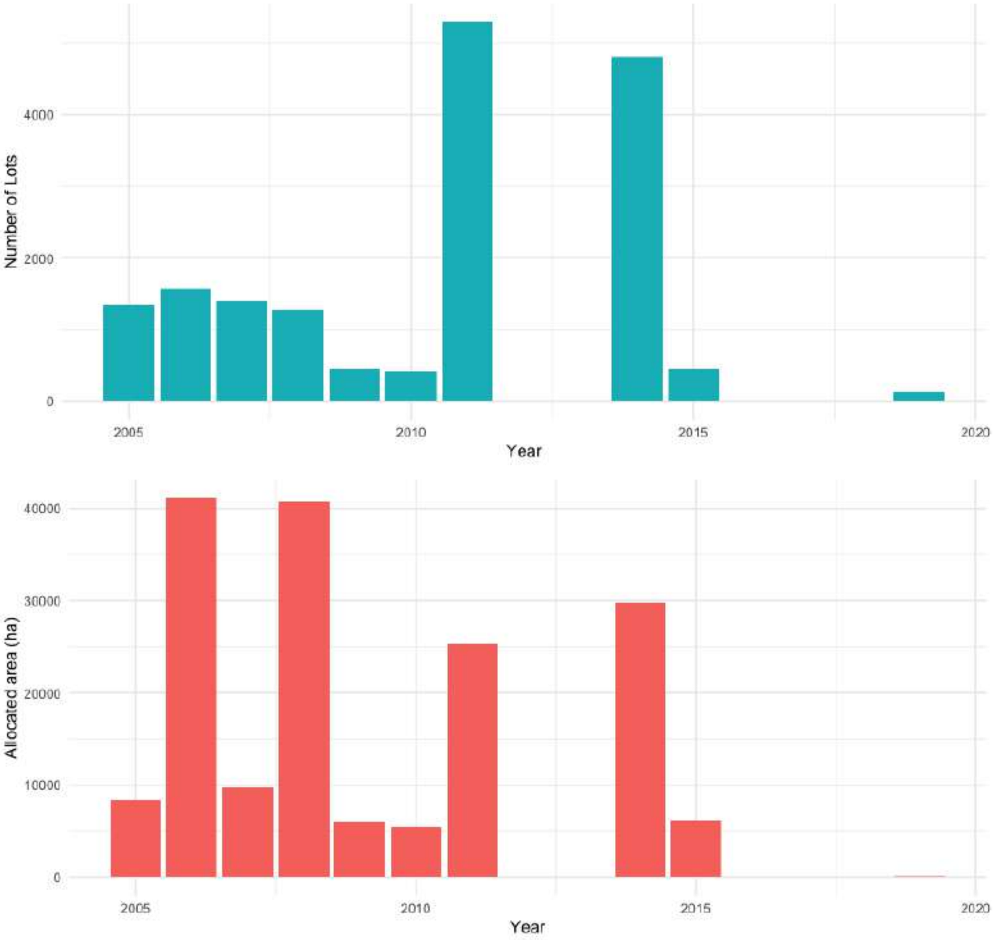
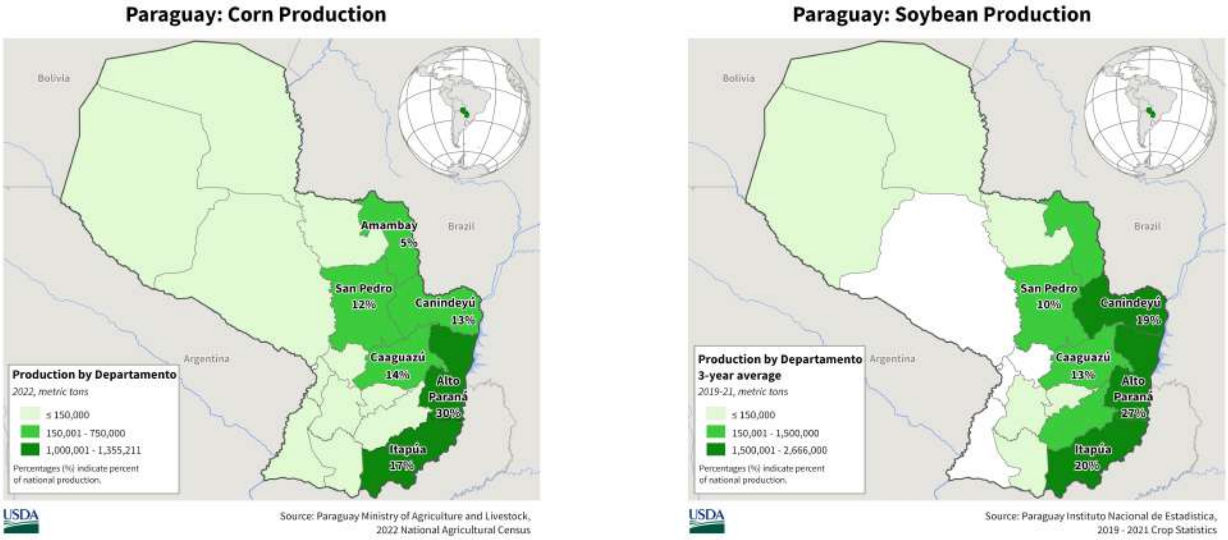


Figure A.6: Paraguay's agricultural production



Paraguay: Corn Production

Source: Paraguay Ministry of Agriculture and Livestock, 2022 National Agricultural Census

Paraguay: Soybean Production

Source: Paraguay Instituto Nacional de Estadistica, 2019 - 2021 Crop Statistics

Source: USDA (2024).

Figure A.7: Eastern Paraguay - Deforestation Rates: 1986 - 2015

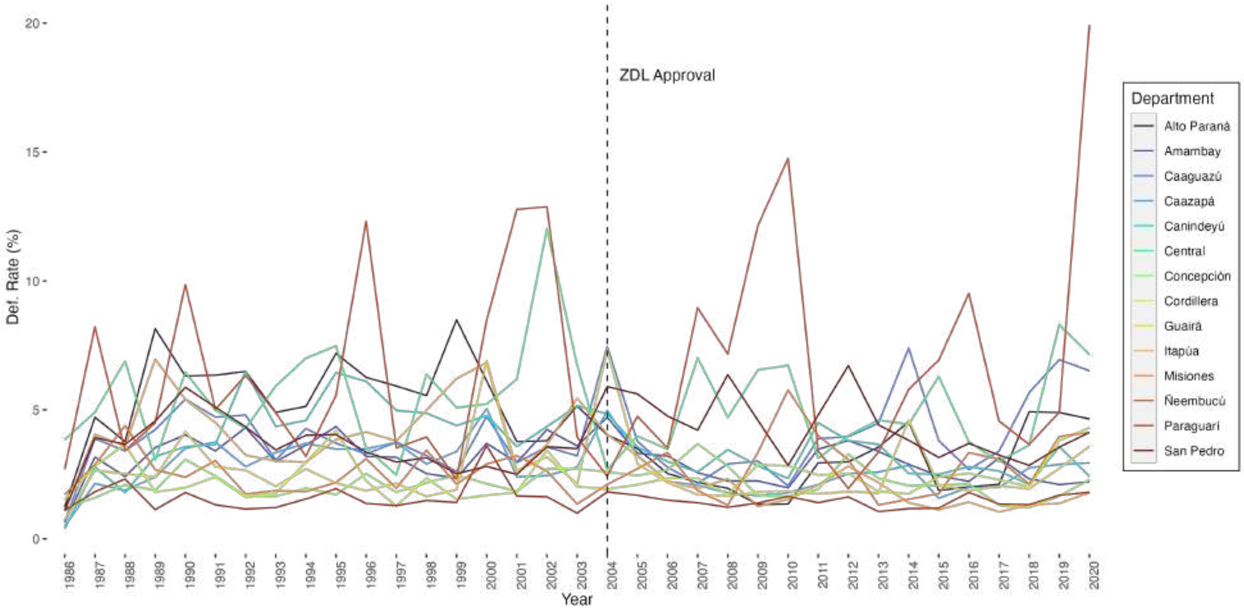


Figure A.8: Comparison between SDID, DID and SC estimates for the effect of Paraguay's Zero Deforestation Policy

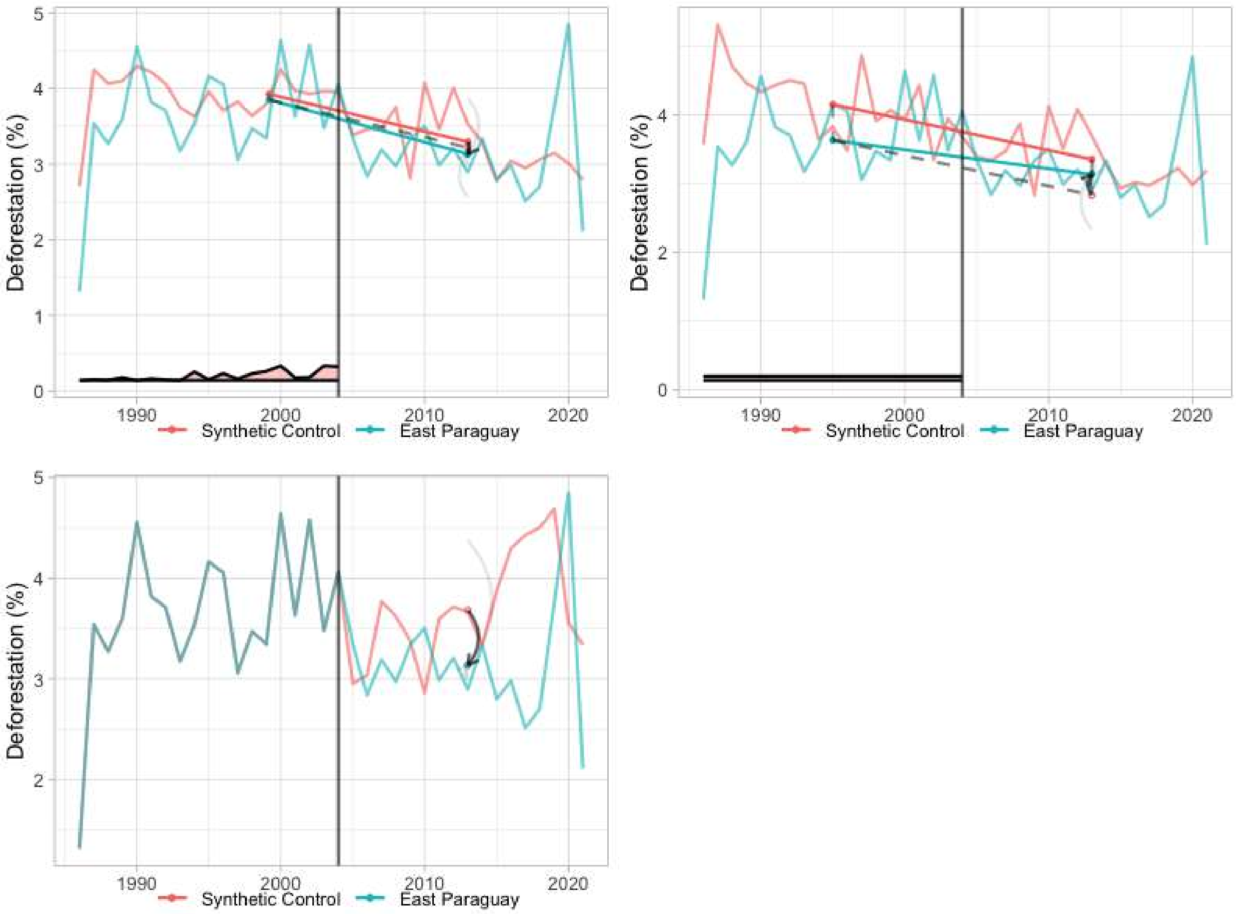


Figure A.9: Placebo test - Treatment backdating

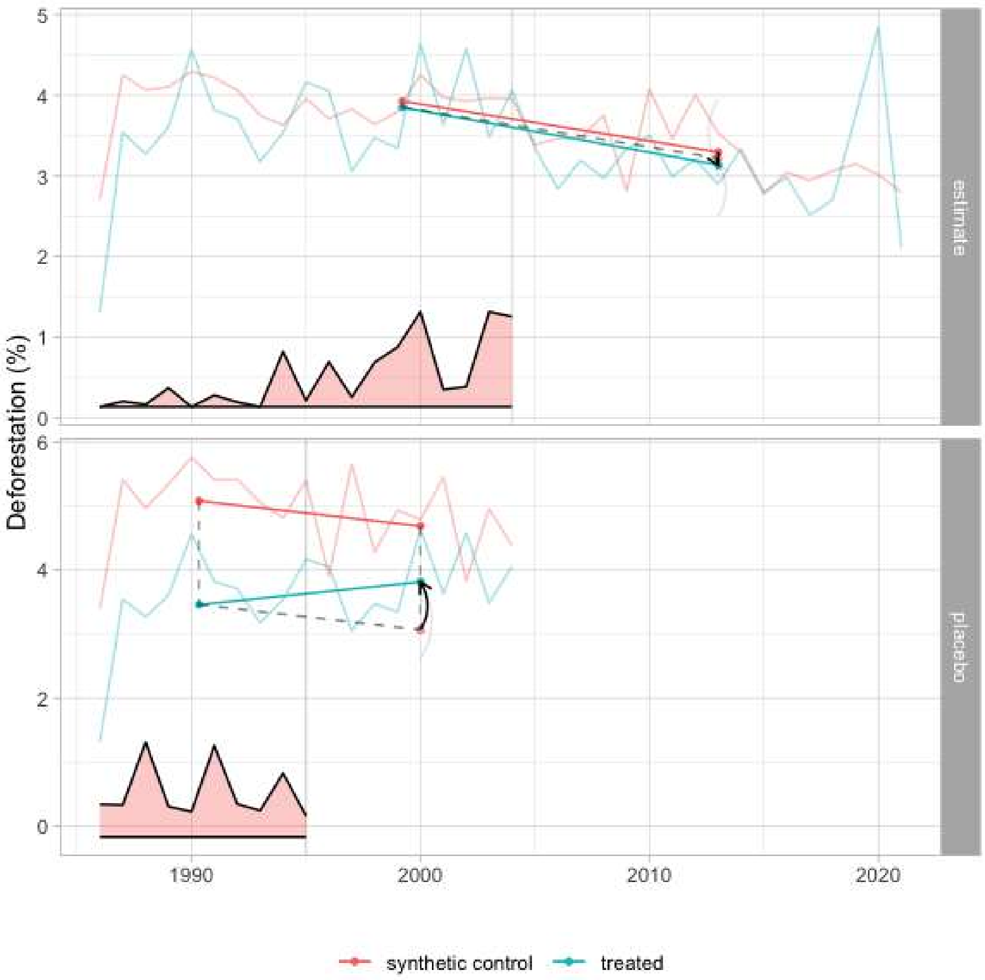


Figure A.10: Pre-treatment forest cover - INFONA 2004 data

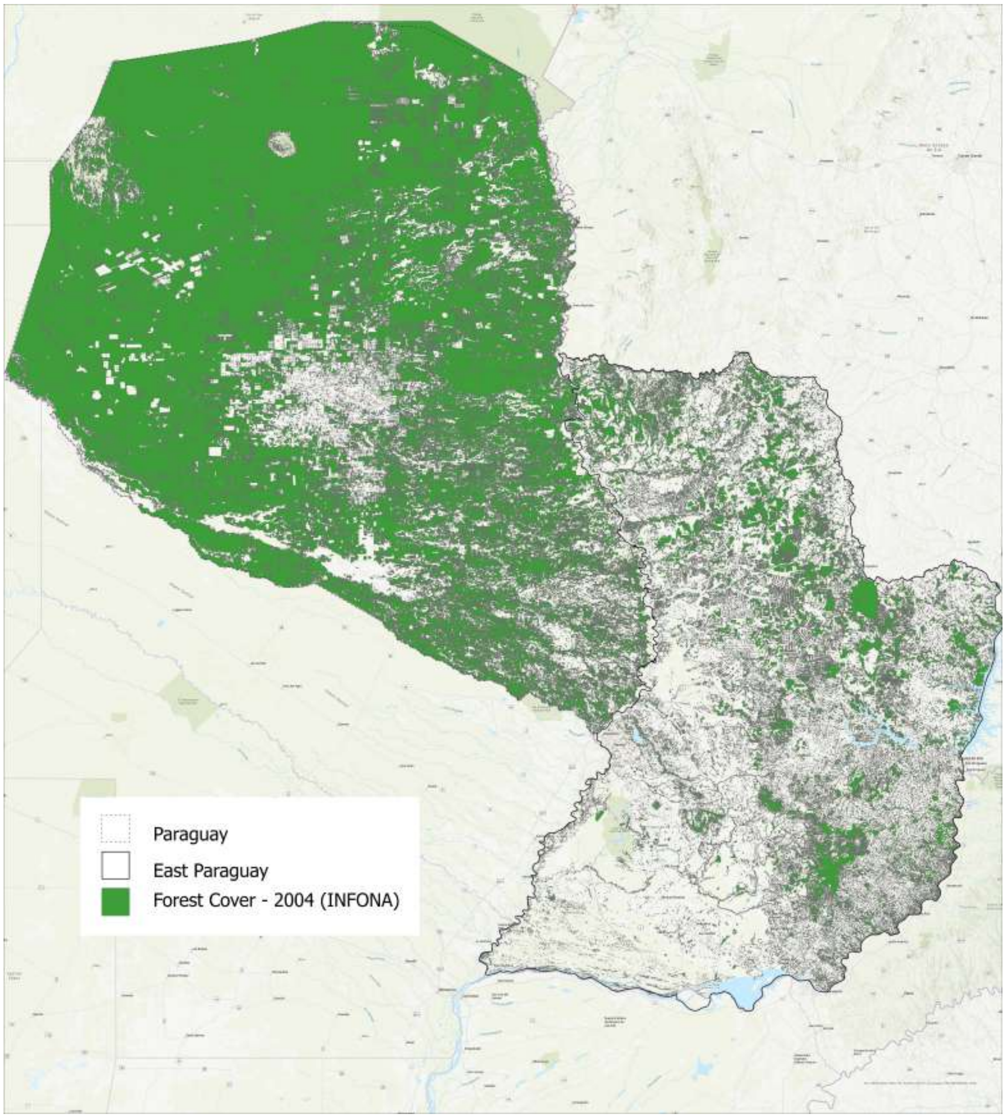


Figure A.11: INDERT Colonies in eastern Paraguay