Payments for Ecosystem Services under Regulation: Evidence from Brazil's *Reflorestar* Program

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Abstract

Forest restoration is a critical strategy to improve ecosystem services and mitigate climate change. To induce restoration, governments often use both command and control regulation and incentive-based payments for ecosystem services (PES), but the interactions of these instruments are not well understood. We study the impacts and cost-effectiveness of voluntary restoration PES in the context of overlapping direct regulation. Specifically, we analyze Brazil's *Reflorestar* program, a large-scale PES for forest restoration that operates under laws requiring private landowners to maintain native vegetation on a fixed share of their land. We study enrollment patterns, estimate program additionality using staggered difference-in-differences, and estimate willingness to accept using plausibly exogenous spatial variation in offered payments. We find positive but modest reforestation impacts, with additionality of 4-9 % of the initial restoration commitment. The estimated welfare costs of the program are comparable to other avoided deforestation initiatives and to the estimated benefits of forest restoration. We demonstrate that cost-effectiveness could be improved by targeting rules such as allocating more program funds to landowners who are already compliant with the Forest Code or are in municipalities with greater enforcement capacity.

JEL Classification Codes: Q15, Q28, Q58, O13

Keywords: Forest Restoration, Reforestation, Payments for Ecosystem Services, Land Conservation

1 Introduction

Forest restoration is an essential global strategy to mitigate climate change, protect watersheds, enhance micro-climate precipitation and cooling, stabilize soil, and provide wildlife habitat (Griscom et al. 2020, dos Reis Oliveira et al. 2025, Hector et al. 2026, Liang et al. 2025). Large scale forest restoration will require the participation of private landowners, who face substantial labor, input, and opportunity costs (Brancalion et al. 2017, Niemeyer et al. 2015). Payments for ecosystem services (PES) programs can incentivize these private contributions to public benefits by compensating landowners in exchange for maintaining or restoring natural land covers (Wunder et al. 2020). PES can also address important equity concerns raised by mandatory conservation through forest laws or parks, and are thus a particularly important strategy for climate mitigation in developing economies (Pande 2024, Duflo 2025, Alix-Garcia et al. 2015, Zilberman et al. 2008). Yet despite increasing attention to incentive-based restoration, there is limited evidence about their environmental and cost effectiveness (Vincent et al. 2021). These voluntary programs may fail to deliver full additionality due to adverse selection in the pool of participants, poor contract implementation, or low ecological yield of restoration efforts. In addition, most PES programs operate under mandatory command and control (CAC) regulations, but these interactions are not well understood. Evaluation of restoration efforts at scale can improve design and targeting and provide information about the costs of restoration PES relative to other land-based mitigation strategies.

In this paper, we evaluate the additionality, enrollment patterns, and welfare costs of a large, government-sponsored PES for forest restoration and conservation in the Brazilian Atlantic Forest: *Reflorestar*. The program operates under command-and-control regulation that requires private landowners to maintain a fixed percentage of their land in native vegetation (Brazil's Forest Code) as well as prohibitions on deforestation (Atlantic Forest Law). This regulatory environment mirrors many situations worldwide, in which forest protection efforts combine regulations and incentives (Börner et al. 2017, Sims & Alix-Garcia 2017).

We begin by presenting a simple model of participation in a restoration PES that highlights the potential relationships between PES and direct conservation mandates. The model illustrates that landowners compliant with the conservation mandates enroll larger areas in the PES program than non-compliant landowners. The main reason for this difference is that compliant landowners have lower opportunity cost of land, whereas non-compliant landowners use the PES to reduce their expected enforcement costs. We also discuss how threats to the additionality of restoration PES, including adverse selection, moral hazard, and low ecological yield of efforts are likely to be affected by the presence of overlapping command-and-control regulation. The conceptual framework demonstrates how understanding the interactions between PES and command-and-control can potentially improve the targeting of restoration programs.

We then analyze a rich dataset combining *Reflorestar* administrative information for more than 5000 contracts from the 2013 to 2025 cohorts, boundaries of rural properties, and satellite-based land-use data from MapBiomas. We use covariate matching to create balance across the characteristics of the treated and plausible control groups drawn from similar properties. We then exploit spatial and temporal variation in enrollment across the program cohorts to estimate the effect of *Reflorestar* on forest cover using a staggered difference-in-differences approach.

We find that *Reflorestar* significantly increases forest cover within four years after landowners begin their contracts, with an estimated magnitude of 4-9 % additionality. The estimated impacts are positive for all modality types (active, passive, and productive restoration), are from restoration both inside of demarcated protected zones and outside of them, and are persistent. In addition, we find larger effects in municipalities with higher enforcement intensity and among properties that are already compliant with the command and control policy. Although modest, the estimated additionality of this restoration program is similar to the additionality reported in several studies of avoided deforestation initiatives (Ordóñez et al. 2023, Börner et al. 2016). A decomposition analysis suggests that low ecological yields are the primary reason for modest additionality, with adverse selection being a secondary concern.

Finally, we seek to understand how the economic costs of the program compare to other methods of forest protection and whether targeting changes could improve cost-effectiveness. To do so, we exploit a set of plausibly exogenous bonus payments for priority areas to estimate willingness to accept (WTA) restoration contracts. We find a mean WTA of approximately 148 USD per ha among enrolled properties, capturing opportunity and participation costs. Taking into account our estimated additionality, and including the cost of raising public funds for the financial transfers of the PES (assumed to be 20 % of the transfers), we estimate that the average welfare cost of the program is approximately 16 USD per ton of sequestered CO2. The financial cost based on the full transfer payment values and estimated additionality is around 43 USD per ton of sequestered CO2. These values compare favorably both with other estimates of the costs of avoided deforestation and with the potential benefits of climate mitigation and ecosystem services from forest restoration (Ordóñez et al. 2023, Alix-Garcia et al. 2019, Jack 2013, Hellerstein 2017, Assunção et al. 2026). In addition, we demonstrate with a simulation that program cost-effectiveness could be improved by re-targeting the program budget towards already compliant properties or high-enforcement municipalities. Overall, our findings highlight that forest restoration PES can complement CAC efforts, and may be a cost-competitive nature-based climate solution, particularly if carefully targeted.

Our paper contributes to the limited literature on incentive-based forest restoration, and in particular fills an important gap in the assessment of the interactions between command-and-control and incentive-based policy. The additionality and cost-effectiveness of incentive-based forest protection have been and remain important questions in the literature. Prior work, mainly on avoided deforestation programs, indicates modest success of PES in reducing deforestation (Jayachandran et al. 2017, Alix-Garcia et al. 2015, Alix-Garcia & Wolff 2014, Wong et al. 2022, Fiorini et al. 2020, Costedoat et al. 2022, Ordóñez et al. 2023, Börner et al.

2016). This literature also highlights the importance of targeting, including to high threat regions, and of ensuring credible enforcement of landowner contracts (Wunder et al. 2020, Alix-Garcia et al. 2015, Jack & Jayachandran 2019, Jones et al. 2020, Alix-Garcia et al. 2008).

However, few studies have rigorously evaluated at-scale PES restoration programs, particularly in developing regions (Busch et al. 2024, Vincent et al. 2021, Tedesco et al. 2023). Prior studies have assessed payments to convert degraded farmland to vegetative cover in the U.S. (Hellerstein 2017, Liu et al. 2023, Aspelund & Russo 2025) and China (Fu et al. 2019), silvopastoral practices in Colombia (Pagiola & Rios 2013, Pagiola et al. 2016), and restoration support from an NGO alliance in Brazil (Toto et al. 2025). Our paper advances this literature by evaluating an at-scale restoration program in an ecologically and socially important context. *Reflorestar* warrants careful evaluation as a potential model for restoration in agriculturally productive and densely populated landscapes (Crouzeilles et al. 2019, Pagiola et al. 2019). Compared to a concurrently developed evaluation of *Reflorestar* by Bucher & Seixas (2026), our use of contract-level data for a larger set of enrollees allows us to conduct a more comprehensive evaluation, to estimate WTA, and to evaluate policy design under command-and-control. In doing so, we also add to the literature evaluating Brazil's globally-important forest protection policies (Assunção et al. 2023, Assunção & Rocha 2019).

Our paper provides novel insights on the interactions between PES and the forest code, contributing to a gap in the literature about how incentive-based policies operate in the context of overlapping direct regulation. We are aware of only two prior papers that specifically consider how PES additionality may interact with command-and-control regulation (Cisneros et al. 2022, Sims & Alix-Garcia 2017), both of which consider avoided deforestation programs rather than forest restoration. In assessing these interactions, we also contribute to the broader and far more extensive literature on the choice of environmental policy tools (Malik 1990, Livernois & McKenna 1999, Glaeser & Shleifer 2001, Montero 2002), which can depend on factors including cost-heterogeneity, compliance, and political feasibility.

In addition, our research adds to the ongoing debate regarding the economic costs and benefits of forest protection efforts generally and forest restoration specifically (Vincent et al. 2021, Busch et al. 2024, 2019, Busch & Engelmann 2017, Alix-Garcia et al. 2019, Jack 2013, Hellerstein 2017, Araujo et al. 2026). Restoration has often been characterized as more costly per hectare than avoided deforestation, but less subject to adverse selection problems. For example, Brancalion et al. (2019) report restoration costs of up to 2,330 USD per hectare enrolled with active reforestation from seedlings in Brazil, while a study by Jayachandran et al. (2017) estimated that avoided deforestation in Uganda cost just 115 USD per additional ha and could sequester CO2 for a cost of less than 1 USD per ton.

At first glance, restoration PES may seem to eliminate the adverse selection problems common to avoided deforestation PES by crediting only observably new forest. However, as our model emphasizes, the true additionality of restoration PES must still be measured relative to a counterfactual scenario, and as our empirical findings show, yield may be lower than expected. However, our estimates still suggest that restoration PES is cost-competitive with avoided deforestation PES. Our estimated carbon sequestration costs are close to the level of an optimal carbon tax of 10 USD for the Amazon recently proposed by Araujo et al. (2026), and in the middle of cost ranges estimated by modeling responses to agricultural prices by Busch & Engelmann (2017), Busch et al. (2019). Our work complements these previous estimates by using individual PES contract behavior as the basis for costs. However, as responses may be context-specific, additional research on forest restoration potential and costs across multiple global settings is also clearly warranted.

The remainder of this paper is organized as follows. Section 2 presents a stylized model of land use and enrollment in restoration PES under overlapping command and control regulation. Section 3 provides background information on the *Reflorestar* program. Section 4 describes the data, while Section 5 describes the empirical strategy to estimate additionality and results. Section 6 presents the results on enrollment and the estimation of WTA. Section 7 discusses counterfactual exercises around the question of optimal PES design under overlapping regulation, and Section 8 concludes.

2 Conceptual Framework: PES under Command-and-Control

This section discusses how payment for ecosystem services (PES) interacts with a command-and-control conservation regulation through a stylized model of landowners with heterogeneous land productivity. We adapt a simple enforcement model which reflects the incentives to comply with the law given the landowner's opportunity costs and expected enforcement costs (e.g. Phaneuf & Requate (2016)). This model can help to understand the design of restoration PES in contexts where a CAC regulation already provides some incentive for forest cover. We study landowners' incentives to restore forest and threats to additionality.

Land Use and Regulation: Each landowner owns a unit of land, with heterogeneous productivity per plot. The landowner chooses the share $a \in [0, 1]$ to allocate to agricultural production, with the remainder left under forest cover. Agricultural profits depend on land productivity v and are given by

$$\pi(a) = va - \frac{a^2}{2}. \tag{1}$$

Profits from land in forest, which is the alternate land use, are assumed to be constant and normalized to zero. A command-and-control regulation limits agricultural development to $\bar{a}$. If the landowner exceeds this threshold, he faces an expected enforcement cost that is quadratic in the degree of non-compliance:

$$E(a) = \frac{\phi}{2}(a - \bar{a})^2 \cdot \mathbb{I}(a > \bar{a}), \tag{2}$$

where $\phi > 0$ captures enforcement intensity. The quadratic enforcement cost reflects a higher marginal penalty for larger violations, or a higher probability of detection.

The landowner chooses a to maximize:

$$\max_a \; va - \frac{a^2}{2} - \frac{\phi}{2}(a - \bar{a})^2 \cdot \mathbb{I}(a > \bar{a}). \tag{3}$$

Given these incentives, low-productivity landowners optimally choose $a \leq \bar{a}$ and are compliant, while high-productivity landowners optimally choose $a > \bar{a}$ and are (partially) non-compliant. These optimal choices are illustrated in Figure A.1, Panels (a) and (b).

Enrolling in a restoration PES: We then consider what happens if landowners are offered a PES to restore forest. For simplicity, we assume that restoration can occur by abandoning cropland and only costs the opportunity cost of agricultural use. We also assume that this restoration is immediately visible to the regulator, so restored areas contribute to compliance, thus lowering enforcement costs.

The PES pays p per unit of land in "new" forest, relative to the baseline. The payment is a per unit subsidy, leading landowners to re-optimize their land-use choice. To maximize profits, the landowner chooses a new level of agricultural area a to equalize their marginal returns from developed land ($v - a$) and the marginal returns from forest with the PES payments.

For compliant landowners, their optimal choice satisfies: $v - a = p$. For non-compliant landowners, their optimal choice satisfies $v - a = \phi(a - \bar{a}) + p$, with their optimization problem including the marginal cost

$\phi(a - \bar{a})$ of expected punishment from the command and control regime.[1] Reducing a through restoration therefore both earns PES payments and lowers expected enforcement costs for the units restored. The optimal choices after the introduction of the PES are illustrated in Figure A.1, Panels (c) and (d).

This illustrates that both high and low compliance landowners have incentives to enroll and restore under the PES, but the impact varies by type. Compliant landowners have low opportunity costs of restoration and thus may restore a larger area for the same incentive. The PES incentives lead to a smaller restoration share for non-compliant landowners, because they already have the marginal incentive to restore through the enforcement costs. However, non-compliant landowners may be more likely to enroll some land in order to signal their willingness to comply with the law and thus avoid penalties.

Threats to Additionality: Additionality refers to the extent to which the program leads to additional restoration that would not have occurred otherwise. Conceptually, threats to additionality may stem from i) adverse selection of participants who likely would have restored forest anyway, ii) moral hazard in the implementation of the contract, and iii) low yield of restoration efforts. Here we consider these threats and how they may change in the presence of CAC.

i) In the context of PES, adverse selection means that the offered payments are particularly attractive to landowners who would have restored forest even without the PES. PES may thus disproportionately enroll and compensate landowners who do not contribute to additionality. This is a well-known problem in avoided deforestation PES, where many landowners may have low opportunity costs of forest conservation and thus would have conserved anyway (Ferraro 2008, Wunder et al. 2020). In the context of restoration PES, adverse selection may be less of a problem if restoration is costly and thus less likely to occur without incentives. However, as our model illustrates, adverse selection can still arise if landowners are facing changing relative returns to land uses that favor land abandonment or reforestation, or if there is increased enforcement of command-and-control regulation. We illustrate how these changes can lead to non-additional restoration in Figure A.2 (for declining productivity or rising returns to forestry) and Figure A.3 (for increased enforcement).

ii) In addition, moral hazard related to unobservable effort in the implementation of the contract can

[1] This first-order condition applies as long as the optimal a remains above $\bar{a}$. For landowners with v close to $\bar{a}$, a sufficiently large p can push the optimal a below $\bar{a}$; at that point the enforcement-cost term no longer applies and the compliant landowner's first-order condition, $v - a = p$, governs instead. The optimal level of agriculture is therefore kinked at $a = \bar{a}$.

threaten additionality. For example, landowners may enroll in active restoration PES and receive the upfront portion of the payments, but then fail to exert the necessary effort to keep trees alive or to exclude grazing livestock. This is particularly likely if monitoring and enforcement of the PES contract is weak. This source of non-additionality occurs for both restoration and avoided deforestation PES, but may be more likely for restoration PES if there are higher costs and effort required to restore land than to conserve existing forest.

iii) Finally, low ecological yield of restoration activities can also threaten additionality. Forest regrowth is a complex ecological process that can be affected by many factors, such as soil quality, rainfall, temperatures, fire, and the presence of invasive species. Landowners who undertake considerable efforts may still fail to restore forest, reducing the measured additionality of the program.

Our model indicates that when PES is implemented under a CAC regime, the policies should generally interact in a complementary way. Landowners facing potential enforcement of the CAC are more likely to enroll, and since they are also generally the higher productivity landowners (less likely to abandon land), this should reduce adverse selection. The threat of monitoring or enforcement related to the CAC should also induce greater effort, mitigating potential moral hazard concerns and potentially improving ecological yield. In addition, although the PES may "reward" the non-compliant, it does not differentially reward them compared to compliant landowners. Further, the model illustrates that we can potentially use knowledge of the interactions to improve targeting.

3 Background: *Reflorestar* and Forest Law in Brazil

Reflorestar is a payments for ecosystem services program run since 2013 by the Brazilian coastal state of Espírito Santo, located in the region covered by the Atlantic Forest, a global biodiversity hotspot (Eisenlohr et al. 2015, Rezende et al. 2018). The program offers financial incentives to rural property owners to restore and conserve natural areas on their properties. The Atlantic Forest region is densely populated and is estimated to contain only 10% of its original forest, thus holding significant potential for forest restoration (Crouzeilles et al. 2019, Pagiola et al. 2019).

Reflorestar operates in the context of Brazil's federal forest law, often referred to as the "Forest Code." The law requires rural landowners to keep a set share of land in native vegetation. For the Atlantic Forest, this standard is generally 20%. However, recognizing that the forest code requirements could conflict with economic development for the poor, a 2012 update to the law provided amnesties for small landowners who had already cleared the land before 2008 (Zakia & Pinto 2014, Machado & Anderson 2016).[2] Landowners in the Atlantic Forest also face legal standards under the 2006 Atlantic Forest Law, which officially prohibits deforestation after 2006 in this biome; any conversion of restored forest back to pasture, agriculture, or timber uses is thus illegal (Observatorio do Codigo Florestal 2017). Violations of the National Forest Code or the Atlantic Forest Law can result in fines for landowners and ineligibility for agricultural credit from the government (Observatorio do Codigo Florestal 2017). Enforcement of these laws is mostly carried out by the state's environmental agency IDAF, supplemented by enforcement action by federal environmental agency IBAMA.

Generally, landowners can choose which area of their property to conserve with native vegetation, which they spatially demarcate as a "*Reserva Legal*" (RL). However, the federal forest code also mandates the specific protection of areas with high ecological value, including riparian corridors and steeply sloping areas. These areas must be demarcated based on rules from the government about geographic features, and are denoted "*Área de Preservação Permanente*" (APP). The APP and RL areas must be geo-referenced and submitted by the landowner to the state and federal governments in the ("*Cadastro Ambiental Rural*", CAR). Our analysis relies on this database, which includes the CAR property boundaries, as the basis of our spatial analysis.

Espírito Santo's *Reflorestar* program arose with the intention to improve downstream water quality, given the perceived high-levels of non-compliance with the Forest Code conservation obligations and the importance of forest for watershed protection (Pagiola et al. 2019). *Reflorestar*'s payments are structured with the recognition that forest restoration may include both upfront costs and forgone revenues, and that these costs vary depending on the type of restoration. In total, there are six project modalities supported by *Reflorestar*, which we group into three types for our analysis: passive restoration, active restoration, and productive restoration. Table 1, which is adapted from *Reflorestar's* website, summarizes the maximum area that may be enrolled in each modality and the payments (in 2025 USD) associated with each one. Modalities can include two components: conservation payments over 5 years, and input subsidies distributed over 3 years.[3]

[2]Technically, the Forest Code allows landowners to trade conservation areas across farms, but this system has rarely been utilized (Pagiola et al. 2019). Small landowners are defined as smaller than four "Fiscal Modules," a legal definition that varies by municipality.

[3]In *Reflorestar*'s internal terminology, conservation payments are called "long-term PES" and input subsidies are "short-term" PES.

The input subsidies are earmarked payments intended to compensate for the costs of restoration activities, while the conservation payments are intended to offset ongoing costs for the property owner (Sossai et al. 2024).

The passive restoration modality ("passive regeneration") does not provide any upfront payments ("input subsidies"), but provides annual conservation payments across five years. Landowners are responsible for removing pressures like livestock grazing in these areas, which must be suitable for restoration. Active restoration includes "monitored natural regeneration" and "planting native species." Natural regeneration receives higher annual conservation payments but lower upfront payments than planting native species, in recognition of the extra material and labor costs of direct planting. Finally, productive restoration includes "agroforestry systems", "silvopastoral systems" and "managed forest." These modalities receive only the earmarked input subsidies, in recognition that these land uses should also generate revenue in the longer term, and no conservation payments. Landowners can choose where to restore within their properties, and are allowed to receive payments for areas that are part of their legally mandated conservation areas.

The projects are created with the support of local program consultants, who help the landowner gather documentation, prepare a project proposal, submit it to the state government, and enroll in the program. The consultants are remunerated by the state government per contract signed. The consultants also perform monitoring activities during the extent of the program, reporting to the state government.

The program has evolved since its first cohort in 2013. At first, it was open to nearly all properties in the state, conditional on basic compliance requirements ((being registered in the Rural Environmental Registry (CAR) and not having outstanding debt with the state). Starting in 2015, managers created specific eligibility areas and capped property size at 50 ha. In 2019, the property created a set of "priority areas," which were eligible to receive bonuses of up to 50% of the conservation payments. These priority areas are polygons which were created by the state using the hydrological model InVEST (Sossai et al. 2024). The program also gives bonuses conditional on the baseline area of native forest cover, compliance with the Forest Code, private natural heritage reserves, having a female landowner sign the contract, and being located inside of a conservation area (Pagiola et al. (2019)). Figure 1 shows points for enrolled properties shaded by cohort of enrollment.

Table 1: Description of *Reflorestar* modalities and payments

Modality	**Max. ha**	Conservation payments **USD/ha 5 yrs**	Input subsidies **USD/ha 3 yrs**
Restoration modalities			
Passive restoration			
Passive regeneration	10	70	0
Active restoration			
Monitored natural regeneration	10	62	765
Planting native species	6	60	2,370
Productive modalities			
Agroforestry systems	4	0	2,500
Silvopastoral system	5	0	1,050
Managed forest	2	0	1,650

Note: The disbursement of the conservation payments occurs once a year for five years. The payments for the input subsidies occur in three installments during three years: 50% at the contract signature, 30% one year later, and 20% two years later, conditional on compliance with the contract. The sum of areas with planting of native species, managed forest, and agroforestry is capped at 6 hectares. The values and limits in this table reflect the rules of the program as of 2025. The structure of payments has been similar over time with different specific values; this table reflects the basic payments. For the analysis below, we group modalities together as they are shaded in the table: all productive modalities are analyzed as one group, monitored natural regeneration is grouped together with planting native species, and passive regeneration constitutes its own analysis category.

A survey of participants conducted by the *Instituto Jones dos Santos Neves* with landowners in 2018 provides socio-demographic characteristics of landowners in Reflorestar: enrolled households tend to have deep experience in agriculture, and typically do not receive poverty-alleviation cash transfers (Bolsa Familia). The modal type of production is coffee, followed by banana producers and cattle ranchers (Table A.1). Among participants, 35 percent believe that there has been less water in the past 5 years, and 62 percent list improving water quality as a reason to enroll in Reflorestar. Motivations to join Reflorestar also include improving environmental quality and receiving money. Less than 20 percent of participants state that they are enrolling in Reflorestar to comply with the law, and roughly 40 percent state that they do not know about the forest code. Among those who are aware of the laws governing forest management, the majority believe that they are compliant with the requirements for managing protected zones (APP and RL) within their property.

4 Data

To assess the effectiveness of restoration PES, we construct a dataset at the rural property-year level, containing properties' characteristics, PES enrollment in Espírito Santo, and land use measured with satellite-imagery. We overlay polygons of rural properties, administrative data from *Reflorestar*, land use data from MapBiomas, and geographic data from multiple sources. We use this dataset to analyze both enrollment and additionality, as well as to conduct simulated targeting exercises.

Rural property shapes from CAR registry: We obtain private properties' boundaries from the Rural Environmental Registry (CAR, *Cadastro Ambiental Rural*), reported by landowners as an obligation under the revised Forest Code.[4] We extract from the CAR data the boundaries of the whole property (our primary unit of analysis) and the portions of the property declared as "Legal Reserve" (RL, *Reserva Legal*) and "Permanent Preservation Area" (APP, *Área de Preservação Permanente*). We refer to the combined APP and RL as "protected zones".

Administrative data from Reflorestar: The list of *Reflorestar* contracts stems from the Environmental Department of Espírito Santo (SEAMA, *Secretaria do Meio Ambiente e Recursos Hídricos*). The data contains all contracts signed with *Reflorestar*, with the coordinates of the enrolled area, the date of signature, the area (in hectares) enrolled in each modality of the program, and the monetary values agreed to in the contract. [5] Additionally, we also use shapefiles of *Reflorestar* "eligibility" areas and "priority areas," where restoration activities benefited from up to 50% additional conservation payments, as discussed in Pagiola et al. (2019). These datasets are publicly available on *Reflorestar*'s website.

The original list contains 5,423 *Reflorestar* contracts signed between 2013 and September 2025, of which 5,213 have valid coordinates. We use the coordinates to search for the corresponding property in the CAR registry and match the contracts to properties. Details of the matching procedure are described in Appendix A.3. Of the 5,213 unique contracts used in the analysis, 4,525 are matches of the contracts' coordinates to CAR properties, while 688 are artificial polygons. We created these artificial polygons when the contract's coordinates do not match any CAR property, even in close proximity. They are circles around the contract's

[4] CAR is a self-reported system and may have inaccuracies. As of 2024, the Espírito Santo government analyzed and validated 66% of the registries, while the national average was 3.3% in 2024 (Lopes et al. 2024).

[5] The contractual values are expressed in VRTE, a notional value used by the state of Espírito Santo. We express these values in USD by converting the values from VRTE to Brazilian Reais, then converting each year's values in BRL into 2019 values using each year's mean Brazilian CPI (IPCA), and finally converting to USD using the mean 2019 exchange rate.

coordinates with the same area as the enrolled area in the contract. Therefore, they are likely much smaller than the actual property area and do not have the same boundaries. Because of these differences in data treatment, we assess the robustness of our additionality results to the inclusion of these artificial polygons.

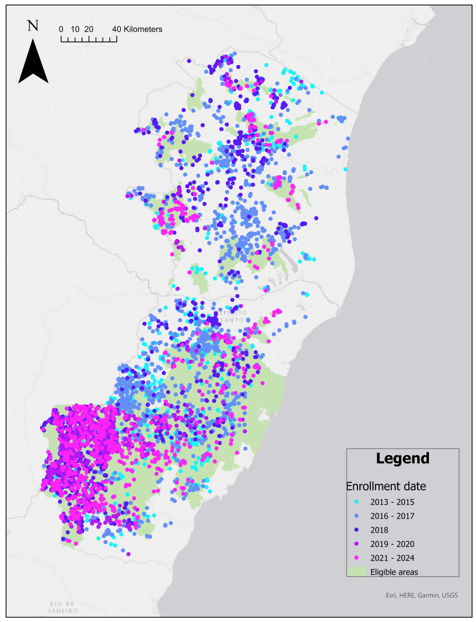


Figure 1: Evolution of *Reflorestar* Contracts

Note: This figure shows the coordinates of properties enrolled in different phases of *Reflorestar* as dots. The green areas are eligibility areas, which started binding in 2019.

Land use data from MapBiomas: Our main outcome of interest is land use, which comes from the 9th Collection of MapBiomas' maps from 2010 to 2024 (MapBiomas Project 2024, Souza et al. 2020) . This data series consists of a complete annual classification of the land use in the country at a 30 meter resolution based on Landsat imagery. The classification distinguishes between forest, pasture, agriculture, mixed use or "mosaic" (agriculture and pasture), and coffee plantations among others. We use this data to compute the annual land use for every rural property in Espírito Santo based on their shapes. We aggregate the land use categories at the property level (making the distinction between areas inside or outside the legally protected areas, RL and APP). This yields property observations for each year from 2010 to 2024 measuring the areas covered by forest (natural forest formation, grassland, savanna) or land development (pasture or agriculture).[6]

[6] In line with the Forest Code's rules, we only consider developable land areas, thus excluding land cover categories such as rocks and water bodies.

In summary, we create a balanced panel dataset of rural properties in Espírito Santo from 2010 to 2024, some of which are enrolled in *Reflorestar* and some of which are not. Because *Reflorestar* explicitly focuses on smaller properties, we restrict the pool of analysis properties (unenrolled and enrolled) to properties below 60 ha, which is the 95th percentile of the enrolled properties in the sample, and greater than .5 ha. This results in a sample of 97,605 unique properties from the state, with 5,213 unique polygons corresponding to contracts. When studying additionality, we restrict our sample to properties that enrolled between 2013 and 2021 to ensure at least three years of post-enrollment remotely-sensed forest data (since the MapBiomas data is available until 2024). For the analysis of enrollment and willingness to accept, we use the full sample of contracts between 2013 and 2025.

Additional variables: For our analysis of compliance with the Forest Code, we compute the conservation requirement for each property. For landowners who provide RL and APP shapefiles (the majority), we set their conservation requirement equal to the share of land occupied by those areas. Some landowners did not submit APP or RL shapefiles in their CAR declarations (full geo-referencing of the APP and RL is not required for small landowners).[7] In this case, we impute the conservation requirement as the minimum of 20% of their area or the share of forest they had in 2010, to reflect the amnesty given by the Forest Code. In order to create a measure of compliance with the Forest Code, we compute the share of the property covered in native vegetation minus the percent of the property in the conservation requirement. We use 2010 as baseline, since that is the earliest year we collected from the Mapbiomas data.

Environmental enforcement data stems from the state of Espírito Santo's environmental enforcement agency, IDAF, which publishes information on environmental inspections since 2018 (IDAF - Instituto de Defesa Agropecuária e Florestal do Espírito Santo 2026). Our main measure of enforcement is the inspection rate: the number of IDAF inspections divided by the number of registered rural properties in each municipality, averaged over 2018–2023. This ratio captures the average probability that a property is inspected within a municipality, reflecting how actively local environmental authorities enforce land-use regulations. Aggregating at the municipality level is appropriate because municipalities represent the relevant administrative and operational scale for IDAF's enforcement logistics: inspection teams are typically organized and dispatched at this level, and enforcement resources and monitoring capacity are budgeted municipally. We also collect data on environmental fines issued by the federal agency IBAMA (IBAMA - Instituto Brasileiro do Meio

[7] 10% of properties in Espírito Santo do not have RLs declared in the CAR.

Ambiente e dos Recursos Naturais Renováveis 2025) in the state of Espírito Santo, which are infrequent as IBAMA takes a secondary role in environmental enforcement in this region.

Finally, we collect geographic fundamentals measured at a fine scale, and compute their averages at the property level. The geographic characteristics that we include in the analysis are altitude (U.S. Geological Survey 2018), slope (computed from the altitude data), coffee maximum attainable yield (FAO & IIASA 2021), and the mean value of nighttime lights within the property boundaries detected in 2010 (NOAA National Geophysical Data Center 2013). We also gather information at the municipality-year level on agricultural GDP, municipality expenditure on environmental activities, the municipality's stock of rural credit, rural population, and the municipality's exports. Each of these variables are obtained from IPEAData (Instituto de Pesquisa Econômica Aplicada 2026) .

4.1 Descriptive Statistics

Table 2 shows summary statistics about the enrolled properties and other CAR properties between 0.5 and 60 ha in size. In total, *Reflorestar* enrolled more than 24,000 ha of land between 2013 and 2025, committing around 21 million USD (at 2019 values). The total area of properties in our sample is approximately 1.6 million ha. The columns show totals for the properties that were never enrolled, enrolled between 2013 and 2021 (the sample used for the additionality analysis), and enrolled between 2022 and 2025 (the remaining sample, also used for the analysis of enrollment).

The average *Reflorestar* contract is 4.98 ha, with larger shares of area enrolled in passive restoration than in the other two modalities. Producers tend to split their contracts across multiple modalities, although some contracts have a majority in one type of restoration. The average contract value is just over 4,000 USD.

Properties are mostly covered in pasture, then mosaic (mixed land uses, including pasture, crops, and potentially forest in early stages of regeneration), then crops, of which coffee is the most prevalent in this region. In 2024, over 25% of the rural properties' area was covered with forest, indicating that the total percentage of forest actually exceeds the 20% conservation requirement of the Forest Code for the Atlantic Forest region. In other words, if the goal were simply to reach 20% forest across all private properties in Espírito Santo, no further PES would be required. However, at the same time, 56% of the properties in our sample have less forest than their mandated conservation requirement. The mean mandated conservation is above 20%, despite the amnesty, reflecting the fact that many properties have large APP areas.

Table A.3 shows the mean of the geographic controls for properties in Espírito Santo, disaggregating by enrolled properties, non-enrolled properties, and matched non-enrolled properties. Enrolled properties tend to be at higher elevation than non-enrolled ones, have higher slope, and more water sources. Properties that enroll also tend to be in areas with less agricultural GDP per area, are closer to the municipal seat, have fewer nighttime lights, and are slightly larger than the unenrolled properties that are eligible for the program. Enrolled properties are slightly more out of compliance at baseline than eligible properties that do not enroll. Enrolled properties also have somewhat more forest at baseline compared to all other properties (5.45 ha vs. 4.10 ha); by 2024 there is an increase in forest for enrolled properties (to 5.74 ha on average) and a very small decrease in forest for unenrolled properties (to 4.06 ha on average). This indicates that overall, the region neither lost nor gained substantial forest cover across this period.

Table 2: Forest outcomes across all properties in Espírito Santo

	Never Enrolled	Enrolled 2013-2021	Enrolled 2022-2025
Property Characteristics (2024)			
Total area (ha)	1,499,097.25	78,523.83	22,318.74
Share of total in forest	24.88	28.56	29.34
Share of total in pasture	40.28	36.29	36.66
Share of total in mosaic	26.05	25.41	22.52
Share of total in coffee	7.27	9.19	11.02
Percentage of mandated conservation	23.68	24.60	22.91
Share of forest minus mandate, 2010	-1.54	-2.05	-2.02
Share in non-compliance	0.56	0.53	0.49
Reflorestar characteristics			
Sum of values across all properties			
Total enrolled		19,537.67	5,073.48
Total value of Reflorestar contracts (USD)		16,244,649.00	4,763,885.50
Mean value per enrolled property			
Reflorestar contracts USD		4,138.76	3,698.67
Ha enrolled Reflorestar		4.98	3.94
Ha passive restoration		2.62	2.07
Ha active restoration		1.37	0.67
Ha productive modalities		0.98	1.20
Percent contract passive restoration		38.57	32.11
Percent contract active restoration		32.84	22.09
Observations	97,605	3,925	1,288

Note: This table shows total values for land cover across all properties, those never enrolled, those enrolled between 2013 and 2021, and those enrolled between 2022 and 2025 in *Reflorestar*. The top panel provides aggregates over the entire landscape of these subsamples and the bottom statistics on enrollment in *Reflorestar*. The sample includes all properties in CAR with area greater than 0.5 and smaller than 60 ha. Compliance here is defined as the property's having more forest than its conservation requirement, regardless of whether the forest's location is measured within the areas declared as RL or APP in the CAR polygons.

5 Additionality of the PES

We use matching and difference in differences to estimate the additionality of PES by comparing forest cover in properties that participated in *Reflorestar* with a suitable comparison group of properties. We estimate effects at the level of the property as a whole, within protected areas under the Forest Code (those identified as being part of the RL or APP), and within unprotected areas. We also investigate the heterogeneity of additionality by program modality, baseline compliance, and municipality level enforcement.

5.1 Pre-matching

Matching has been established as a useful way to pre-process data to reduce potential bias in subsequent estimation (Ferraro & Miranda 2014). We apply nearest-neighbor matching using Mahalanobis distance within modality group and historical program phase. We take the two nearest neighbors to form the comparison group. We divide the sample into pre-2019 and post-2019 cohorts when matching, reflecting the two main distinct phases of the program (Table A.2). We define a property as being in a particular modality if they have any part of their contract in that modality.

The matching covariates are meant to capture features related to the costs and benefits of enrolling in the program, including opportunity costs and enforcement risk. We include: property area, coffee productivity, elevation, nighttime lights within the property in 2010, slope, distance to the municipality seat, mean agricultural GDP per farmed area at the municipality level, mean expenditures on environmental protection at the municipality level, the number of water sources within the property, mean environmental fine rate at the municipality level, percent forest at baseline, an indicator for no declared protected zone, latitude, and longitude.[8] All variables are measured in 2010, with the exception of the environmental fine rate for which we use the inspection rate variable as described above, since the data is only available starting in 2018. The same is true of the average municipal expenditures on environmental enforcement.

Table A.3 provides a balancing test of the treatment and control groups using normalized differences. This shows that matching improves balance compared to the unmatched sample and results in normalized differences below 0.10. Figure A.4 demonstrates the similarity in distribution of covariate values after matching, and Table A.4 shows the same statistics for the different modalities. In Figure A.5, we show the average

[8]We do not match strictly within municipality, as some municipalities are very small, but rather include latitude and longitude as matching covariates to ensure that matched properties are geographically proximate.

per property forest trends over time. The matched control group remains essentially flat over time, with very little net forest cover gain. In contrast, the *Reflorestar* cohorts all show gains in forest cover after program enrollment.

5.2 DiD Estimation

To obtain plausibly causal estimates of program impacts, we use the doubly robust staggered difference-in-differences estimator proposed by Callaway & Sant'Anna (2021) on the matched subset of properties. This approach avoids the "bad" or "forbidden" comparisons problem highlighted by Goodman-Bacon (2021) and Borusyak et al. (2024), among others. The estimator computes group-time average treatment effects $ATT(g,t)$ separately for each enrollment cohort g at each time period t, using only never-treated units as the comparison group.

The estimator proceeds in two steps. First, for each cohort g and time period $t \geq g$, the group-time average treatment effect is estimated using a doubly robust approach that combines outcome regression adjustment with inverse probability weighting. Let Y_{it} denote the outcome for property i in year t, G_g indicates membership in cohort g (i.e., enrollment in year g), C indicates never-treated status, and $\mathbf{X}_i$ denotes a vector of baseline covariates. The doubly robust estimator identifies:

$$ATT(g,t) = E\left[Y_t - Y_{g-1} - m_{g,t}(\mathbf{X}) \mid G_g = 1\right] - E\left[\omega(\mathbf{X})\left(Y_t - Y_{g-1} - m_{g,t}(\mathbf{X})\right) \mid C = 1\right] \quad (4)$$

where $m_{g,t}(\mathbf{X}) = E\left[Y_t - Y_{g-1} \mid \mathbf{X}, C = 1\right]$ is an outcome regression model for the change in outcomes among the comparison group, estimated as a function of baseline covariates, and $\omega(\mathbf{X})$ are inverse probability weights that reweight the never-treated group to match the covariate distribution of cohort g. This doubly robust formulation ensures consistency if either the outcome regression model $m_{g,t}(\mathbf{X})$ or the propensity score model underlying $\omega(\mathbf{X})$ is correctly specified.

We include ln(property area), an indicator for whether the property does not contain a legally required reserve (RL), and hectares of the property in forest in 2010 as baseline covariates. The outcome is hectares of the property in native vegetation as measured by MapBiomas for each year from 2010 to 2024. From here forward, we refer to native vegetation as "forest", since that is by far the majority land use. Standard errors are clustered at the municipality level (75 municipalities).

In the second step, the group-time treatment effects are aggregated into interpretable summary parameters. We report both a simple average treatment effect across all cohorts and post-treatment periods and event-study aggregations that average treatment effects by time relative to enrollment. The event studies allow us to present a pre-trend test and to examine the dynamics of treatment effects over time.

5.3 *Reflorestar* Impacts on Land Use: Main Effects and Event Study

We first estimate the impacts of the *Reflorestar* restoration incentives on forest cover, measured in hectares within the entire property. Table 3 shows treatment effects on the treated from our preferred specification using the estimator from Callaway & Sant'Anna (2021). In addition, as robustness checks of this main estimate, we show estimates from standard two way fixed effects with and without matching, and a DID imputation-based estimator from Borusyak et al. (2024). The two-way-fixed effects (TWFE) estimates for any enrollment are smaller in magnitude with matching, and the point estimates for the matched sample are similar across all of the estimators (Column 1). The point estimates from the Callaway & Sant'Anna (2021) method give the most conservative overall estimates in this set. Specifically, enrollment in any modality results in an approximately 0.073 hectare increase across all post-contract years.

Table 3 also shows the estimated impacts of each modality of *Reflorestar*, allowing for a comparison of effectiveness across passive restoration, active restoration, and productive restoration types (Columns 2-4). We find that passive restoration generally results in the largest estimated magnitude of forest gains (0.119 ha for the CSDID estimator), followed by active restoration (0.090 ha) and then productive restoration (0.052 ha), although these estimates are not statistically significantly different from each other.

Table 3: Main estimates of impacts on hectares of forest cover

		Type of contract		
	Any	Passive restoration	Active restoration	Productive
	(1)	(2)	(3)	(4)
Average effect over all post-treatment years				
TWFE – unmatched sample				
Enrolled (0/1)	0.198***	0.331***	0.227***	0.161***
	(0.034)	(0.048)	(0.036)	(0.038)
Observations	1444755	1417200	1432590	1416015
TWFE – matched sample				
Enrolled (0/1)	0.089***	0.163***	0.103***	0.052*
	(0.022)	(0.035)	(0.026)	(0.028)
DID imputation – matched sample				
ATT	0.085***	0.149***	0.104***	0.045*
	(0.023)	(0.036)	(0.027)	(0.026)
CS DID – matched sample				
ATT	0.073***	0.119***	0.090***	0.052**
	(0.020)	(0.032)	(0.025)	(0.022)
Observations	176310	98850	141495	96240
Mean dep. var. treated, 2010	5.452	8.888	5.562	4.571
Mean area enrolled	4.978	6.868	5.243	4.690
Aggregated effect over years 5-9				
Forest				
Avg. effect, yrs 5-9	0.190***	0.262***	0.230***	0.172***
	(0.047)	(0.068)	(0.055)	(0.053)
Forest plus mosaic				
Avg. effect, yrs 5-9	0.441***	0.472***	0.458***	0.502***
	(0.085)	(0.091)	(0.095)	(0.155)

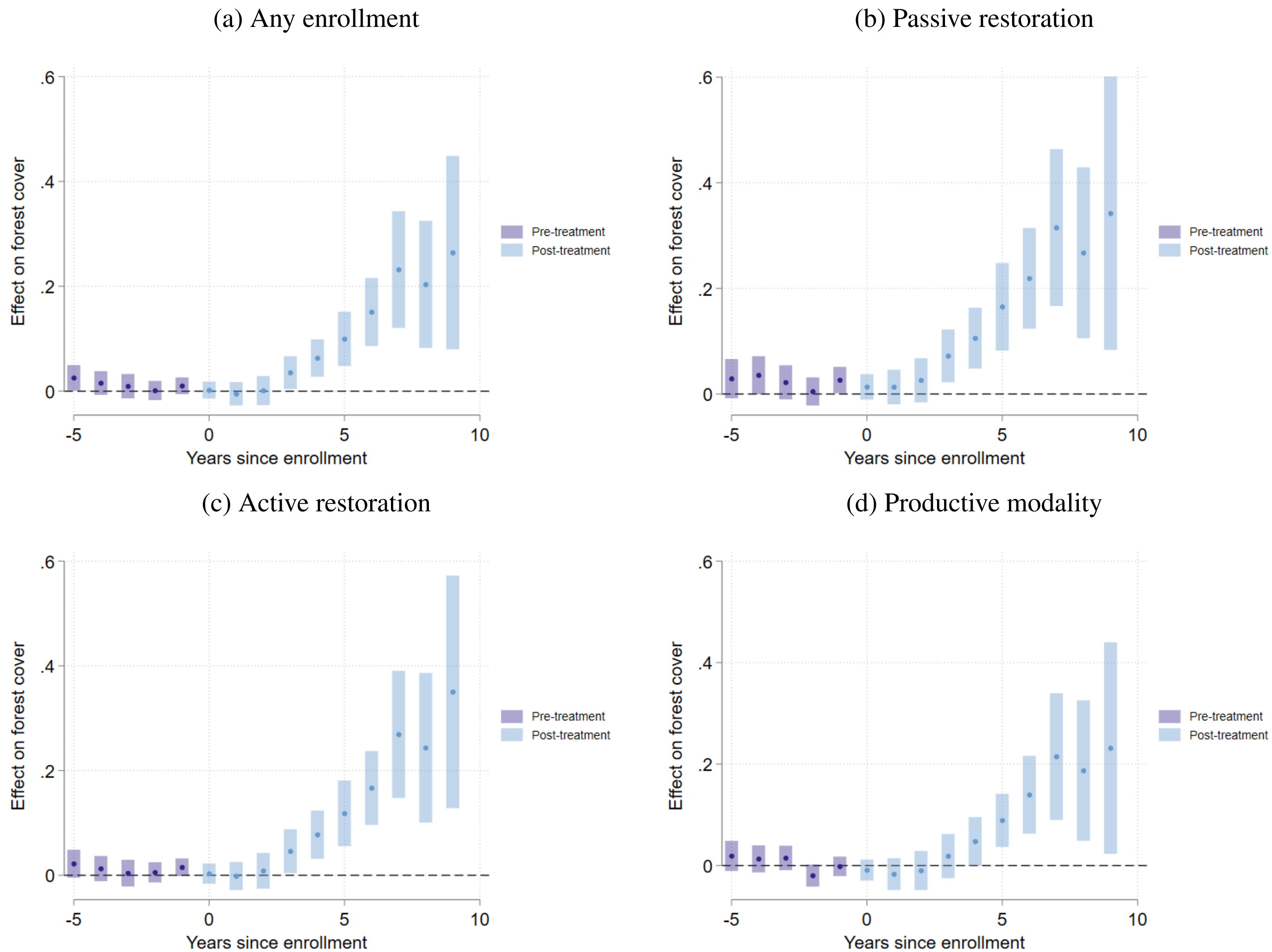
Note: Table shows the average treatment effect and the treatment effects by group using two-way fixed effects with and without matching, the DID imputation estimator from Borusyak et al. (2024), and the estimator from Callaway & Sant'Anna (2021). All estimations include as controls ln(property area), ln(elevation), and area in baseline forest, with standard errors clustered at the level of the municipality. The unit of analysis is the entire registered property under CAR. The outcome variable is the hectares of this area in native vegetation in each year of the analysis. Properties are defined as having enrollment in a particular modality if they have any area in that modality. Standard errors are clustered at the municipality level (75 municipalities). Significance levels: * p<0.1, ** p<0.05, *** p<0.01.

Figure 2 shows the estimated program impacts using event studies and the estimator proposed by Callaway & Sant'Anna (2021). There is generally no detectable difference in pre-treatment forest cover trends between treatment and control groups or evidence of enrollment anticipation, providing reassurance regarding the estimation assumptions. Across all modalities, treatment effects are small or zero at first. After year three or four, we observe a statistically significant positive impact and a steady increase in forest cover with each year. Note that these estimates are higher in the earlier years after enrollment for passive restoration, where reforestation may be expected to happen more quickly, than for active restoration, where seedlings may take more time to be established.

The greater impacts observed after three-four years is consistent with the advice of remote sensing experts, who suggest that a replanted forest requires 3-5 years of growth before being detectable on a satellite image of the resolution used by MapBiomas (30m) (although the literature on this topic is somewhat thin for this region). Estimates from Canada suggest 6 to 10 years before reforestation can be detected using Landsat data (White et al. 2022), and estimates from the U.S. Pacific Northwest suggest 5 years to detectable reforestation (Kennedy et al. 2012). For the Atlantic Forest, Rodrigues et al. (2009) suggest that it may take three to five years for tree cover to be sufficient to shade the soil and therefore be detectable via remote sensing. Our results also accord with recent findings by (Rayden et al. 2023) that highlight the potential for rapid sequestration through restoration of degraded land. This prior research indicates that the longer term gains are a better measure of true program effects.

Given these dynamics, we base our primary additionality estimates on the average event study results from year 5 through year 9, as this is likely to best represent program impacts. As reported in the bottom panel of Table 3 and Figure 2, the effect across all modalities after five years is 0.190 ha and the impact of passive restoration is 0.262 ha. Compared to the average area enrolled in *Reflorestar* (4.98 ha), these results imply an average additionality of 4%; or for every hectare of area enrolled, about 0.04 hectares is additional.

Figure 2: Event studies by modality, matched sample using area as outcome



Note: Event study analyses with the CSDID estimator from Callaway & Sant'Anna (2021). Unit of analysis is the entire property registered with the CAR. Covariates include baseline area forest, ln(property area), and ln(elevation). Standard errors are clustered by municipality (75 municipalities). Properties are defined as having enrollment in a particular modality if they have any area in that modality. The outcome variable is hectares of forest cover. See more details in Table 3.

We also estimate the effect on a comprehensive classification of forest that includes the land use classification "mosaic," which captures areas with a mixture of land uses, including early stages of forest regrowth (Table 3). This category may be capturing forest regrowth that is not yet detectable as mature forest cover. The results for this outcome of forest including the mosaic category, indicate that enrollment in *Reflorestar* leads to an increase in forest-plus-mosaic of 0.44 ha, which more than doubles the additionality estimate to 9% per enrolled hectare.

Thus together, our estimates suggest that the average medium-term additionality in the program is 4-9% per hectare enrolled. Furthermore, we note that the estimates also provide no indication that producers remove forest after their 5-year contract ends, as our event study estimates generally show increasing impacts past year five. This alleviates a potential concern about the long-term sustainability of the program. One explanation for this is that the presence of the overlapping command and control federal and state regulations provide sufficient incentive to keep the restored forest once the initial barriers have been overcome.

We note that although these additionality estimates may seem small, they are in fact larger than has been found for other prominent avoided deforestation studies. For example, Ordóñez et al. (2023) find that average additionality from Costa Rica's avoided deforestation program was 0.09 ha for an average contract size of 39 ha; or just 0.23% additionality. Alix-Garcia et al. (2015) estimated approximately 1-2% additionality from Mexico's avoided deforestation PES as a percentage of area (although change as a percentage of expected forest loss rates was far greater, at 40-51 percent). In both situations, deforestation rates for these countries as a whole fell to low levels at the same time that the PES programs were implemented. In a context with higher deforestation trends, Jayachandran et al. (2017) find a village level additionality of approximately 4 percent.

5.4 Robustness, Slippage, and Heterogeneity

We provide several additional robustness tests of our main results. First, we run a specification where the outcome is the percentage of the property in forest rather than the hectares, shown in Table A.5. We also estimate the effects for alternate specifications of the dependent variable using the winsorized area, and the winsorized area for protected and unprotected areas of the property (Table A.7). We also drop the contracts that could not be matched to a CAR property and for which we had created artificial polygons (Table A.7). The results confirm positive additionality of the program with similar magnitudes.

Second, we examine other outcomes from the MapBiomas dataset in order to deduce where land-use tradeoffs might be occurring. These three other main land uses in the dataset, aside from forest, are pasture, coffee, and mosaic (already discussed above). Table A.8 suggests significant reductions in the area of land devoted to pasture, increases in the area of mosaic, and no change in the area planted in coffee. This suggests that restoration is occurring mainly on land previously used for pasture, as expected.

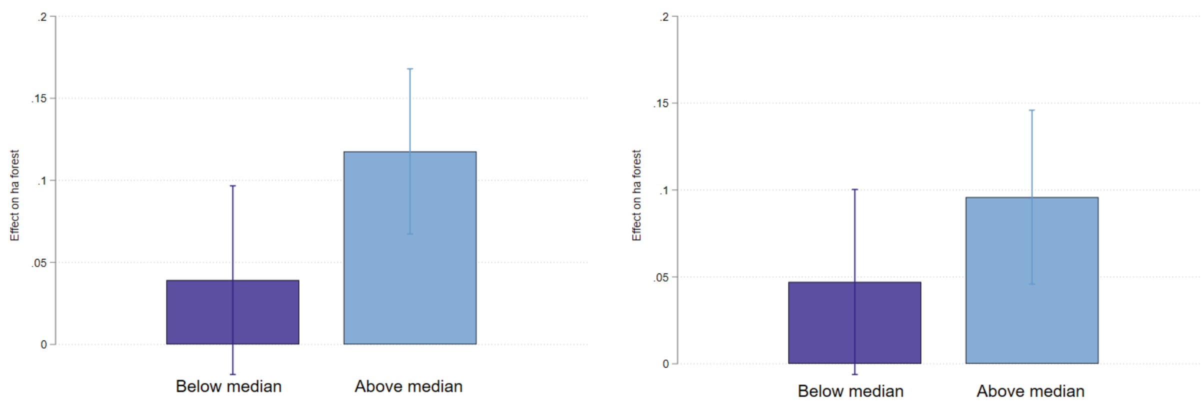
Next, we compare the impacts inside and outside of the portions of the property demarcated as protected by the Forest Code (RL or APP). This exercise responds to concerns that landowners may be reforesting some areas while deforesting others, and also informs whether landowners are more likely to reforest areas that are already protected and therefore under greater enforcement scrutiny. The results are shown in the Table A.6. Overall, we find that effects are consistently positive among both protected and non-protected areas, indicating a lack of negative spillovers from restoration efforts. In addition, as a percent of land area, we find greater impacts within the RL/APP areas of the property.

Finally, we examine impacts across levels of enforcement intensity and compliance with the Forest Code. These estimates are implemented on subsamples of the full dataset defined by the covariate that determines the heterogeneity. Figure 3 indicates greater additionality among properties in municipalities with higher enforcement intensity by the state environmental agency. The magnitudes of the estimated treatment effects for enforcement above the median level are roughly triple the point estimates for enforcement below the median level (0.118 vs. 0.039 ha). This result underscores the potential role of complementary policy in driving success of restoration efforts. We caution that this is not necessarily interpretable as a causal effect, since this measure is likely to be correlated with institutional capacity and other municipal characteristics that might make enforcement easier or more difficult depending upon the setting. However, we do include event study estimates of these subgroups (Figure A.8) in which we find no evidence of differential trends before the treatment.

Figure 3 also demonstrates a much higher level of additionality among properties that begin with above-median compliance in the sample. This difference persists across restoration modalities, and is especially pronounced for active restoration, where additionality among above-median-compliance properties is more than double that of below-median-compliance properties (0.130 vs. 0.046 ha); the gap is more modest for passive restoration (0.135 vs. 0.091 ha) (Table A.9). We also find similar results if we consider a comparison between properties with baseline forest or without (Table A.9).

Figure 3: Heterogeneity in treatment effects: area outcomes

(a) By enforcement intensity (b) Compliance, 2010



Note: Unit of analysis is the entire property registered with the CAR. Each bar shows a separate subgroup estimation using the Callaway & Sant'Anna (2021) estimator with standard errors clustered at the municipality level (75 municipalities). Controls include ln(property area), an indicator for if the mapped property does not contain a protected zone, and baseline forest cover. The outcome variable is hectares of forest cover. Point estimates and standard errors for all modalities are shown in Table A.9.

5.5 Mechanisms for Low Additionality

Above we discussed two possible explanations for low additionality – the rate at which forest is actually regrown and also the ability of remote sensing products to capture this regrowth. This section examines other potential sources of low additionality. As discussed in our theory section, low additionality may reflect adverse selection, moral hazard, or low ecological yield. In order to further explore the role of these potential mechanisms in driving our additionality estimates, we assess how our results compare to alternate specifications as shown in Figure A.9.

If restoration were perfectly successful and there were no adverse selection, we would expect projects to yield one hectare of new forest for every hectare enrolled, or 100% additionality. The difference between our CS-DID estimates, shown in the light blue line in the figure ("CS-DID"), and the ideal yield corresponding to the full average area enrolled of 4.98 ha thus reflects a combination of mechanisms driving low additionality.

To understand the role of low ecological yield versus adverse selection and moral hazard, we show simple before-after estimates which are obtained from a regression of forest cover on years relative to treatment. This specification includes property but not time effects, with the period immediately before enrollment ($t-1$) as the reference category. It therefore captures the observed trajectory of forest expansion over time for enrolled properties. We show two trajectories: the medium blue "Before-After" line includes all enrolled properties, while the purple "Before-After Compliant" line includes only landowners who did not have their contracts interrupted or terminated early for non-compliance (just under 20% of the contracts for our analysis years were interrupted early).

We observe that even for compliant landowners and not accounting for adverse selection (the top, purple line), at most about .4 ha becomes reforested on average after 6-8 years. This is less than 10 % of the average enrolled area. The large difference between the area actually reforested according to these trajectories and the area enrolled in the program indicates that low ecological success is an important source of low additionality. This result is consistent with emerging research in the forest restoration literature, which has documented challenges in keeping saplings alive years after restoration efforts in tropical forest, even in well-managed situations (Banin et al. 2022, Scoles & Gribel 2021, Charles et al. 2018).

Next, we compare restoration patterns for properties with contracts that were terminated early versus not. The before-after trajectory excluding the early terminations (purple line) is slightly higher than the before-after trajectory including the early terminations (darker blue line), although these coefficients are not statistically different from each other. This indicates that moral hazard is also a factor, but likely plays a smaller role.[9]

Finally, the observed forest cover expansion may not be additional because of adverse selection: landowners who would have restored anyway may be particularly attracted to this program. The difference between the CS-DID effect and the before-after effects reflects the impact of adverse selection. At year $t+8$, the before-after estimate implies an expansion of approximately 0.4 ha, or 0.35 when excluding early termina-

[9]The difference in the expansion rates between these two groups is our best measure of the role of moral hazard, although we cannot rule out that all landowners who were not terminated early are partly non-compliant.

tions contracts, while the CS-DID estimate implies approximately 0.2 ha. This suggests that up to half of the observed forest expansion can be attributed to adverse selection. However, in absolute terms, this difference is small compared to the overall loss of additionality driven by the low ecological yield.

Taken together, these three series suggest that all three sources of non-additionality are present, but that moral hazard and adverse selection play less of a role in this context than potential ecological difficulties in restoring intended areas of forest.

6 Enrollment and Willingness to Accept

6.1 Likelihood of Enrollment and Estimation of WTA

To assess the cost-effectiveness of the program, we estimate the participation costs for producers through a revealed preference approach that models enrollment as a function of prices and characteristics. We then compute the willingness to accept (WTA), in monetary terms, to estimate the program's welfare costs. Unlike the additionality analysis in Section 5, which uses the sample of contracts signed between 2013 and 2021, we use here the full set of *Reflorestar* contracts signed between 2013 and 2025 (see Section 4).

The probability that a landowner i enrolls depends upon the price p_i as well as underlying individual and municipality characteristics that cause variation in the opportunity cost of accepting the contract, as well as other factors that might affect their cost of participation:

$$Pr(E_i = 1) = f(p_i\gamma + X_i\beta + \epsilon_i), \tag{5}$$

where $E_i = 1$ means that landowner i chooses to enroll their property in *Reflorestar*. The vector X_i includes variables that determine the property's opportunity cost, and mirrors the matching variables used to select the control group in the additionality analysis, namely: net compliance with the Forest Code, property size, mean altitude, slope, coffee yield, satellite-measured nightlights, the number of water sources, distance to the municipality's center, municipality-level agricultural productivity (the ratio of the municipality agricultural GDP to the area of non-forest land in the municipality), and municipal environmental expenditure. Unobservables, such as idiosyncratic environmental preferences or landowners' ability, are contained in ϵ_i.

The coefficient γ in this equation reflects the average marginal utility of income for this population

(Phaneuf & Requate 2016). The WTA can be computed as the ratio of the coefficient on the covariates to the coefficient on price, $WTA = \frac{\beta X}{\gamma}$, which can be approximated by the expression $\hat{WTA} = \frac{\hat{\beta} X}{\hat{\gamma}}$ using the estimated coefficients. This can be evaluated at the values of X for each property, or at the mean value of these Xs across the whole sample or within subsamples.

Identification of γ relies on exogenous variation of the offered payment (p). One challenge is that the observed contract price is likely endogenous due to unobserved factors that also affect enrollment decisions, such as landowner preferences or unobserved land characteristics. To address this issue, we leverage exogenous variation stemming from a location-specific policy that introduced potential bonus payments for landowners in "priority areas," starting in 2019. An example of these areas is illustrated in the Figure A.10, where we show boundaries of properties and priority areas within the municipality of Afonso Cláudio. Landowners who enroll in these areas can receive potential bonus payments in the 5-year conservation payments (not for input subsidies), of up to 50%. We use this presence of priority areas and the conditional price variation created by this policy to identify γ and therefore compute WTA. Our main specification uses a binary variable for the presence of priority areas within the property, but we also check robustness to using a continuous measure of potential bonus payments based on the area of priority zones within the property.

For this estimation to identify WTA, priority area status must create variation in payment levels (relevance) and also affect enrollment only through higher offered payments (exclusion restriction). Relevance is demonstrated through the correlation between the contract values of enrolled properties and the presence of priority areas. Table A.10 shows that the binary priority area indicator increases post-2019 contract values by 183 USD (Column 1) in an unconditional correlation and by 169 USD once we account for property-level controls (Column 2). Using the continuous measure of potential bonus payments, we find that for each additional dollar in potential bonus, the value of the signed contract is higher by around 0.2 USD (Columns (4)-(6)).[10] We use the conditional variation in bonus payments (169 USD) to obtain the WTA estimates.

Considering the exclusion restriction, the main threat to validity is that priority areas may be correlated with property characteristics that also affect willingness to enroll in ways outside of their impact on the contract price. The priority areas were based on a hydrological services model created by InVEST; we therefore control for geographic characteristics and use the remaining conditional variation in area locations,

[10]Only 20% of potential bonus payments are realized because: i) these areas may already be preserved and not eligible for reforestation, ii) landowners may decide not to enroll these areas, iii) *Reflorestar* gives bonus payments for other reasons, and these bonuses are capped at 50% of the conservation payments.

which is plausibly exogenous. To assess the validity of this approach, we perform a placebo test where we estimate the conditional correlation of priority areas on enrollment before 2019, when the bonus payments did not yet exist but the property's geography was the same (Column 3). This exercise indicates that it is unlikely there are time-invariant unobservable characteristics that are correlated with priority areas and affect enrollment.

Table 4: Correlates of enrollment and priority areas (binary measure) – Full Sample

	Post-2019 Contracts		Pre-2019 (Placebo)
	(1)	(2)	(3)
1(priority area)	0.665***	0.518***	0.047
	(0.105)	(0.092)	(0.064)
Net compliance		-0.002	-0.000
		(0.001)	(0.001)
Log(Coffee Potential Yield)		0.565***	-0.138*
		(0.164)	(0.083)
Log(Altitude)		0.271***	0.178***
		(0.066)	(0.042)
Log(Nightlights 2010)		-0.103***	-0.039*
		(0.025)	(0.022)
Log(Slope)		-0.010	-0.111**
		(0.083)	(0.056)
Log(Area)		-0.003	0.144***
		(0.032)	(0.031)
Log(Distance Mun.)		-0.102**	-0.041
		(0.041)	(0.040)
Log(Productivity Mun.)		-0.265**	-0.012
		(0.128)	(0.108)
Log(Env. Expenses Mun.)		0.108	0.012
		(0.066)	(0.024)
No RL		0.507***	0.339***
		(0.089)	(0.066)
Water Sources		0.103***	0.108***
		(0.018)	(0.013)
Share Coffee		0.071	-0.019
		(0.127)	(0.138)
Constant	-2.241***	-8.217***	-2.051***
	(0.090)	(1.028)	(0.525)
N	94507	94506	97604
Pseudo R-sq.	0.06	0.15	0.03

Note: This table shows coefficients of a probit model of enrollment in *Reflorestar* using the full sample, which includes areas outside the eligibility zones of the program, created in 2015. The dependent variable in Columns (1)-(2) is a binary variable for enrollment since 2019, when the priority areas were officially created in the *Reflorestar* program, estimated without controls (Column 1) and with controls (Column 2). Columns (1)-(2) use the full sample of CAR properties in Espírito Santo that are within the allowable property size of the program (0.5 to 60 ha; see Section 4). The dependent variable in Column (3) is a binary variable for enrollment before 2019, and serves as a placebo test. Standard errors are clustered at the municipality level (75 municipalities). Significance levels: * p<0.1, ** p<0.05, *** p<0.01.

Table 4 shows the probit regressions used for estimating the WTA based on the indicator for whether a property is in a priority area. The effects of these variables are shown both without additional covariates (column 1) and with controls (column 2). For the post-2019 sample, these variables are positive and significant, even with the full set of controls.

Table A.11 shows a similar analysis using a continuous measure of potential bonus payments. The results are qualitatively similar, but we use the binary measure as our preferred specification because it better matches the heuristic criteria for the WTA estimation as described below.

We also study how the properties' characteristics influence the intensive margin of enrollment, namely the size of the enrolled areas and the modalities. Consistent with our theoretical model (Section 2), the results in Table A.12 show that compliant landowners, who face lower opportunity costs of restoration, enroll larger areas into restoration (Column 1, with a coefficient of 0.038 ha per unit of net compliance). Columns (2)-(4) show that more compliant landowners enroll area more often in the passive restoration modality, and less in the active and productive modalities, which require more active management or continued production. This indicates that compliant landowners concentrate their larger commitments in the lowest-cost modality, consistent with the prediction that lower opportunity costs allow compliant landowners to expand the area they restore.

We note that in addition to the identification challenges for γ, there are several modeling choices required for the estimation of the WTA, in particular the underlying utility function specifications, for which we lack clear theoretical or empirical guidance. We therefore estimate and compare several potential models, with the range of WTA estimates derived shown in Table 5. Our preferred specification is a probit model with a binary variable for price variation and continuous controls (Column 1). We provide additional discussion of the criteria to choose this model in the A.6.

6.2 Results: Estimated WTA

We report the mean WTA to accept *Reflorestar* contracts evaluated at individual characteristics and key percentiles in Table 5. The mean estimate across the strategies ranges from 788 to 2,354 USD per property. Our preferred specification is given by Column 1, which yields the lowest number of "negative surplus" contracts. For this specification, the mean estimated WTA for all properties is 788 USD per property, with a median of 795 USD. Among enrolled properties, the mean estimated WTA is 702 USD, with a median of 688 USD. Given the average contract size of 4.72 ha for the full sample of 5,213 contracts, this estimate translates to a mean of 148 USD per hectare enrolled for our preferred specification; this value is similar to the limited set of estimates of PES WTA in the existing literature.[11]

In comparison, Alix-Garcia et al. (2019) estimated WTA for avoided deforestation of between 174-199 USD in Mexico from a survey-based referendum question; Gasparinetti et al. (2026) reports WTA ranges of 230-440 USD per ha to convert high value soybean farmland in Brazil. Using production from the MapSPAM spatial dataset (International Food Policy Research Institute (IFPRI) 2019), we calculate the three most common crops in 2010 and the average revenue per hectare for those crops using 2010 prices (FAO 2026, World Bank 2026). Coffee is the most-planted crop in the state, with an average value per hectare of 3,400 USD (this is a weighted average of arabica and robusta varieties). The next two most common crops are sugarcane and maize, with average revenues per ha of 1,500 and 420 USD, respectively. Given that producers are unlikely to enroll their most productive land in this program, the range of WTA estimates relative to these production possibilities seems reasonable.

An important caveat for this estimate is that some *Reflorestar* contracts enroll land exclusively in productive modalities (agroforestry, silvopastoral systems, or managed forest; see Table 1), which continue to generate revenue for the landowner rather than foregoing it entirely. For these contracts, the true opportunity cost of enrolling is likely much lower than for passive or active restoration, so including them in the pooled estimation may bias our estimated WTA downward. However, excluding these contracts entirely is not obviously correct either, since landowners still incur some costs of participation, such as compliance and monitoring requirements, and some production may still be foregone even under these modalities. We therefore retain these contracts in our preferred specification, which we use for the cost-benefit analysis in Section 7; this is a deliberately conservative choice, since a lower estimated WTA does not overstate the welfare costs of the program. Figure A.13 reports a robustness check that re-estimates the WTA excluding contracts enrolled only in productive modalities, and shows that the resulting distribution shifts toward higher values, consistent with this expected downward bias.

Table 5 also presents estimates of producer surplus for those who are actually enrolled in the program. This is calculated as the difference between their allocated payment and their individually estimated WTA. In all cases the mean and the median surplus are positive, and are a substantial fraction of the mean value of

[11] For the additionality exercise, we only consider contracts signed between 2013 and 2021 (there were zero enrollments in 2021). The average enrolled area in that sample is 4.98 ha as previously reported.

Table 5: Descriptive Statistics for WTA Estimation Models

	(1)	(2)	(3)	(4)	(5)
	Binary	Binary Flexible	Continuous	Continuous Flexible	Continuous Concave
Mean WTA	788.44	873.22	1882.46	2354.45	1072.18
Pct 25th WTA	672.7	749.26	1571.32	1988.06	883.68
Median WTA	795.11	891.14	1892.6	2403.86	1054.28
Pct 75th WTA	897.14	997.52	2170.52	2723.44	1209.52
Mean Surplus	3327.58	3275.96	2372.22	2035.51	3001.61
Median Surplus	2417.61	2373.42	1489	1220.83	2093.36
Share Neg Surplus	.07	.08	.25	.31	.13
Share Surplus $<$ -500	.02	.02	.16	.22	.05
Pseudo R2	.02	.03	.02	.03	0
N total	97605	97605	97605	97605	97605
N with surplus	5213	5213	5213	5213	5213

Note: This table shows descriptive statistics regarding our WTA estimation results. The sample includes all properties registered in the CAR in Espírito Santo that are between 0.5 and 60 hectares in size. Each column shows the summary statistics for the full sample and for the subsample of properties that ever enrolled in *Reflorestar*, according to five different ways of estimating WTA. The WTA estimates are obtained from different specifications of the probit model of enrollment, as described in Section 6. The WTA estimates are expressed in USD per property. Column 1 shows the results of a probit model where price variation is a binary variable that indicates that the property contains a priority area, scaled by 169 USD. Column 2 uses the same model, but allows controls to enter flexibly by interacting the continuous variables with quintiles of the same variables. Column 3 estimates a probit model where price variation is a continuous variable that captures the potential bonus payment for each property scaled by 20%. Column 4 uses the same model as Column 3, but allows controls to enter flexibly by interacting the continuous variables with quintiles of the same variables. Column 5 uses the same model as Column 3, where the price enters the utility function exponentiated by 0.9. The property-level control variables included in the models are net compliance, share of mandated protected areas, a dummy for no protected areas, number of water sources, share of coffee crops, log of mean potential coffee yield, log of mean altitude, log of mean slope, log of mean nightlights area, log of property area, and log of distance to the municipality seat. Municipality-level controls are the log of productivity (agricultural GDP divided by crop area) and log of municipal environmental expenditure.

the contract of around 4000 USD. For all approaches, there are some estimated negative surpluses. Although negative surpluses are indicative of non-rational behavior, they are expected to arise in probabilistic models of WTA.

7 Welfare, Cost-effectiveness and Re-targeting

Using the WTA estimates above as well as our estimates of program additionality, we can assess the cost-effectiveness and potential welfare implications of *Reflorestar*.

7.1 Welfare Framework

The welfare impact of the program can be expressed as the difference between the benefits of restoration and the costs of restoration, including the welfare cost of transfers:

$$W = \sum_{i=1}^{N} \left[B_i - WTA_i - \rho T_i \right], \tag{6}$$

The benefits of the program B_i are assumed to represent the ecosystem services provided by the restored forest while costs are represented by the WTA_i and the costs of raising revenue to fund the transfers (T_i weighted by the (ρ). When estimating benefits, we consider only the additional forest generated by the program. Our additionality analysis indicates that enrollment in *Reflorestar* adds between 0.04 and 0.09 ha of forest per hectare enrolled. Taking into account the total program enrollment between 2013 and 2021, this yields a lower bound of 673 hectares of new forest (using the more conservative 4% figure). If the average additionality rate is constant for the contracts enrolled after 2021, this would yield a total of 853 hectares of new forest.

We assume that the restored forest that is additional is permanent and regains its full ecosystem service values. Measuring benefits from forest restoration is highly uncertain. For this reason, we will mainly focus on comparisons of cost-effectiveness, but to benchmark how these estimates may compare to benefits, we provide approximations of the value of ecosystem services provided by the Atlantic Forest. Vieira et al. (2011) estimate that the mean aboveground carbon content per hectare in the hilly areas of the Atlantic Forest lies between 100 and 150 metric tons. Altomare et al. (2025) estimate a potential of 165 tons per hectare for aboveground biomass of secondary forest in the same biome. Following these estimates, we assume an aboveground carbon density of 150 tons per hectare. This is equivalent to 550 tons of CO2 per hectare, which can then be valued according to the social cost of carbon, which can vary from a conservative 30 USD (Nordhaus 2017) to higher values. In terms of the full set of ecosystem services from forestry, including biodiversity and water regulation benefits, estimates are scarcer, with one estimate for the Amazon Forest putting the yearly value of ecosystem services at 410 USD per hectare (Brouwer et al. 2022). Using a 5% discount rate and assuming these benefits are constant over time, this implies a net present value of 8,200 USD per hectare.

The primary costs of the program are the opportunity and participation costs of landowners, who may forego agricultural activities and undertake costly restoration activities. These are measured by the willingness to accept restoration contracts by the landowners, WTA_i.

In addition, although the transfers themselves are not true economic costs, they affect welfare to the extent that there are distortionary effects of taxation to raise the revenue to fund the program, and from administrative costs. We assume these are proportional to the size of the transfers, and subtract them for $\rho \geq 0$, considering a range of values. [12]

Also, we assume that landowners incur the WTA cost regardless of their additionality. This scenario is consistent with the landowners incurring costs, such as planting trees, monitoring, and maintenance, regardless of whether the restoration is successful. It is also consistent with our previous finding that the main source of non-additionality is the low yield of restoration activities, as opposed to adverse selection or moral hazard.

7.2 Welfare Costs

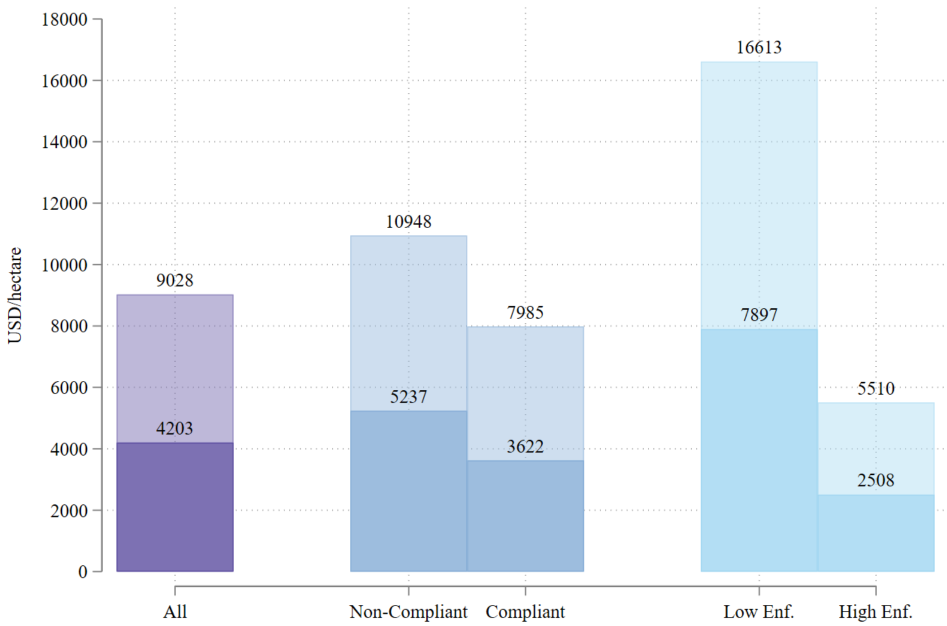
Given the uncertainty in benefit estimates, we first focus on calculating the welfare costs per hectare of additional forest and per sequestered metric tons of carbon dioxide. Figure 4 shows estimated welfare costs per hectare for $\rho = 20\%$. We calculate costs per hectare enrolled for all properties, as well as for the compliant vs. non-compliant properties and for those in municipalities above and below median enforcement levels. The WTA estimates are the sum of the individually evaluated WTAs in the sample. The calculations show higher WTA associated with properties that are non-compliant and those that are located in low enforcement municipalities.

These calculations allow us to compare costs to the minimum value of ecosystem service benefits per hectare that would be required for the program to have a positive welfare impact. Overall, we find that for

[12] To compute the welfare cost of the transfers, we need to estimate the cost of raising the revenue to fund the program. Bastani (2025) argues that most estimates suggest the additional welfare cost per unit of public funds to be between 0 and 50%, whereas Auriol & Warlters (2012) estimates that ρ is around 20% for African countries. In our scenarios, we compute the welfare gains of *Reflorestar* under the assumptions of $\rho = 0\%$, $\rho = 20\%$, and $\rho = 50\%$.

a transfer cost of $\rho = 20\%$, the average welfare cost for all properties is approximately 9,000 USD per hectare. Compliant and high enforcement properties, however, are less costly than the overall set, indicating the potential importance of targeting.

Figure 4: Costs of additional restoration



Note: This figure shows the welfare costs (WTA of enrolled properties plus 20% of payments) per additional hectare, and the financial cost (total payments) additional hectare of forest. The solid column shows the welfare costs as measured only by the WTA per additional hectare. The transparent column above shows the additional welfare costs due to transfer costs, evaluated at 20% of the total payment value. The different columns show the computations for the whole sample, and the heterogeneity based on compliance with the Forest Code and the enforcement level of the Forest Code. Compliance is defined at the property level, but enforcement intensity is defined at the municipality level. All values are in 2019 USD.

We also compute the financial or budgetary costs per hectare of additional CO2, which is the total payments to enrolled landowners, divided by the total additionality, divided by 555, the assumed per hectare yield of captured CO2 by restored forest described above. This is a useful measure for policymakers, as it captures the cost-effectiveness of the program in terms of financial costs per unit of additional CO2, while accounting for additionality. This implies a carbon cost of 43 USD across the enrolled properties on average. If we consider the true welfare costs of carbon sequestration, using our previously derived welfare costs and assuming a moderate marginal cost of public funds of 20%, our estimates imply that it is approximately 16 USD per ton of additional CO2.

Interestingly, this value is comparable in magnitude to recent calculations from Costa Rica's longstanding avoided deforestation program of approximately 71 USD per ton of avoided CO2 (Ordóñez et al. 2023). It also compares favorably to estimates of the social cost of carbon (Rennert et al. 2022) and ecosystem service benefits (Brouwer et al. 2022). In addition, it is in the low to mid range of modeled values of restoration costs from Busch et al. (2019), Busch & Engelmann (2017) and similar to the optimal carbon tax of 10 USD proposed by Araujo et al. (2026). However, some other studies have found much lower costs, such as Jayachandran et al. (2017) who estimate a cost of 115 USD per additional hectare of avoided deforestation and less than 1 USD per ton of CO2 in a small-scale PES for avoided deforestation program in Uganda. The differences in these estimates likely reflect differences in the opportunity costs of land and labor, the design of the programs, and the earlier time frame.

7.3 Targeting to High-additionality Areas

A significant question for policy is whether changes in program targeting could increase additionality, thus making the program more cost-effective and increasing the likelihood that it is net benefit positive. Targeting rules ought to condition eligibility on clear and observable characteristics that are positively correlated with additionality, thereby decreasing the cost per unit of additional forest, and negatively correlated with WTA, decreasing costs. Our impact analysis suggests greater additionality among properties that are compliant in the baseline year, and in municipalities with higher enforcement probability. We therefore examine two different targeting approaches that prioritize either the compliant or the high enforcement municipalities while holding the budget constant.

In the first case, the counterfactual analysis consists of simulating the enrollment and additionality of the program under a targeting rule that restricts eligibility to compliant landowners. We proceed as follows. First, we compute the total payments that are currently allocated to non-compliant landowners. We then reallocate these payments to compliant landowners, and compute the expected enrollment and additionality under this new targeting rule. This exercise relies on our estimates of enrollment and additionality by compliance status.[13] We conduct a parallel exercise re-allocating payments from municipalities with low enforcement to

[13]This counterfactual exercise entails a few important simplifications. First, we assume that the proportions of new enrolled compliant landowners in each compliance group would remain the same as observed empirically in the data. Implicitly, this assumes that the growth rate of contracts within each group would be the same as it has historically been. Second, we assume that the additionality of the new enrolled compliant landowners is the average estimated additionality for the ones that enrolled. This implicitly assumes that the WTA is a sufficient dimension to investigate the heterogeneity in treatment effects in this problem.

municipalities with high enforcement. [14]

Figure 5 shows estimates of the welfare costs per hectare under these re-targeting scenarios and various costs of transfers. Table A.13 shows the total additionality and total WTA under the current distribution of payments and under the two targeting scenarios. Both targeting approaches decrease the costs per hectare relative to the actual scenario. Under the current distribution of payments, enrolled properties in the low compliance group generate 267 ha of additional forest, while enrolled properties in the high compliance group generate 394 ha, with a total of 661 ha.[15] Reallocating the budget from non-compliant to compliant properties would yield 83 ha of additional forest from the new contracts, raising total additionality to approximately 744 ha, an increase in additionality of 12.5%. Total WTA would fall by around 5% (132,492 USD), reflecting the lower opportunity costs of compliant landowners. The WTA per hectare of additionality falls from 4.3 to 3.6 thousand USD, a reduction of 15%.

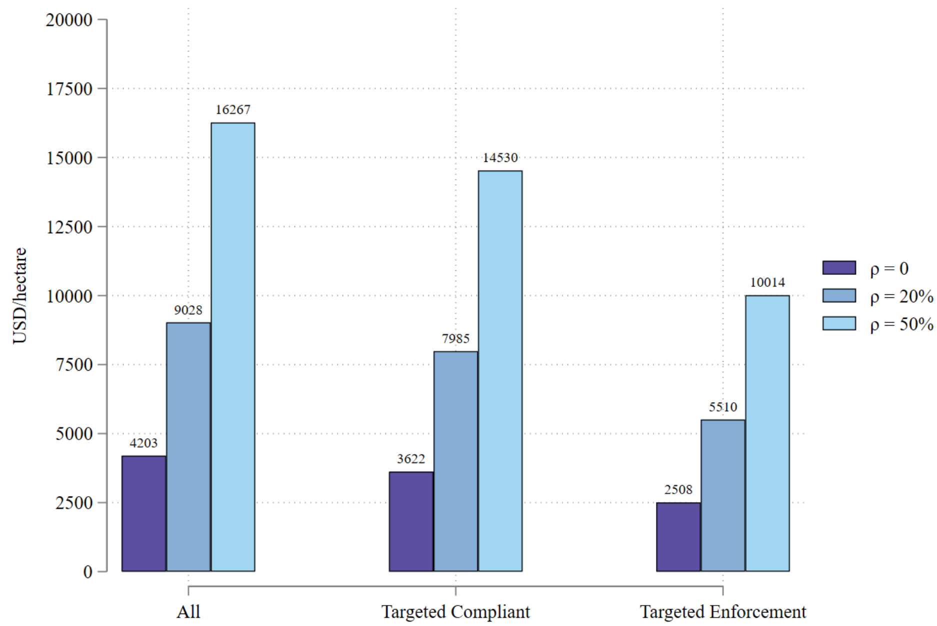
Under the current rules, enrolled properties in low-enforcement municipalities generate 187 ha of additional forest, and enrolled properties in high-enforcement municipalities generate 540 ha, with a total of 727 ha.[16] Reallocating the budget from low-enforcement to high-enforcement municipalities would yield 356 ha more additional forest, increasing total additionality to 1,083 ha; an increase of 49%. In turn, total WTA would fall by 4% (115,115 USD), since high-enforcement municipalities tend to have lower opportunity costs. The WTA per hectare under this targeting rule would fall from 3.9 to 2.5 thousand USD per hectare, a reduction of 36%. The implied welfare costs per hectare under both targeting rules and various costs of transfers are shown in Figure 5.

[14] This assumes that the total costs of enforcement do not change as a result of payments being re-targeted. However, it is possible that enforcement costs overall might change as a result of changes in program implementation, for example if there is a shifting of resources such as personnel to new and unfamiliar areas, particularly in the longer term.

[15] This value is remarkably close to the additionality of the main estimate, ignoring the heterogeneity in treatment effects, which is 673 ha. Small differences are expected because they stem from separate estimations.

[16] As with the compliance-based split above, this total is close to, though not identical to, the additionality of the main estimate ignoring heterogeneity in treatment effects (673 ha). The two splits are each estimated from separate subgroup regressions, so small differences relative to the pooled estimate, and between the two splits themselves, are expected; the values remain close in magnitude.

Figure 5: Welfare costs per hectare in targeted scenarios



Note: This figure shows the welfare cost per hectare of additional forest for the whole sample, counterfactual costs under two different targeting rules: one in which only compliant landowners are eligible, and another in which only landowners in high-enforcement municipalities are eligible. The counterfactual exercise was done by reallocating the budget of the excluded group into the new group according to the average contract cost, and assuming that the same ATT for the new contracts. The three bars per group represent the different scenarios to account for the financial cost of transfers: no financial costs ($\rho = 0$) or positive financial costs ($\rho = 20\%$ and $\rho = 50\%$). Compliance is defined at the property level, but enforcement intensity is defined at the municipality level. All values are in 2019 USD.

8 Conclusion

We study the design of a forest restoration PES operating alongside a command-and-control regulation, using Brazil's *Reflorestar* program as a large-scale empirical laboratory. We show that restoration PES can generate meaningful increases in forest cover in a regulated landscape, and that the command-and-control regulation reveals helpful information for targeting the PES.

Our results offer guidance on PES design. The program generates larger additionality among compliant landowners and in municipalities with stronger enforcement. Non-compliant landowners contribute less additional forest per hectare enrolled, reflecting the partial incentive already provided by enforcement. We document that *Reflorestar* induces additionality of 4-9 percent five years after enrollment, with effects growing over time. All modalities generate additional forest cover within the areas demarcated as protected under the Forest Code and other areas of properties. These magnitudes are comparable to those found for avoided deforestation PES programs, consistent with restoration being a viable and cost-competitive alternative strategy. At the same time, our findings highlight the limits of untargeted payment schemes. As documented for avoided deforestation programs, cost-effectiveness is reduced by the need to pay for more area enrolled than is truly additional.

Spatial variation in bonus payment zones also allows us to estimate WTA from this restoration program data. We use this revealed-preference distribution of restoration costs to assess how alternative policy designs affect both environmental outcomes and public expenditures. Our simulations show that modest changes in targeting, such as conditioning payments on enforcement intensity or baseline compliance, can substantially improve cost-effectiveness by shifting enrollment toward higher-additionality landowners.

These findings have broader implications for climate mitigation and biodiversity policy. As governments increasingly rely on private landowners to deliver ecosystem services, the interaction between incentives and regulation becomes central to policy design. Here we find that restoration PES programs are most effective when they are explicitly designed to complement enforcement, recognize heterogeneity in opportunity costs, and limit payments to inframarginal participants. Future work on forest restoration payments can continue to build understanding of who enrolls, why they enroll, and how incentives interact with existing institutions. As restoration becomes a central pillar of global climate strategies, evidence from large-scale programs such as *Reflorestar* will be crucial for designing policies that deliver durable environmental gains at reasonable cost.

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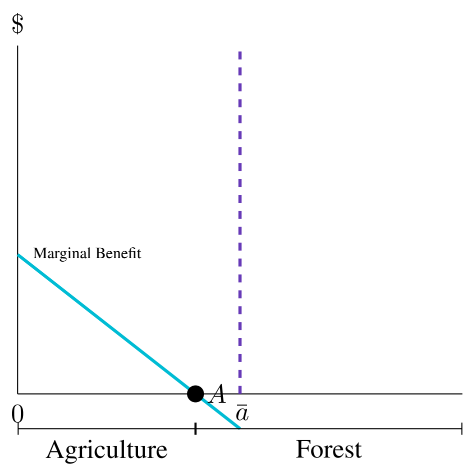
ONLINE APPENDIX

Payments for Ecosystem Services under Regulation: Evidence from Brazil's *Reflorestar* Program

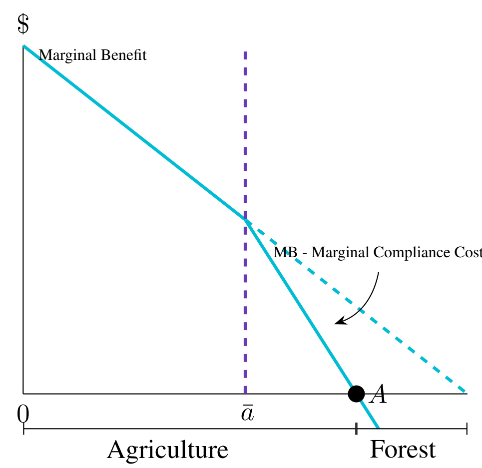
A.1 Theoretical Framework Figures

Figure A.1: Agriculture and forest choices

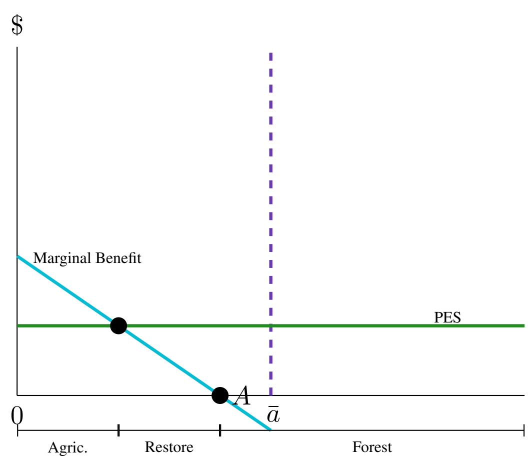
(a) Optimal agriculture level, low productivity



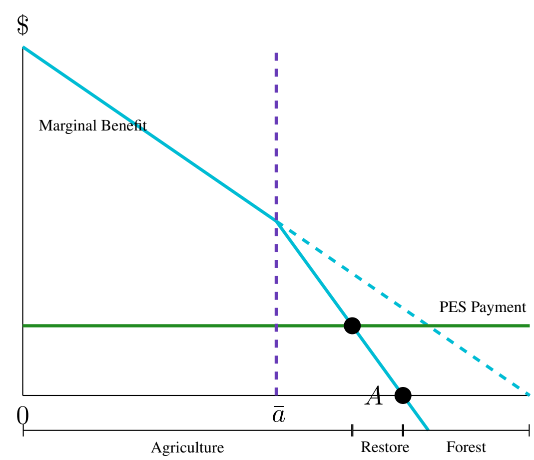
(b) Optimal agriculture level, high productivity



(c) Low productivity with PES



(d) High productivity with PES

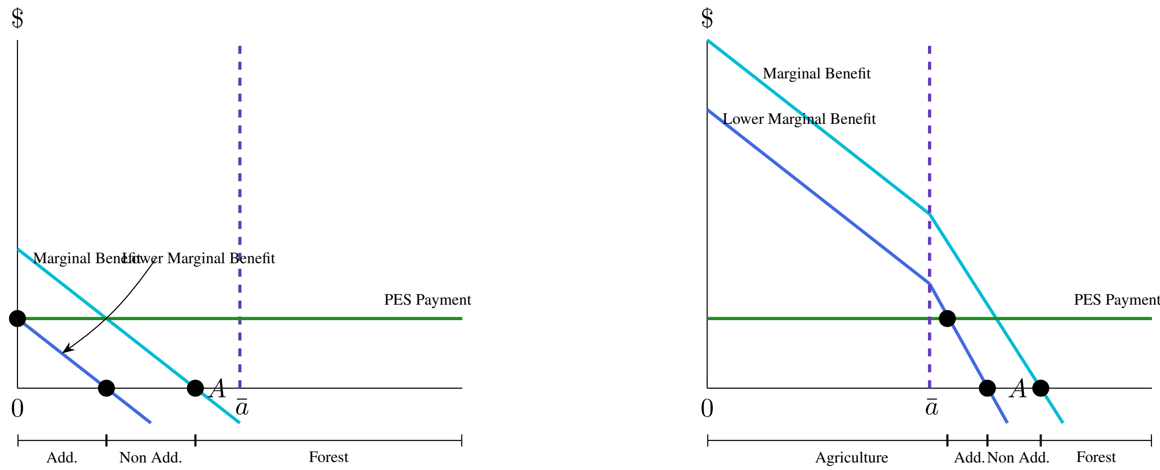


Note: This figure illustrates the optimal choice of agriculture vs. forest land share for two types of landowners. Both face a command-and-control policy that requires that a maximum of $\bar{a}$ of their property be developed. Panel (a) shows a low v landowner for whom the policy is not binding. Panel (b) shows a high v landowner, for whom it is optimal to comply partially with the policy. This figure illustrates the optimal agriculture and forest level for the two types of landowners, with the introduction of PES. Panel (c) shows a low v landowner for whom the policy is not originally binding. Panel (d) shows the decision of a landowner with high v, who decides to comply partially with the policy. In both cases, PES induces forest restoration.

Figure A.2: Agriculture and forest choices under PES + CAC with declining agricultural returns

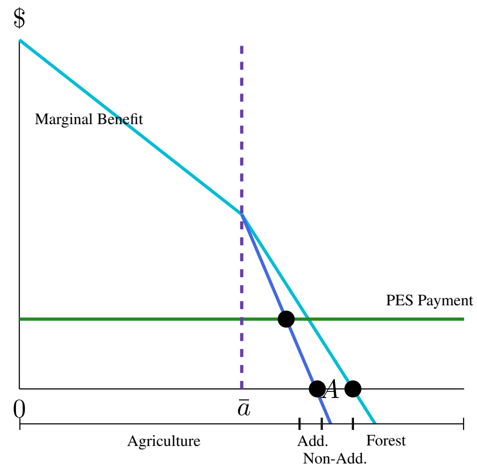
(a) Optimal agriculture level, low productivity

(b) Optimal agriculture level, high productivity



Note: This figure illustrates changes in the optimal agricultural level for two types of landowners, resulting from declining agricultural returns. Both facing a command-and-control policy that requires that a maximum of $\bar{a}$ of their property be developed and the option to receive PES payment for land in forest. Panel (a) shows a low v landowner for whom the policy is not originally binding. Panel (b) shows the decision of a landowner with high v, who originally decides to comply partially with the policy.

Figure A.3: Agriculture and forest choices under PES + CAC with increasing enforcement



Note: This figure illustrates changes in the optimal forest level for a landowner, who is facing a command-and-control policy that requires that a maximum of $\bar{a}$ of their property be developed and the option to receive PES payment for land in forest. This landowner has high v, and originally decides to comply partially with the policy. The figure shows the change in their optimal decision if the enforcement penalty increases.

A.2 Summary Statistics

Table A.1: *Reflorestar* participant survey

	Mean	SD	Min	Max	Count
Demographics					
Household size	3.72	2.24	0.00	32.00	1348
Has non-ag income	0.68	0.47	0.00	1.00	1392
Receive bolsa escola	0.04	0.20	0.00	1.00	939
Household works in ag	0.93	0.25	0.00	1.00	1392
Live on property	0.59	0.49	0.00	1.00	1390
Age of property manager	55.64	12.85	18.00	94.00	1363
Manager yrs experience in ag	41.44	18.22	0.00	91.00	1329
Manager no formal education	0.45	0.50	0.00	1.00	1392
Main crops produced					
Banana	0.15	0.35	0.00	1.00	1088
Coffee	0.67	0.47	0.00	1.00	1088
Eucalyptus	0.12	0.32	0.00	1.00	1088
Vegetables	0.09	0.29	0.00	1.00	1088
Beef cattle	0.14	0.35	0.00	1.00	1088
Dairy cattle	0.13	0.34	0.00	1.00	1088
Perceptions environmental change					
Less water, past 5 yrs	0.35	0.48	0.00	1.00	1356
Cause of water chg: less rain	0.69	0.46	0.00	1.00	855
Cause of water chg: deforestation	0.23	0.42	0.00	1.00	855
Reasons for enrolling in Reflorestar					
To comply with the law	0.16	0.37	0.00	1.00	1302
To improve water availability	0.59	0.49	0.00	1.00	1302
To improve environmental quality	0.62	0.49	0.00	1.00	1302
To receive payments	0.39	0.49	0.00	1.00	1302
Compliance with forest code					
Doesn’t know about Forest Code	0.39	0.49	0.00	1.00	1356
Perfectly compliant with RL	0.78	0.41	0.00	1.00	816
Perfectly compliant with APP	0.75	0.43	0.00	1.00	816

Note: This table presents summary statistics from a survey of *Reflorestar* participants conducted by the *Instituto Jones dos Santos Neves* in 2018. The survey covered enrolled landowners in Espírito Santo and collected information on sociodemographic characteristics, production activities, motivations for enrollment, and awareness of the Forest Code.

Table A.2: Summary statistics by enrollment year

	Never	Ever	2013	2014	2015	2016	2017	2018	2019	2020	2022	2023	2024
Property size (ha)	16.31	19.44	31.72	23.84	21.97	21.92	22.80	17.95	16.80	19.03	15.85	16.97	31.72
	(13.54)	(15.00)	(14.78)	(15.54)	(15.80)	(15.34)	(15.02)	(14.60)	(14.03)	(16.36)	(13.75)	(13.85)	(14.78)
Percent protected (RL/APP)	23.18	24.56	27.51	27.48	25.05	25.00	24.66	24.51	25.00	21.50	22.88	23.95	27.51
	(16.87)	(16.61)	(13.76)	(16.68)	(18.16)	(16.20)	(15.56)	(16.81)	(16.42)	(13.46)	(17.71)	(14.62)	(13.76)
% property forest	22.08	22.03	19.51	25.20	28.03	24.79	24.49	18.67	20.61	17.74	19.07	21.97	19.51
	(26.09)	(25.51)	(17.44)	(24.56)	(29.83)	(26.29)	(25.37)	(24.11)	(24.33)	(22.36)	(23.85)	(26.95)	(17.44)
% property pasture	44.55	47.76	49.91	46.82	47.22	47.82	40.84	53.08	45.22	43.79	52.66	51.10	49.91
	(34.12)	(34.51)	(30.18)	(34.33)	(38.17)	(35.53)	(31.12)	(34.25)	(33.15)	(30.27)	(35.61)	(36.27)	(30.18)
% property coffee	5.60	7.73	2.83	4.14	5.18	4.77	6.64	7.82	12.36	11.55	7.76	6.27	2.83
	(13.65)	(15.18)	(6.35)	(9.08)	(11.45)	(11.21)	(14.19)	(15.68)	(18.93)	(15.17)	(15.10)	(12.49)	(6.35)
Night lights	6.42	4.50	2.62	4.82	4.37	5.26	4.55	4.08	4.18	6.63	4.19	4.72	2.62
	(9.85)	(6.93)	(4.45)	(8.40)	(6.78)	(7.50)	(7.04)	(6.05)	(7.05)	(10.40)	(5.95)	(6.45)	(4.45)
Number water sources	0.36	0.66	0.69	0.56	0.63	0.58	0.59	0.70	0.80	0.90	0.58	0.54	0.69
	(0.74)	(1.05)	(0.93)	(0.84)	(1.05)	(0.91)	(0.94)	(1.07)	(1.17)	(1.12)	(1.12)	(1.02)	(0.93)
Average elevation (m)	416.05	542.20	454.81	478.63	449.78	412.37	437.68	562.87	727.34	703.86	570.68	622.35	454.81
	(327.90)	(318.29)	(281.05)	(329.63)	(339.72)	(317.14)	(316.41)	(301.93)	(219.71)	(238.61)	(304.62)	(311.64)	(281.05)
Coffee pot. yield	1161.55	1237.76	804.28	912.80	1196.35	1035.82	1009.43	1296.72	1469.61	1431.38	1287.51	1410.84	804.28
	(510.03)	(489.83)	(468.46)	(439.13)	(514.33)	(511.32)	(474.19)	(480.99)	(369.58)	(410.27)	(432.69)	(421.93)	(468.46)
Ha enrolled Reflorestar	.	4.77	8.11	7.04	5.85	6.02	5.57	4.15	3.74	4.51	3.91	3.86	8.11
	(.)	(4.43)	(6.28)	(6.50)	(4.39)	(5.56)	(5.07)	(3.81)	(3.17)	(5.26)	(3.53)	(3.43)	(6.28)
Ha passive restoration	.	2.50	3.12	3.21	3.52	3.24	3.21	2.02	1.69	2.16	1.91	1.94	3.12
	(.)	(3.38)	(3.73)	(4.21)	(3.90)	(3.72)	(3.51)	(3.06)	(2.75)	(3.90)	(2.97)	(3.06)	(3.73)
Ha active restoration	.	1.25	3.52	3.07	1.29	1.88	1.69	1.22	0.60	0.85	0.71	0.74	3.52
	(.)	(2.60)	(3.69)	(3.97)	(2.21)	(4.08)	(3.49)	(1.93)	(1.15)	(2.00)	(1.40)	(1.02)	(3.69)
Ha productive modalities	.	1.03	1.46	0.76	1.04	0.90	0.67	0.91	1.45	1.50	1.28	1.18	1.46
	(.)	(1.58)	(3.14)	(1.90)	(1.86)	(1.98)	(1.41)	(1.37)	(1.46)	(1.42)	(1.36)	(1.30)	(3.14)
Observations	92678	4804	35	100	526	624	772	1047	807	20	371	136	35

Note: This table shows the mean and standard deviation of variables measured at the property level. Each observation is a property enrolled in *Reflorestar* according to official statistics. The first column shows the means and standard deviations for properties never enrolled, and then second ever enrolled. The remaining columns are conditional on the year in which the property was enrolled in *Reflorestar*. We obtained information on number of water sources, Reserva Legal and APP from the CAR shapefiles, and land use data from MapBiomas. All areas are measured in hectares, and vegetation characteristics are for the year 2010.

A.3 Property Data Processing

We use administrative data on *Reflorestar* contracts and their recorded locations to match with boundaries of properties registered in the Rural Environmental Registry (CAR). We proceed by steps, given that the coordinates of the contracts do not always match with the coordinates of the properties, and that some contracts do not have coordinates.

In the first step, we assign contracts to the properties where their coordinates overlap, matching 76% of the contracts. (Note that we exclude possible matches if the area enrolled in the *Reflorestar* contract is 1 or more hectares greater than the area of the CAR polygon or if the area of the CAR polygon is more than 50 hectares greater than the enrolled area in *Reflorestar*.) Secondly, for contracts that did not overlap with any valid property, we create a buffer around the contract's coordinates of 5 times the enrolled area, and then find the best overlapping property in terms of area. This procedure allows us to assign an additional 11% of contracts to properties. For the remaining 13% of contracts, we create artificial polygons as circles around the coordinate indicated in the contract, where the circular buffer has the same area as the enrolled area.

A.4 Pre-matching: Supplemental Tables and Figures

Table A.3: Matched sample vs. unmatched sample

	Never enrolled (matched)	Enrolled	Norm. Diff.	Never enrolled (full)	Diff. in means
Any enrollment					
Outcomes 2024					
Ha forest	5.26	5.74	0.06	4.06	1.68
Ha pasture	7.37	7.26	-0.01	6.54	0.72
Ha mosaic	4.77	5.08	0.06	4.23	0.86
Ha coffee	1.81	1.84	0.01	1.18	0.66
Covariates					
Ln(Property area, ha)	2.63	2.63	-0.01	2.43	0.20
Net compliance, 2010	-2.24	-2.05	0.01	-1.51	-0.54
Ha forest, 2010	5.20	5.45	0.03	4.10	1.35
Ln(Coffee productivity)	7.03	7.01	-0.04	6.96	0.05
Ln(Elevation, m)	6.01	6.00	-0.00	5.59	0.41
Ln(Night lights, 2010)	1.07	1.03	-0.03	1.27	-0.24
Ln(Slope, degrees)	2.57	2.55	-0.03	2.41	0.14
Ln(km to municipality center)	2.28	2.27	-0.01	2.31	-0.03
Mun. ag GDP/area developed (R/ha), mean 2010–2024	2.11	2.17	0.04	2.46	-0.29
Mun. environmental expenditures (R), mean 2018–2023	2,270,896.47	2,237,634.76	-0.02	2,995,387.72	-757,752.94
No legal reserve (0/1)	0.10	0.12	0.07	0.10	0.02
Number water sources (#)	0.63	0.67	0.03	0.36	0.31
Mun. mean IDAF fine rate, mean 2018–2023	0.01	0.01	0.04	0.01	-0.00
Obs, 2010	7,829	3,925	11,754	92,392	96,317

Note: This table shows the means of outcome and matching covariates for properties with and without *Reflorestar* contracts, as well as the normalized differences between these variables for the matched sample. The same statistics for different contract types are found in Appendix Table A.4.

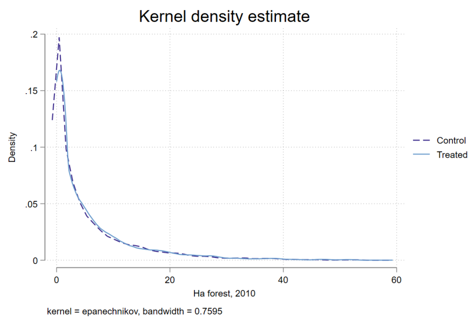
Table A.4: Matched samples

	Passive restoration			Active restoration			Productive		
	Never enrolled	Enrolled	ND	Never enrolled	Enrolled	ND	Never enrolled	Enrolled	ND
Ln(Property area, ha)	2.82	2.89	0.08	2.70	2.72	0.02	2.51	2.45	-0.06
Net compliance, 2010	3.19	4.37	0.05	-3.30	-3.19	0.01	-2.80	-2.70	0.00
Ha forest, 2010	7.87	8.89	0.11	5.20	5.56	0.04	4.68	4.57	-0.01
Ln(Coffee productivity)	7.06	7.04	-0.05	7.01	6.99	-0.04	7.13	7.11	-0.04
Ln(Elevation, m)	6.09	6.10	0.01	6.00	6.00	-0.00	6.13	6.11	-0.03
Ln(Night lights, 2010)	1.05	1.05	-0.00	1.04	1.01	-0.03	1.11	1.05	-0.05
Ln(Slope, degrees)	2.72	2.73	0.04	2.58	2.57	-0.01	2.60	2.56	-0.08
Ln(km to municipality center)	2.31	2.30	-0.01	2.29	2.29	-0.00	2.27	2.24	-0.04
Mun. ag GDP/area developed (R/ha), mean 2010–2024	2.20	2.27	0.04	2.06	2.12	0.04	2.14	2.21	0.05
Mun. environmental expenditures (R), mean 2018–2023	2,248,452.44	2,242,285.67	-0.00	2,213,763.86	2,177,932.65	-0.02	2,230,883.29	2,207,573.54	-0.01
No legal reserve (0/1)	0.05	0.05	-0.01	0.09	0.10	0.03	0.12	0.16	0.12
Number water sources (#)	0.70	0.74	0.04	0.68	0.73	0.04	0.66	0.68	0.01
Mun. mean IDAF fine rate, mean 2018–2023	0.01	0.01	0.03	0.01	0.01	0.03	0.01	0.01	0.05
Obs, 2010	4,502	2,088	6,590	6,319	3,114	9,433	4,407	2,009	6,416

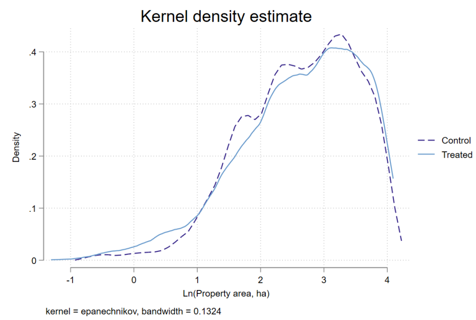
Note: This table shows the means of matching covariates for properties with and without *Reflorestar* contracts, as well as the normalized differences between these variables for the matched samples by contract type.

Figure A.4: Matching covariates in matched sample

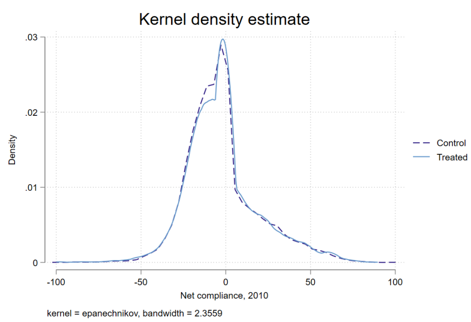
(a) Baseline forest



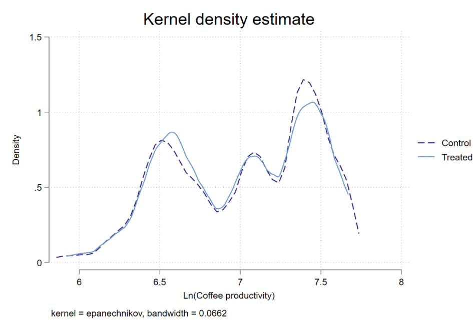
(b) Ln(Area CAR)



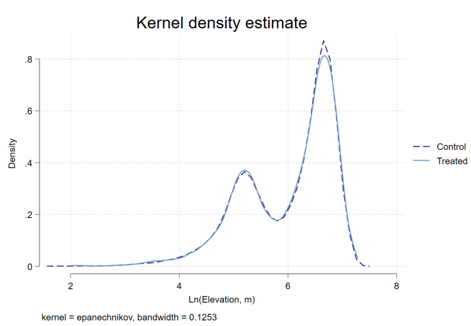
(c) Compliance



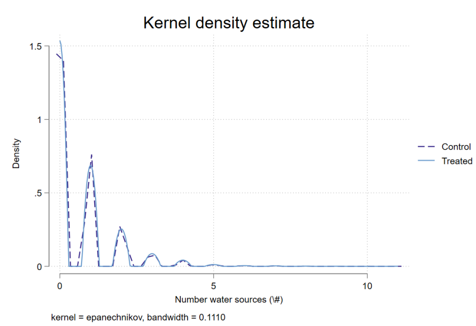
(d) Coffee



(e) Ln(Elevation)

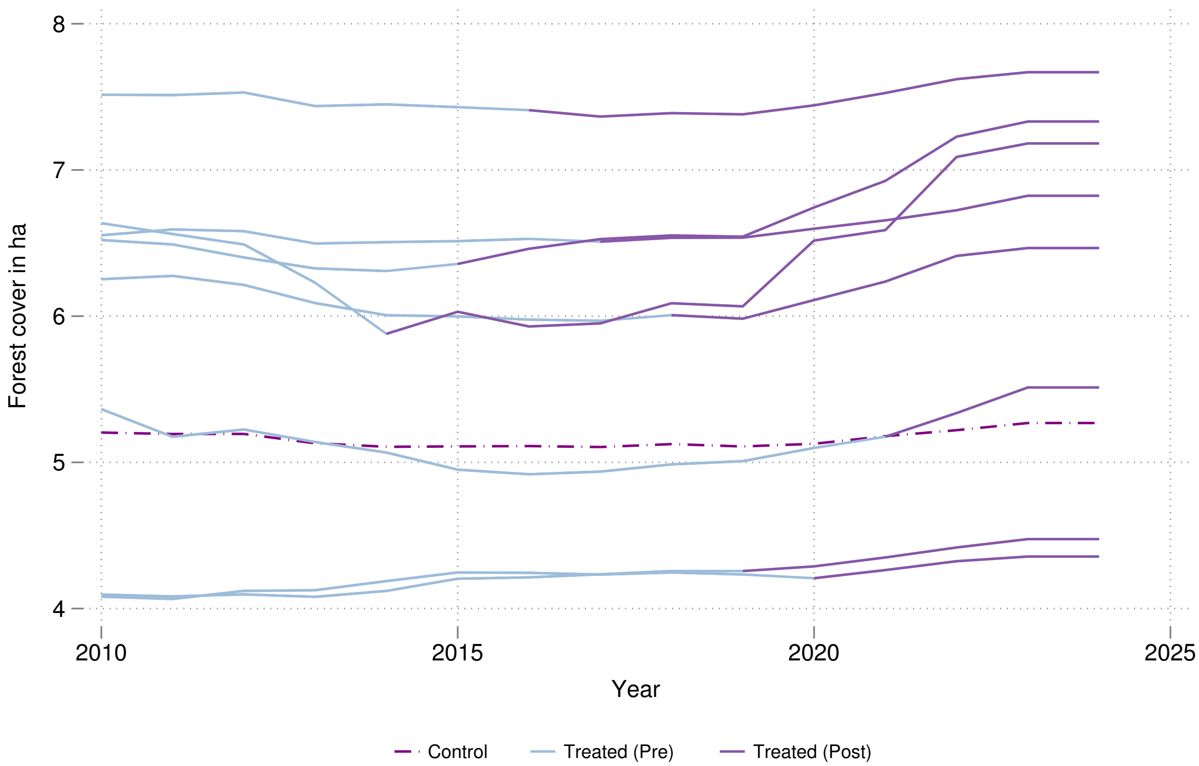


(f) Total water sources)



Note: Smoothed kernel density estimates for key matching covariates, separately for treated (enrolled) and control (never enrolled) properties in the unmatched sample.

Figure A.5: Forest cover trends in matched data



Note: This figure shows the average hectares forest cover across time for each cohort in the matched sample. The light color denotes periods in which there is no enrollment for a given cohort, while the darker purple shows when a given cohort enters treatment. The dashed line in the middle of the figure represents the trend for never-treated matched properties. Each line represents the average percent forest cover across time for a given cohort, including only cohorts used for analysis. The light color denotes periods in which there is no enrollment for a given cohort, while the darker purple shows when a given cohort enters treatment. Within cohorts, we see small to medium size increases in forest cover after treatment. Although different cohorts start with different average levels, the trends are mostly parallel with each other across time. The dashed line in the middle of the figure represents the trend for never-treated matched properties.

Table A.5: Main estimates of impacts on percent forest cover

	Type of contract			
	Any	Passive restoration	Active restoration	Productive
	(1)	(2)	(3)	(4)
TWFE – unmatched sample				
Enrolled (0/1)	1.278***	1.727***	1.389***	1.234***
	(0.180)	(0.226)	(0.184)	(0.213)
Observations	1444755	1417200	1432590	1416015
TWFE – matched sample				
Enrolled (0/1)	0.463***	0.798***	0.489***	0.316**
	(0.097)	(0.137)	(0.111)	(0.140)
Observations	176310	98850	141495	96240
CS DID – matched sample				
ATT	0.390***	0.563***	0.370***	0.362***
	(0.084)	(0.108)	(0.109)	(0.120)
Observations				
DID imputation – matched sample				
Treatment effect	0.426***	0.682***	0.436***	0.298**
	(0.106)	(0.130)	(0.127)	(0.143)
Observations	163878	92536	131805	89256

Note: Table shows the average treatment effect and the treatment effects by group using two-way fixed effects with and without matching, the estimator from Callaway & Sant'Anna (2021), and the estimator from Borusyak et al. (2024). All estimations include as controls ln(property area), an indicator for if there is no delimited protected zone, and percent area in baseline forest, with standard errors clustered at the level of the municipality (75 municipalities). The unit of analysis is the entire registered property under CAR. The outcome variable is the percent of this area in native vegetation in each year of the analysis. Properties are defined as having enrollment in a particular modality if they have any area in that modality.

Table A.6: Estimates for protected and unprotected areas of properties, area outcome

	Type of contract			
	Any	Passive restoration	Active restoration	Productive
	(1)	(2)	(3)	(4)
Panel A: Area forest outcome				
Protected area of property				
Treatment effect	0.025***	0.031**	0.029***	0.023***
	(0.009)	(0.015)	(0.010)	(0.007)
obs	176370	98835	141480	96240
Non-protected area of property				
Treatment effect	0.049***	0.088***	0.061***	0.028
	(0.015)	(0.022)	(0.018)	(0.018)
obs	176370	98835	141480	96240
Percent forest outcome				
Protected area of property				
Treatment effect	0.713***	0.591***	0.751***	0.749***
	(0.178)	(0.221)	(0.170)	(0.265)
obs	163155	96690	132195	86880
Non-protected area of property				
Treatment effect	0.359***	0.560***	0.330**	0.341***
	(0.104)	(0.130)	(0.134)	(0.131)
obs	175980	98505	141270	96060

Note: Table shows the average treatment effect and the treatment effects by group using the estimator from Callaway & Sant'Anna (2021). All estimations include as controls ln(property area), an indicator for if there is no delineated protected area in the property shapefile, and percent area in baseline forest, with standard errors clustered at the level of the municipality (75 municipalities). The unit of analysis is the entire registered property under CAR. In Panel A, the outcome variable is the hectares of this area in native vegetation in each year of the analysis. In Panel B, the outcome variable is the percent of this area in native vegetation in each year of the analysis. Properties are defined as having enrollment in a particular modality if they have any area in that modality.

Table A.7: Impact of *Reflorestar* on forest cover – robustness checks

	Type of modality			
	Any	Passive restoration	Active restoration	Productive
	(1)	(2)	(3)	(4)
Area forest, dropping artificial polygons				
ATT	0.070***	0.121***	0.089***	0.046*
	(0.023)	(0.034)	(0.028)	(0.026)
obs	169095	97005	136440	91500
Area forest, dropping discontinued contracts				
ATT	0.084***	0.122***	0.102***	0.058***
	(0.025)	(0.034)	(0.030)	(0.021)
obs	165270	94830	132735	88860
Winsorized area				
ATT	0.045***	0.070***	0.054***	0.030
	(0.016)	(0.023)	(0.020)	(0.020)
obs	176310	98850	141495	96240
Area forest plus mosaic				
ATT	0.193***	0.249***	0.230***	0.137**
	(0.042)	(0.042)	(0.049)	(0.062)
obs	176310	98850	141495	96240
Winsorized area – unprotected property				
ATT	0.022*	0.042**	0.026*	0.010
	(0.013)	(0.018)	(0.016)	(0.015)
obs	176310	98850	141495	96240
Winsorized area – protected property				
ATT	0.018**	0.022*	0.022***	0.015**
	(0.007)	(0.012)	(0.008)	(0.007)
obs	176310	98850	141495	96240

Note: Table shows the average treatment effect using the Callaway & Sant'Anna (2021) estimator with standard errors clustered at the level of the municipality (75 municipalities). The unit of analysis is the entire property as registered under the CAR. The outcome variable is the number of hectares of this property in forest for each year. Outcomes are winsorized at the 95th percentile to help reduce the influence of outliers. Properties are defined as having enrollment in a particular modality if they have any area in that modality.

Table A.8: Entire property, other land use types in hectares

	Type of contract			
	Any	Passive restoration	Active restoration	Productive
	(1)	(2)	(3)	(4)
Pasture				
ATT	-0.198***	-0.261***	-0.235***	-0.136**
	(0.043)	(0.045)	(0.051)	(0.060)
obs	176370	98835	141480	96240
Mosaic				
ATT	0.129***	0.143**	0.145***	0.086
	(0.045)	(0.056)	(0.054)	(0.058)
obs	176370	98835	141480	96240
Coffee				
ATT	-0.004	0.002	-0.000	-0.003
	(0.016)	(0.018)	(0.020)	(0.017)
obs	176370	98835	141480	96240

Note: Table shows the average treatment effect and the treatment effects by group using the Callaway & Sant'Anna (2021) estimator with standard errors clustered at the level of the municipality (75 municipalities). The unit of analysis is the entire property as registered under the CAR. Outcomes are the hectares of the property in each land use category (pasture, coffee, and mosaic).

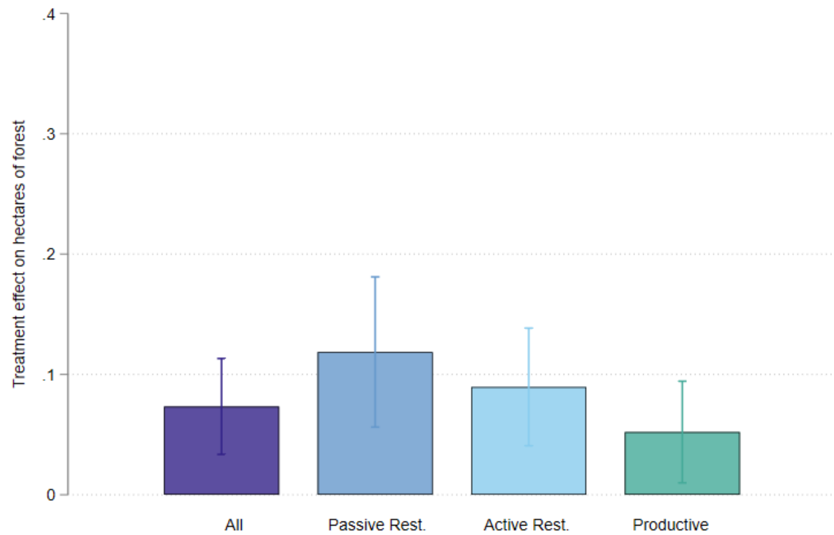
Table A.9: Impact of *Reflorestar* on area of forest cover – heterogeneity

	Type of modality			
	Any	Passive restoration	Active restoration	Productive
	(1)	(2)	(3)	(4)
Compliance				
Below median compliance	0.047*	0.091**	0.046	0.046*
	(0.027)	(0.042)	(0.030)	(0.024)
obs	88710	40650	74325	48750
Above median compliance	0.096***	0.135***	0.130***	0.054
	(0.026)	(0.035)	(0.033)	(0.034)
obs	87600	58200	67170	47490
Baseline forest				
No forest in baseline	0.040**	0.063	0.058**	0.030
	(0.019)	(0.043)	(0.024)	(0.023)
obs	49110	11010	38550	29370
>0 forest in baseline	0.080***	0.122***	0.096***	0.056*
	(0.026)	(0.033)	(0.032)	(0.029)
obs	127200	87840	102945	66870
Enforcement intensity				
Below median enforcement	0.039	0.092*	0.047	-0.002
	(0.029)	(0.048)	(0.035)	(0.034)
obs	88590	45870	72945	44730
Above median enforcement	0.118***	0.157***	0.147***	0.107***
	(0.026)	(0.038)	(0.034)	(0.025)
obs	87720	52980	68550	51510

Note: Table shows the heterogeneity of average treatment effects on hectares of forest cover using the Callaway & Sant'Anna (2021) estimator with standard errors clustered at the level of the municipality (75 municipalities). The unit of analysis is the entire property as registered under the CAR. Properties are split by whether the municipality's enforcement intensity is above or below median, by baseline compliance (net vegetation share minus conservation requirement), and by baseline percent forest. Properties are defined as having enrollment in a particular modality if they have any area in that modality.

A.5 Additionality: Supplemental Tables and Figures

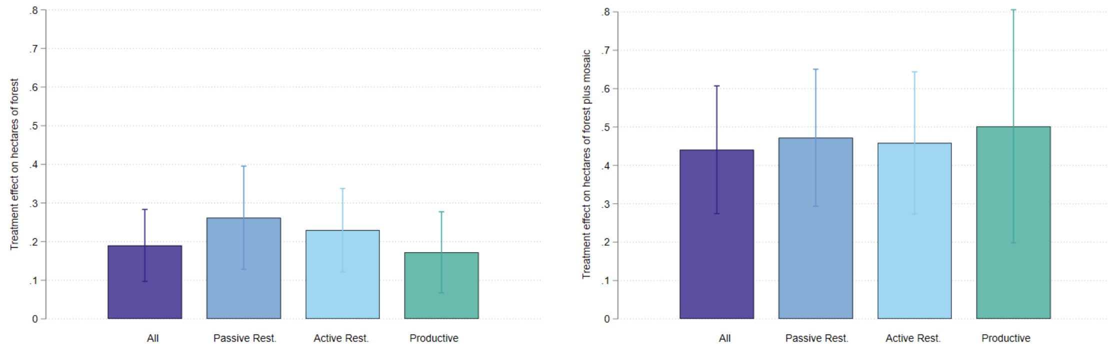
Figure A.6: Average treatment effects on ha of forest on full property years, average treatment effects



(a) Full property

Note: Figures show average treatment effects on hectares of forest cover across all cohorts and time periods estimated using the Callaway & Sant'Anna (2021) estimator. Coefficients come from Table 3 . Properties are defined as having enrollment in a particular modality if they have any area in that modality. The first bar in each graph gives estimates from regressions where the treatment is any enrollment in *Reflorestar*, and the other three give estimates of the impacts of enrollment from each modality subgroup.

Figure A.7: Average treatment effects on ha of forest on full property years 5-9, forest outcome versus forest plus mosaic outcome



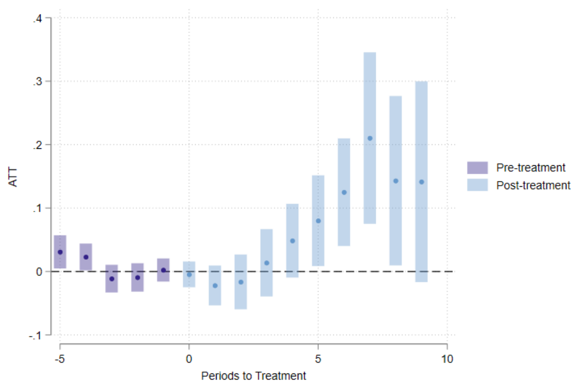
(a) Forest outcome

(b) Forest plus mosaic

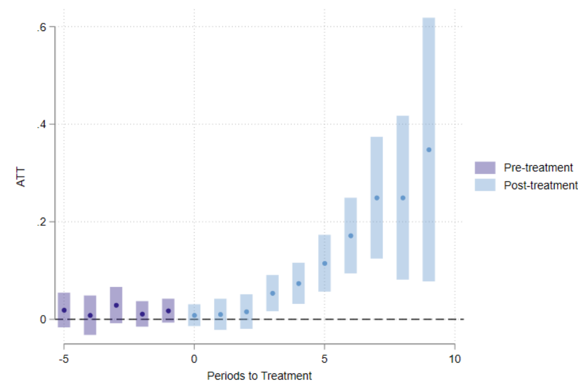
Note: Figures show average treatment effects on hectares of forest cover across years 5 through 9 estimated using the Callaway & Sant'Anna (2021) estimator. Panel (a) the effects using the outcome of hectares of forest and (b) adds forest and mosaic categories. Coefficients for (a) and (b) both come from Table 3. Properties are defined as having enrollment in a particular modality if they have any area in that modality. The first bar in each graph gives estimates from regressions where the treatment is any enrollment in *Reflorestar*, and the other three give estimates of the impacts of enrollment from each modality subgroup.

Figure A.8: Event studies by heterogeneity subgroup, matched sample using area as outcome

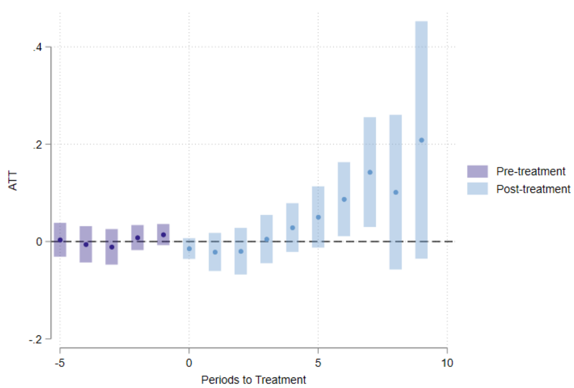
(a) Low compliance



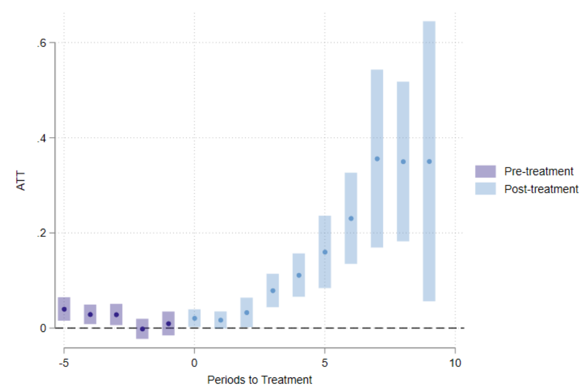
(b) High compliance



(c) Low enforcement

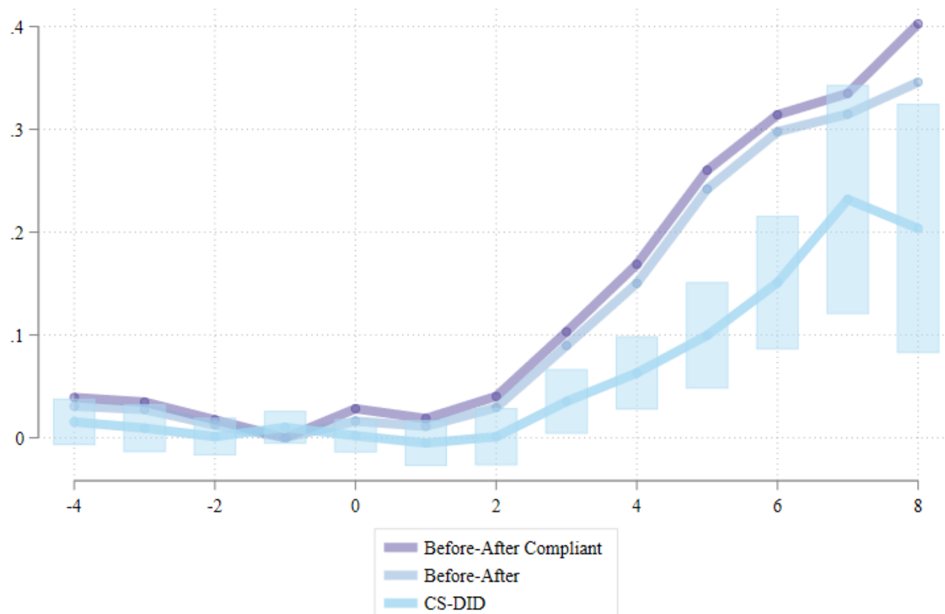


(d) High enforcement



Note: Event study analyses with the CSDID estimator from Callaway & Sant'Anna (2021). Unit of analysis is the entire property registered with the CAR. Covariates include baseline area forest, ln(property area), and ln(elevation). Standard errors are clustered by municipality (75 municipalities). The outcome variable is hectares of forest cover. Estimates are for properties with enrollment in any modality, for subsamples of above/below median compliance (a,b) or in above/below median level of enforcement (c,d).

Figure A.9: Disentangling Mechanisms for Low Additionality



Note: This figure plots three event-study estimates of the effect of *Reflorestar* enrollment on forest cover (in hectares), expressed relative to the enrollment year. The horizontal axis denotes years relative to the enrollment year, and the vertical axis denotes the estimated change in hectares of forest cover relative to $t-1$. The purple series (*Before-After Compliant*) is an estimate constructed from a regression of forest cover on relative-time dummies with property fixed effects but no calendar time fixed effects, using only enrolled properties in the sample, but excluding contracts that faced early terminations. Each coefficient captures the average observed change in forest cover within enrolled properties from $t-1$ to period t. The darker blue series (*Before-After*) does the same exercise, but includes all the enrolled contracts. We do not plot the confidence intervals to facilitate visualization. The light blue series (*CS-DID*) reports the event-study aggregation of the doubly robust staggered difference-in-differences estimator of Callaway & Sant'Anna (2021), estimated on the matched sample. We show the 95% confidence interval for the coefficients in this series. For the estimation of these series, we used forest data from 2010 to 2024, and included the contracts signed between 2013 and 2021 (there were zero enrollments in 2021, as noted in Section 4).

A.6 WTA Estimation: Supplemental Tables and Figures

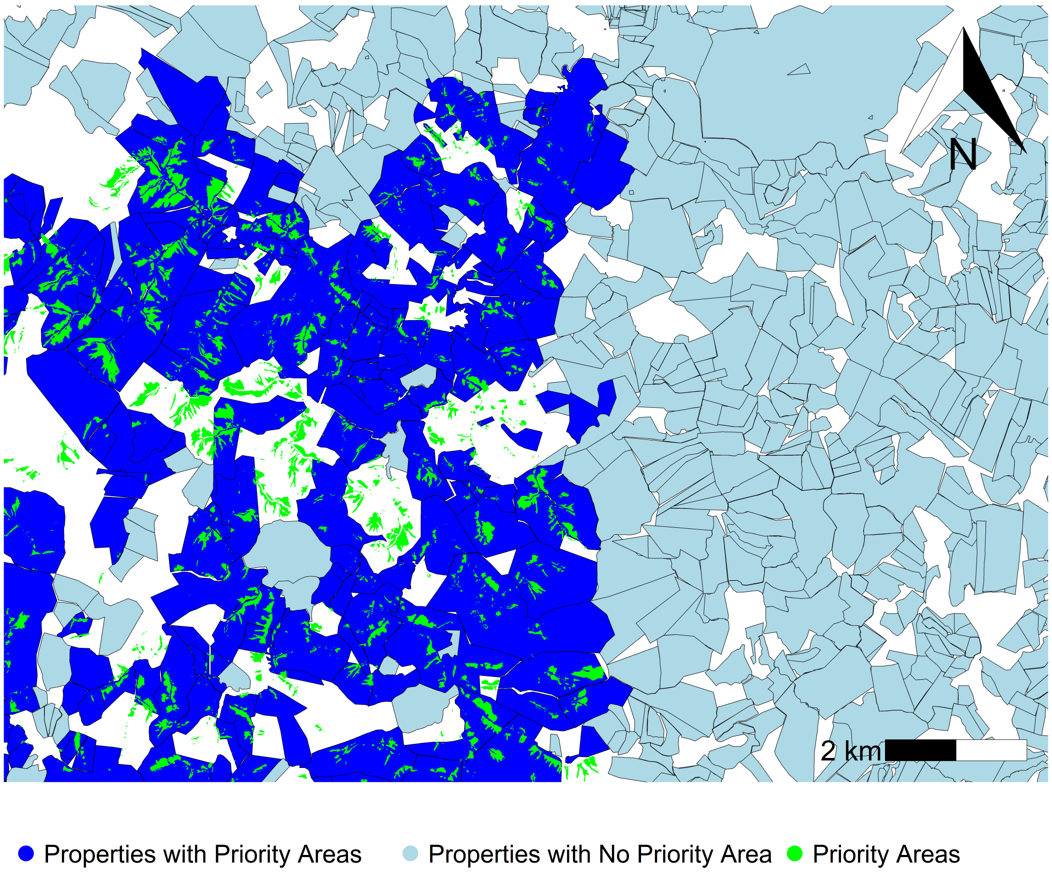


Figure A.10: Detail in the Municipality of Afonso Claudio

Note: This figure depicts properties with their boundaries as black, solid lines. This map is based on the information registered in the official CAR registry, in the municipality of Afonso Claudio, Espírito Santo. The green polygons are priority areas of the program *Reflorestar*, computed by the model InVEST. Light blue polygons are properties with no overlapping priority area. Dark blue properties are those with an overlapping priority area.

Table A.10: Correlation between potential bonus payments and contract value

Dependent variable: contract value (USD)						
	(1)	(2)	(3)	(4)	(5)	(6)
Post 2019 x 1(priority area)	183.37*	168.99*	189.90**			
	(97.18)	(91.48)	(83.46)			
Post 2019 x Potential bonus				0.20*	0.18*	0.21**
				(0.10)	(0.10)	(0.09)
Area Passive Rest.	445.62***	430.76***	446.56***	440.88***	430.95***	447.00***
	(16.75)	(10.77)	(11.50)	(8.75)	(10.66)	(11.39)
Area Active Rest.	817.44***	785.83***	907.89***	812.61***	784.68***	906.45***
	(74.88)	(12.06)	(14.45)	(11.22)	(12.03)	(14.42)
Area Productive Rest.	1278.40***	1241.33***	1353.96***	1278.54***	1241.13***	1353.51***
	(62.60)	(18.76)	(20.56)	(18.49)	(18.67)	(20.45)
Controls	No	Yes	Yes	No	Yes	Yes
Sample	All	All	Eligible	All	All	Eligible
N. Obs.	5213	5213	4128	5213	5213	4128
R2	0.69	0.70	0.74	0.69	0.70	0.74

Note: This table shows the correlation between the potential bonus payments and the value of the signed contract. The potential bonus payment is computed as the area of priority zones within the property multiplied by the maximum potential bonus payment per hectare. The control variables are property size, elevation, slope, distance to municipality center, nighttime lights, number of water sources, coffee productivity, agricultural GDP per farmed area at the municipality level, expenditures on environmental protection at the municipality level. Standard errors are clustered at the municipality level (75 municipalities). Significance levels: * $p<0.1$, ** $p<0.05$, *** $p<0.01$.

Table A.11: Correlates of enrollment and potential bonus (continuous measure) – Full Sample

	Post-2019 Contracts		Pre-2019 (Placebo)
	(1)	(2)	(3)
Potential bonus	0.345***	0.245***	-0.001
	(0.057)	(0.055)	(0.051)
Net compliance		-0.003***	-0.001
		(0.001)	(0.001)
Log(Coffee Potential Yield)		0.610***	-0.129
		(0.166)	(0.083)
Log(Altitude)		0.279***	0.179***
		(0.068)	(0.042)
Log(Nightlights 2010)		-0.099***	-0.039*
		(0.023)	(0.021)
Log(Slope)		0.027	-0.107*
		(0.086)	(0.057)
Log(Area)		0.001	0.146***
		(0.032)	(0.031)
Log(Distance Mun.)		-0.125***	-0.043
		(0.045)	(0.039)
Log(Productivity Mun.)		-0.328**	-0.018
		(0.136)	(0.109)
Log(Env. Expenses Mun.)		0.111	0.013
		(0.070)	(0.023)
No RL		0.490***	0.341***
		(0.091)	(0.066)
Water Sources		0.100***	0.109***
		(0.018)	(0.013)
Share Coffee		0.063	-0.022
		(0.125)	(0.138)
Constant	-2.064***	-8.469***	-2.131***
	(0.093)	(0.919)	(0.508)
1(priority area)			
N	94507	94506	97604
Pseudo R-sq.	0.02	0.13	0.03

Note: This table shows coefficients of a probit model of enrollment in *Reflorestar* using the full sample, which includes areas outside the eligibility zones of the program, created in 2015. This exercise is a robustness test for the preferred sample presented in the main text. The dependent variable in Columns (1)-(2) is a binary variable for enrollment since 2019, when the priority areas were officially created in the *Reflorestar* program, estimated without controls (Column 1) and with controls (Column 2). Columns (1)-(2) use the full sample of CAR properties in Espírito Santo that are within the allowable property size of the program (0.5 to 60 ha; see Section 4). The dependent variable in Column (3) is a binary variable for enrollment before 2019, and serves as a placebo test. Standard errors are clustered at the municipality level (75 municipalities). Significance levels: * p<0.1, ** p<0.05, *** p<0.01.

Table A.12: Correlates of enrolled area, by modality (intensive margin)

	Total (1)	Passive (2)	Active (3)	Productive (4)
1(priority area)	-1.047***	-6.852**	-2.373	9.225***
	(0.213)	(2.689)	(1.615)	(2.885)
Net compliance	0.038***	0.578***	-0.356***	-0.223***
	(0.004)	(0.032)	(0.033)	(0.038)
Log(Coffee Potential Yield)	0.247	-3.204	-17.272***	20.476***
	(0.371)	(3.595)	(3.170)	(3.246)
Log(Altitude)	-0.343**	-4.672***	1.482	3.191*
	(0.148)	(1.611)	(1.760)	(1.821)
Log(Nightlights 2010)	-0.117*	0.817	0.873	-1.690**
	(0.068)	(0.934)	(0.691)	(0.798)
Log(Slope)	0.701***	17.522***	-7.422***	-10.100***
	(0.143)	(1.808)	(2.368)	(2.230)
Log(Area)	2.289***	6.384***	2.187***	-8.570***
	(0.168)	(0.816)	(0.685)	(0.892)
Log(Distance Mun.)	0.135	4.378**	-0.126	-4.252***
	(0.145)	(1.803)	(1.533)	(1.518)
Log(Productivity Mun.)	0.451*	6.849**	-2.759	-4.090
	(0.242)	(2.686)	(2.093)	(2.831)
Log(Env. Expenses Mun.)	-0.055	1.003	-0.800	-0.203
	(0.093)	(1.175)	(0.736)	(1.461)
No RL	1.707***	-16.308***	1.155	15.152***
	(0.271)	(1.604)	(2.453)	(2.497)
Water Sources	0.009	-0.401	0.510	-0.109
	(0.082)	(0.566)	(0.439)	(0.502)
Share Coffee	-1.753***	-3.507	-3.237	6.744
	(0.434)	(4.219)	(4.876)	(4.693)
Constant	-2.285	10.084	163.896***	-73.980***
	(2.703)	(26.539)	(21.243)	(26.754)
N	5213	5213	5213	5213
Mean outcome	4.72	36.98	30.19	32.84
R-sq.	0.32	0.30	0.13	0.22

Note: This table shows coefficients from separate OLS regressions of hectares enrolled in *Reflorestar*, overall (Column 1) and the shares of the contract in each modality (Columns 2-4: passive, active, productive), on a binary variable of priority areas, the baseline net compliance with the Forest Code, and the covariates used in the enrollment probits (Table 4), restricting the sample to enrolled properties between 2013 and 2025. Standard errors are clustered at the municipality level (75 municipalities). Significance levels: * p<0.1, ** p<0.05, *** p<0.01.

WTA Estimation: Additional Details

We estimate and compare WTA using several models: i) probit model with a binary variable for price variation and continuous controls, ii) probit model with binary variable for price variation, and continuous controls interacted with quintile dummies of the same controls, iii) probit model with a continuous variable for price variation and continuous controls, iv) probit model with a continuous variable for price variation, and continuous controls interacted with quintile dummies of the same controls, and v) probit model with a continuous variable for price variation exponentiated to the power 0.9, and continuous controls. Models ii and iv allow for more flexible relationships between the controls and the enrollment decision, which may improve predictive performance. Model v allows for a concave relationship between price variation and enrollment, reflecting a declining marginal impact of payments on enrollment decisions.

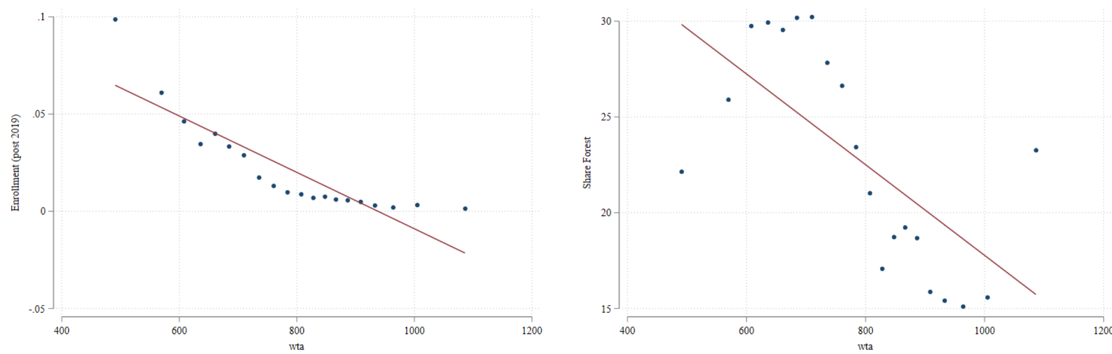
We propose three heuristic criteria to select our preferred model choice. The criteria are: (i) predictive performance, measured by the ability of estimated WTA to rationalize observed enrollment decisions; (ii) internal consistency, requiring that enrolled landowners receive payments exceeding their estimated WTA; and (iii) economic relevance, evaluated through the relationship between WTA and baseline land characteristics, such as forest cover and opportunity costs, which theory predicts should be negatively correlated with compensation requirements.

These criteria follow recommendations in the structural estimation literature, which have long recognized the problem of model selection in the absence of clear theoretical guidance. While the predictive power of the model is an intuitive first test widely accepted, the internal consistency and economic relevance criteria represent a harder standard, as they require that the estimated WTA is consistent with predictions of the underlying theoretical model (Reiss & Wolak 2007, Nevo & Whinston 2010).

Among these estimates, we prefer approach (i). The measure obtained from this method is consistent with our heuristic validation criteria, namely consistency with rational choices by enrolled forest owners, in the sense that they obtain positive surpluses from signing contracts with *Reflorestar* (Figure A.12b). Moreover, as shown in the Appendix, the WTA measure is negatively predictive of enrollment (Figure A.11a), and negatively predictive of baseline forest cover (Figure A.11b).

Appendix Figure A.12a shows the distribution of WTA evaluated using the characteristics of each landowner and the estimates from column (1) of the previous table. For enrolled properties, the mean WTA is USD 702, and for non-enrolled properties, the mean is USD 793. We test for statistical significance of the difference between these two subgroups by evaluating the WTA expression at the mean value of the covariates for enrolled and unenrolled properties and calculating standard errors using the delta method. The difference is significant at less than the 1 percent level. For the enrolled properties, the mean surplus is estimated at USD 3,328, with around 7.3% of properties showing negative surpluses, mostly between 0 and -500 USD.

Figure A.11: Binscatter showing correlation between WTA, share of baseline forest cover, and enrollment probability

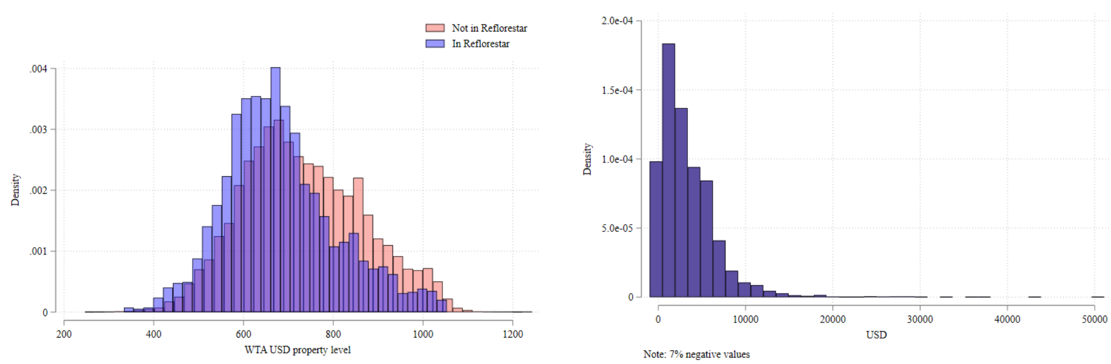


(a) Binscatter showing correlation between WTA and enrollment probability

(b) Binscatter showing correlation between WTA and share of baseline forest cover

Note: WTA is estimated using the re-parameterized probit model described in Section 6.

Figure A.12: WTA distribution for enrolled and non-enrolled properties and surplus



(a) All properties

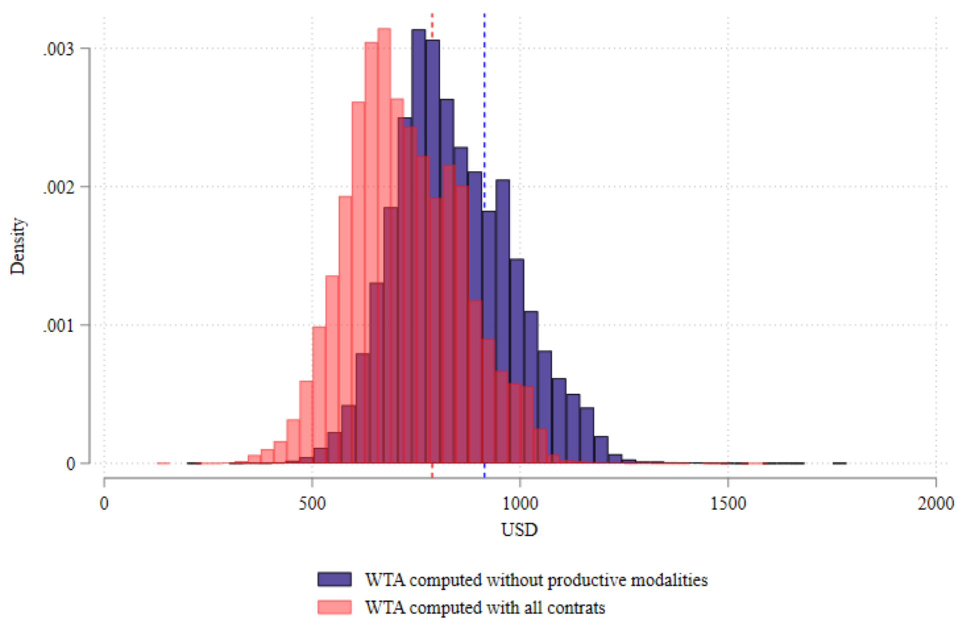
(b) Enrolled properties

Note: Panel (a) of this figure shows the distribution of estimated willingness to accept (WTA) payments for *Reflorestar* enrollment, for all properties the sample, conditional on enrollment status in the program. Panel (b) shows the distribution of surplus, defined as the contract value minus WTA, for the enrolled properties. WTA is estimated using a probit model with a binary variable for priority areas, as described in Section 6.

Robustness: Excluding Productive-Modality-Only Contracts

As discussed in Section 6, some contracts enroll land exclusively in productive modalities (agroforestry, silvopastoral systems, or managed forest), which continue to generate revenue for the landowner and may not represent a genuine restoration opportunity cost. Here we re-estimate our preferred WTA specification after dropping these contracts (those with zero hectares enrolled in passive or active restoration) from the set of enrolled properties, and compare the resulting distribution of WTA to our main estimate.

Figure A.13: WTA distribution, with and without productive-modality-only contracts



Note: This figure shows the distribution of estimated willingness to accept (WTA) payments for *Reflorestar* enrollment. The pink series shows the main-sample distribution, estimated using all enrolled contracts. The dark blue series shows the distribution re-estimated after dropping contracts enrolled exclusively in productive modalities (agroforestry, silvopastoral systems, or managed forest) from the set of enrolled properties. Dashed vertical lines denote the mean of each distribution. WTA is estimated using a probit model with a binary variable for priority areas, as described in Section 6.

A.7 Welfare Analysis: Supplemental Information and Results

Table A.13: Counterfactual exercises and additionality for the 2013-2021 sample

Additionality from actual program	
Additional forest in ha	673
Total WTA for enrolled properties	2,829,313
Total USD value of contracts	16,244,649
Shifting towards high compliance properties	
Additional forest from low compliance properties	267
Additional forest from high compliance properties	394
Total WTA of enrolled properties in low compliance properties	1,400,662
Total WTA of enrolled properties in high compliance properties	1,428,651
Additional forest from moving contracts to high compliance properties	83
Additional WTA from moving contracts to high compliance properties	-132,492
Shifting towards high enforcement municipalities	
Additional forest from low enforcement properties	187
Additional forest from high enforcement properties	540
Total WTA of enrolled properties in low enforcement properties	1,475,488
Total WTA of enrolled properties in high enforcement properties	1,353,826
Additional forest from moving contracts to high enforcement municipalities	356
Additional WTA from moving contracts to high enforcement municipalities	-115,115

Note: This table shows the additionality and WTA for the actual program and for two counterfactual targeting exercises. The first counterfactual reallocates all non-compliant contracts to compliant properties, keeping the proportion of contracts by group. The second counterfactual reallocates all contracts in low-enforcement municipalities to high-enforcement municipalities. The estimated additional forest cover and WTA from different targeting strategies are obtained from regressions of forest cover on the PES contract.