CAF - WORKING PAPER #2025/13
First version: November 10, 2025 (current)

How Do Climate Adaptation Policies Affect Deforestation? Evidence from a Large-Scale Water Policy

Daniel Da Mata[1] | **Rhamon Talles**[2]

[1] Associate Professor, Department of Economics, Sao Paulo School of Economics - FGV.
daniel.damata@fgv.br

[2] Phd Student, Department of Economics, Sao Paulo School of Economics - FGV.
rhamontalles@hotmail.com

This paper examines the effects of a climate adaptation policy on production and environmental outcomes in the context of Brazil's semiarid region, the country's poorest and most drought-prone region. The large-scale, low-cost water policy builds rainwater reservoirs designed to boost production and strengthen rural producers' resilience. Using a difference-in-differences approach and linking property-level administrative data to high-resolution satellite data, we find that cistern construction reallocates land toward higher-productivity uses. Results indicate an increase in cropland area by 7.6% and higher-quality pasture area by 14.5%, while lower-quality pasture area decreases by 3.2%. Forest cover increases by 1.1%, consistent with a land-saving effect driven by a reduction of lower-quality pasture. Effects hold across property sizes and are slightly larger in magnitude for small-sized properties. Our cost-benefit analysis reveals a positive aggregate return with each invested monetary unit generating 1.76 units of benefits, indicating that adaptation policies can also advance mitigation goals via forest preservation.

KEYWORDS
Climate Change Adaptation, Water Policy, Land Use, Deforestation, Environmental Conservation

CAF - DOCUMENTO DE TRABAJO #2025/13

Esta versión: 10 de noviembre de 2025

¿Cómo afectan las políticas de adaptación climática en la deforestación? Evidencia de una política hídrica a gran escala

Daniel Da Mata[1] | **Rhamon Talles**[2]

[1] Associate Professor, Department of Economics, Sao Paulo School of Economics - FGV.
`daniel.damata@fgv.br`

[2] Phd Student, Department of Economics, Sao Paulo School of Economics - FGV.
`rhamontalles@hotmail.com`

Este artículo examina los efectos de una política de adaptación climática en la producción y el medio ambiente de la región semiárida brasileña. La política hídrica de bajo costo construye reservorios de agua de lluvia para impulsar la producción y la resiliencia. Utilizando diferencias en diferencias con datos satelitales y a nivel de propiedad, observamos que las cisternas reasignan la tierra hacia usos de mayor productividad: las tierras de cultivo aumentan un 7.6 %, los pastos de calidad un 14.5 %, mientras que los pastos de baja calidad disminuyen un 3.2 %. La cobertura forestal crece un 1.1 %, lo que sugiere efectos de ahorro de tierras. Los resultados se mantienen en todos los tamaños de propiedad, con efectos ligeramente mayores en las propiedades pequeñas. El análisis costo-beneficio muestra retornos positivos (cada unidad monetaria genera 1.76 unidades de beneficios), lo que indica que las políticas de adaptación pueden impulsar la mitigación mediante la preservación forestal.

KEYWORDS

Adaptación al cambio climático, Política hídrica, Uso del suelo, Deforestación, Conservación ambiental

---

1 | INTRODUCTION

The implications of climate change are at the forefront of current policy debates. Projections indicate more frequent and intense extreme events, disproportionately impacting vulnerable populations and widening social inequality (Dell et al., 2014). In response, governments worldwide have developed climate adaptation policies to neutralize or minimize the adverse effects of climate change. While adaptation policies aim to increase well-being by altering behavioral responses, these policies may have unintended consequences. In particular, less is known about how adaptation policies may (unintentionally) affect environmental outcomes by generating rebound effects. Although climate adaptation policies have been conceptualized as distinct from mitigation efforts, adaptation can generate unintended effects and affect greenhouse gas emissions. For instance, interventions designed to increase energy resilience may inadvertently raise overall energy consumption and emissions, while measures supporting resilience in agriculture may end up promoting cropland expansion and result in the loss of forest cover.[1]

How do climate adaptation policies affect production and environmental outcomes? We examine this question in the context of a large-scale, low-cost water policy in Brazil that aims to boost production and strengthen the resilience of rural producers. More specifically, we evaluate the effects of the Cistern Program on the economic and environmental impacts of rural establishments. The Cistern Program—also known as the Second Water Cistern Program—seeks to provide water access to small rural producers by installing water tanks (cisterns) with sufficient capacity to store water during the rainy season for use in the dry season.[2] The program focuses on low-income rural producers in the Brazilian semiarid region—the country's poorest and most drought-prone region—who do not have access to networked water infrastructure. The semiarid is characterized by dry spells averaging eight months and rains concentrated in short periods. The program aims to provide adaptation to the semiarid climate, support crop farming and livestock, and improve the well-being of the rural population (Santana and Rahal, 2020).

Water-capture techniques improve water availability, an essential factor for crop cultivation and livestock raising, especially in arid and semiarid regions (Grum et al., 2016). By relaxing water constraints, the intervention can increase agricultural output and producers may respond along different margins: they may choose to expand production intensively or extensively, including by deforesting. Agricultural producers may also increase production by recovering degraded land, causing no deforestation. Given these competing channels, the net effect of the cistern construction on deforestation is ultimately an empirical question. While there is evidence of the need for water policies to adapt to drought periods (Aragón et al., 2021; Burney and Naylor, 2012; Dyer and Shapiro, 2023; Sekhri, 2014; Hornbeck and Keskin, 2014; Blakeslee et al., 2020), adaptation policies may unintentionally contribute to increased greenhouse gas (GHG) emissions. This unintended consequence can occur when policies inadvertently encourage deforestation or intensify agricultural practices with a high carbon footprint.

Our context is suitable for at least three reasons. First, the Brazilian semiarid region is one of the most populated arid areas in the world, and extreme climate events have intensified in recent decades (Lima and Magalhaes, 2018). The semiarid is considered one of the six

---

[1] Maladaptation is defined as actions that can lead to increased risk of adverse climate-related outcomes (including increased greenhouse gas emissions), increased or shifted vulnerability to climate change, and more inequitable outcomes (IPCC, 2022). Maladaptation can arise from adaptation policies that fail to consider the full range of interactions arising from planned actions.

[2] The Cistern Program has three components: (i) smaller household cisterns for drinking water (the First Water program, see Da Mata et al., 2023), (ii) a larger, production-oriented cisterns, the Second Water program (the focus of this paper), and (iii) larger cisterns built in schools.

biomes most vulnerable to climate change worldwide Seddon et al. (2016). Occupying 12% of the national territory, the Brazilian semiarid region has about 28 million inhabitants and is populated by small rural landowners dedicated to agriculture (Da Mata and Resende, 2020). For most of these families, the primary water sources for use in agricultural production are intermittent rivers and small community reservoirs—which fill during the rainy season.[3] Second, the policy under analysis presents low-cost and replicable characteristics, making the study of its impacts relevant to other contexts. In arid regions, most precipitation concentrates in a few periods, and most is wasted due to inadequate storage. Installing water collection mechanisms is a low-cost, easy-to-implement, and environmentally sound way to recover much of this water, thereby reducing water stress on main crops (Yosef and Asmamaw, 2015). Third, there is substantial interest in the policy arena about how climate policies influence behavioral responses (Carleton et al., 2024).

To identify the effects of the water policy, we leverage variation in the timing of cistern construction. More precisely, we use a staggered difference-in-differences approach, using the program rollout to compare the outcomes of rural establishments that received treatment early to those that received it later. In the analysis, we combine property-level administrative data with satellite data. The farm-level data allow us to track natural forest cover, pasture area, pasture quality, and crop farming areas before and after the cistern's construction. The production area and environmental outcomes of deforestation and soil degradation are thus constructed using satellite images, which minimizes concerns about measurement errors of self-reported income and production data (commonly found in work scopes similar to ours).

We see three main results in our paper. First, the construction of cisterns led to significant shifts in land-use patterns, with a reduction in lower-productivity activities and an increase in higher-productivity land uses. Crop farming increased by 7.6% and higher-quality pasture increased substantially by 14.5% (while lower-quality pasture decreased by 3.17%). Second, the reallocation of land-use patterns was land-saving. Agriculture (which encompasses both crop farming and pasture) declined by 0.80%, indicating that reductions in lower-quality pasture use offset the substantial growth in higher-quality pasture and crop farming. Third, the intervention generates environmental benefits: forest cover increases by 1.1%, consistent with the intervention being land-saving and the producers reducing their reliance on extensive pasture systems. Taken together, these findings suggest that access to low-cost water infrastructure enabled landowners to re-optimize their land use by transitioning from extensive, lower-quality agricultural practices to more intensive and productive farming systems. Importantly, our findings indicate that the program did not trigger maladaptive responses; on the contrary, the policy is land-sparing and produces environmental co-benefits.

Furthermore, we analyze the policy's heterogeneous effects to shed light on whether the program is relevant for producers or only for a subgroup of farms. The heterogeneity analysis reveals that the effects are present across small and large properties, with slightly larger magnitudes for small-sized properties. In particular, small-sized properties showed a greater relative increase in the proportion of forest cover. We provide evidence of parallel pre-trends for up to five years before treatment and show that our estimates are robust to different robustness checks, including the use of alternative estimators and control groups.

Our cost-benefit analysis reveals that the Cistern Program generates net benefits. We estimate the program's climate benefits by converting observed forest preservation into

---

[3] Water scarcity continues to be the main challenge for this region, where 96% of families in rural areas have inadequate or semi-adequate water and sanitation systems. Water access continues to be a global challenge. In 2022, approximately 1.8 billion people worldwide still relied on distant sources for water collection (Fund and Organization, 2024).

avoided greenhouse gas emissions. Over the period 2012-2018, the program generated an aggregate net benefit with a Marginal Value of Public Funds (MVPF) of 1.76, indicating that each monetary unit spent by the government generated 1.76 units in benefits. To contextualize this result, we compare our MVPF estimates (which accrue from emission reductions) to those of other climate policies analyzed by Hahn et al., 2024, and find that the climate adaptation program can achieve returns comparable to those of mitigation policies that explicitly aim to reduce emissions.

An important takeaway from our findings is that climate adaptation policies can reinforce mitigation effects and generate positive feedback between climate action efforts. In addition, the cost-benefit analysis suggests that, in the event of a market to compensate producers for mitigation results, adaptation policies might be financed by revenues from lower greenhouse gas emissions. Furthermore, the results on forest cover are consistent with ongoing discussions regarding the need for poverty alleviation policies to consider their environmental impacts. Even though cisterns yield positive returns and environmental co-benefits, cisterns' adoption remains limited due to credit constraints and the absence of carbon markets, generating underinvestment in profitable technologies (Jack et al., 2023).

This paper connects to several strands of literature. First, we connect to the literature on the effects of climate adaptation policies (see Kahn, 2016, Fankhauser, 2017 and Carleton et al., 2024, for literature reviews). The literature in economics has also studied private adaptation responses to climate variation (e.g., Barreca et al., 2016; Burke and Emerick, 2016). This paper contributes by providing new empirical facts about how adaptation policies affect environmental outcomes. In particular, we add by examining the relationship between adaptation and mitigation efforts, assessing whether adaptation policies are interfering with mitigation efforts. Recently, Abajian et al. (2025) study how (private) adaptive energy consumption affects emissions; we add by studying the effects of adaptation policies on land-use adaptive behavior and deforestation.

This study also relates to the literature on the determinants of deforestation (e.g., Rocha et al., 2015; Harding et al., 2021; Berman et al., 2023; Cust et al., 2023; Da Mata and Dotta, 2024). To the best of our knowledge, no article has examined how an adaptation policy affects deforestation and whether it is land-saving, highlighting the interaction between adaptation and mitigation efforts. In this literature, there is a long-standing debate in environmental economics about the Borlaug Hypothesis and Jevons Paradox (Jayachandran, 2022). The Borlaug Hypothesis states that shifts in production efficiency would be land-sparing, whereas the Jevons Paradox points out that technological advancements would promote an outward shift (rebound effect) in land demand with a tendency to expand the production area. We contribute by showing that a low-cost water policy did not promote a rebound effect and decreased agricultural areas—so our results favor the Borlaug Hypothesis.

We also contribute to the literature on the impacts of water interventions. One strand of the literature focuses on the impacts on production and income. Duflo and Pande (2007) show that districts downstream of dams benefit from improved irrigation through increased agricultural production and poverty reduction. Embaye et al. (2020) show that water capture technologies in Ethiopia positively influenced agricultural income. Another strand studies how water policies can positively affect health outcomes (e.g., Jalan and Ravallion, 2003; Gamper-Rabindran et al., 2010; Rocha and Soares, 2015; Da Mata et al., 2023; Devoto et al., 2012; Dupas et al., 2023; Kremer et al., 2011). In particular, we are closely related to three studies investigating the effects of cisterns programs: Da Mata et al. (2023) and Barreto et al. (2025) evaluate the smaller-sized cisterns for domestic consumption and show substantial improvements in economic and health outcomes, while Casagrande et al. (2024) studies the effects of cisterns for production using self-reported income data. We add by studying deforestation and land-use changes. Despite the role of water supply in beneficiaries' income and health, much less is known about the interaction between water policies and environmental outcomes. This is relevant because water policies aim to neutralize adverse climate effects but may affect deforestation and other outcomes, interfering with mitigation efforts.

The remainder of this paper is organized as follows. Section 2 provides an overview, contextualizing the Brazilian semiarid region and the Cistern Program. Section 3 presents the data. Section 4 discusses our empirical strategy. Section 5 presents the main results with robustness exercises. Finally, Section 6 concludes.

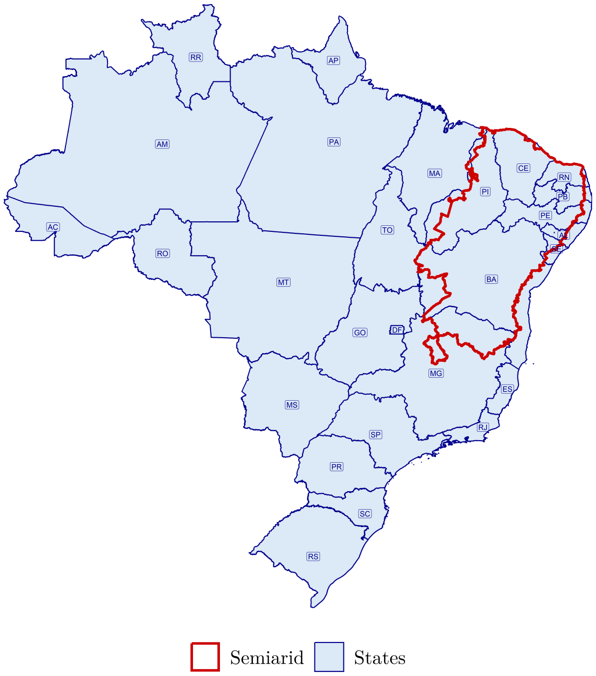
2 | BACKGROUND

2.1 | Semiarid

The Brazilian semiarid is the country's poorest and most drought-prone region. It has the world's largest population living in arid areas with a tropical climate, with around 28 million inhabitants—approximately 12% of the Brazilian population. This region is marked by irregular rainfall, low soil capacity to retain water, and recurrent droughts. The semiarid is characterized by dry spells averaging eight months and rains concentrated in short periods. The area has social indicators, such as health and education, that are lower than those of other regions of Brazil (Da Mata and Resende, 2020), and concentrates the highest proportion of rural poverty in Latin America. The semiarid region is considered one of the six biomes most vulnerable to climate change globally (Seddon et al., 2016). Figure 1 shows the location of the semiarid in the Brazilian territory.

The region is predominantly inhabited by small rural landowners who are heavily dependent on rainfall for their agricultural practices. For most families, the primary water source consists of intermittent streams and community dams at the foot of the hills, which fill during the rainy season. Water scarcity represents a central vulnerability factor (Bobonis et al., 2022), and families often cope with water scarcity through measures such as rationing their use, depleting their savings to buy water, or temporarily or permanently migrating (Da Mata and Resende, 2020). Between 2011 and 2017, the average annual rainfall was approximately 700 mm, equivalent to about half of the average recorded in the rest of the country.

FIGURE 1 Semiarid and Brazilian States



Notes: This figure delimits the extension of the Brazilian semiarid region (in red) in comparison to the limits of the Brazilian states (in blue).

Historically, the region has experienced severe droughts that have caused significant migration flows, famine, and mortality. Between 1825 and 1983, it is estimated that more than 3 million people died as a direct consequence of droughts (Villa, 2000). In addition to low water reliability, the region presents high evapotranspiration and limited water retention, characterized by predominantly shallow and rocky soils. Groundwater wells do not satisfactorily meet local demands, as the extracted water often has a high salinity content (Cirilo, 2008). Approximately 66% of homes lack access to networked water infrastructure (Brazil, 2024).

2.2 | Cistern Program

The Cistern Program is a policy of the Brazilian government to promote the economic inclusion of families in vulnerable situations, focusing on the country's semiarid region. In 2011, the government expanded the rainwater-harvesting program, initially focused on drinking water, to include larger cisterns with a capacity of up to 52 thousand liters to support agricultural production and raise small animals. Rain is collected from a paved apron or runoff channel into a tank designed for food production and livestock. The cistern capacity is not designed for whole-property irrigation, but only for specific areas of the rural property.

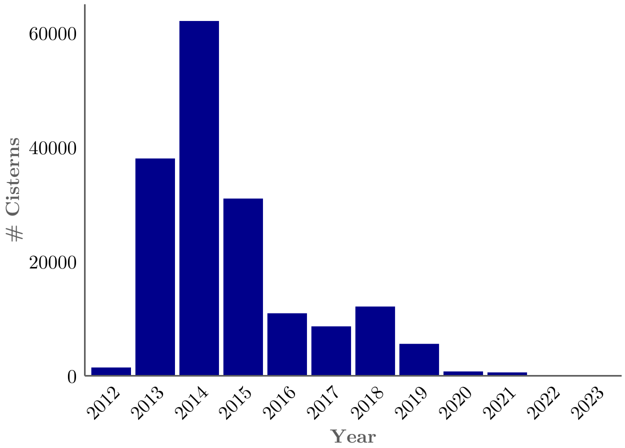
This new initiative, known as the Second Water Cistern Program, seeks to increase water availability for small and micro farmers, strengthening the resilience of low-income families in the face of adverse climate events. In addition to providing the collection infrastructure, the program offers training in water management techniques and distributes production materials, such as seeds, seedlings, and tools. It also prioritizes the inclusion of women in domestic production, giving priority to families headed by women, thus aiming to reduce income inequalities and encourage female participation in family decisions. By expanding access to water in low-income rural areas, the program has significantly impacted economic and health dimensions (Santana and Rahal, 2020; Da Mata et al., 2023).

The allocation mechanism combines federal guidelines with local implementation. Beneficiaries must meet four mandatory requirements: (i) registration in Cadastro Único, an administrative record maintained by Brazil's Federal Government to manage social programs; (ii) monthly per capita income below half the value of the national monthly minimum wage; (iii) rural residence in the semiarid region without adequate water access; and (iv) possession of the program's smaller consumption cistern (AP1MC, 2025; Brazil, 2023). Selection criteria prioritize as follows: extreme poverty families receive first priority, followed by Bolsa Família beneficiaries (Brazil's main conditional cash transfer program), then female-headed households, families with children aged 0-6 years, families with school-age children, households with disabled members, and elderly-headed households (ASA Brasil, 2025). Indigenous people and traditional communities receive priority across all categories (ASA Brasil, 2025). A committee composed of a minimum of three civil society representatives and local government officials validates eligibility and operationalizes selection (Brazil, 2023).

Beyond meeting socioeconomic criteria, properties must have the following characteristics: terrain with a maximum 5% slope, soil depth reaching a minimum of 1.8 meters without rock layers, sufficient space for an 8-meter diameter excavation plus a 200-square-meter concrete catchment area, and being located at least 10-15 meters from contamination sources (Brazil, 2023). Cistern's planning to actual construction lasts 3-5 months, including all phases, such as the committee's articulation, family registration, mandatory training courses (48 hours of training to guarantee proper cistern usage), and construction (which lasts 15-20 days, see ASA Brasil, 2025; AP1MC, 2025).

Between 2012 and 2023, approximately 171,300 small rural properties benefited from cisterns for agricultural production. Figure 2 shows the evolution of the number of properties that received production cisterns. The program reached its highest number of cisterns built in 2014, with more than 60,000 installations, with a significant decrease from 2016 onwards and nearly ceased after 2020. Appendix Figure A.2 shows typical cisterns distributed through the Cistern Program.

FIGURE 2 Number of Cisterns (2012-2023)



Notes: This figure shows the number of cisterns constructed by the Cistern Program (2012–2023).

2.3 | Water Availability, Land Use, and Environmental Outcomes

This section discusses how water infrastructure interventions may affect land use patterns and environmental outcomes in water-scarce rural areas, linking water availability to agricultural intensification and land allocation decisions.

In semiarid regions, water scarcity represents a relevant constraint on agricultural productivity. Limited water availability restricts farmers' ability to maintain productive activities year-round, forcing them to rely on extensive land use practices with lower input intensity. When water becomes more reliably available through infrastructure interventions, producers can shift toward more water-intensive and productive land uses.

The provision of water infrastructure—such as rainwater harvesting cisterns—may trigger changes in land allocation through several pathways. First, improved water access enables producers to maintain activities that require more consistent water availability, such as irrigated cropping or maintaining higher-quality pastures. In our context, cisterns are not for full-farm irrigation so that irrigation systems using cisterns' water only target specific areas of the rural property. Second, the ability to store water reduces seasonal variability in production, allowing farmers to allocate land use (of irrigated cropping or higher-quality pastures) throughout the year rather than concentrating activities in the rainy season. Third, and related to the previous point, water availability may enable investments in land quality improvements that were previously infeasible due to water constraints.

In our context, cisterns have limited storage capacity, and they cannot provide water for irrigating the entire rural property. Instead, they enable targeted intensification in specific areas. As a result, producers concentrate production on smaller, more intensively managed plots while allowing other areas to recover or transition to different uses. The key question is whether this intensification leads to land-sparring effects or promotes expansion into areas with forest cover, representing maladaptation.

The net effect of water infrastructure on land allocation depends on how producers respond along intensive versus extensive margins. Under a land-saving scenario, improved water access increases productivity on existing agricultural areas, potentially reducing the total land required for production. In this case, producers may convert low-productivity extensive pastures to higher-quality intensive pastures or cropland, while allowing degraded areas to regenerate and recover. Such transitions result in a decrease in total agricultural area and an increase in forest cover. Alternatively, reduced water constraints could lower the costs of bringing new land into production, leading to agricultural expansion. In this scenario, if water availability were the binding constraint preventing the cultivation of forested areas, the intervention might be associated with deforestation. Productivity improvements then lead to increased resource use rather than conservation, representing a rebound effect. In sum, the environmental consequences of water infrastructure depend on which adjustment pathways dominate.

A particularly relevant dimension in our context involves shifts in pasture quality. Semiarid regions worldwide typically feature extensive low-quality pastures with low carrying capacity and high land requirements per animal. Reliable water access enables management practices that improve pasture quality—such as rotational grazing, species improvement, and vegetation recovery—resulting in increased productivity per unit area. Consequently, the transition from extensive low-quality to intensive high-quality pastures substantially alters land allocation patterns and environmental outcomes.

3 | DATA

Our analysis period covers 11 years, from 2008 to 2018, and the spatial unit of analysis is the rural property. We work with several datasets to build a panel dataset at the property-year level.

CAR rural property dataset. The Rural Environmental Registry (“Cadastro Ambiental Rural" – CAR) is an administrative registry, mandatory for all rural properties, whose purpose is to generate property-level environmental information (e.g., regarding the status of permanent preservation areas, legal reserve areas, and forests and remnants of native vegetation). Legally established by the Federal Law n. 12,651 in 2012 (a legislation known as the “Forest Code") and implemented through Normative Instruction 2/2014 of the Ministry of the Environment, the CAR consists of a strategic database for controlling, monitoring, and combating deforestation and environmental and economic planning. The CAR dataset provides property-level information such as property area size, geographic limits, and the municipality and state to which they belong.

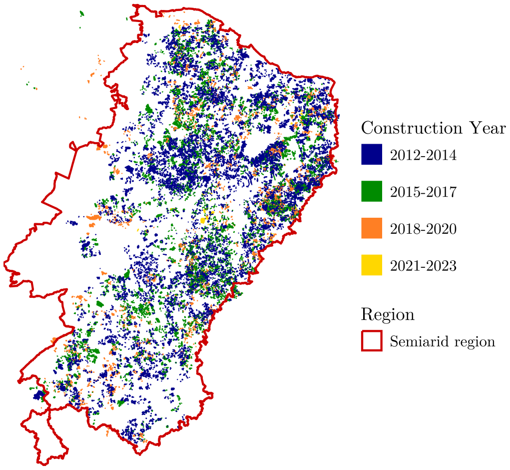
Cisterns program registry. The Cisterns registry provides data for 177,764 cisterns built in properties located in the Brazilian semiarid region. The database contains information on the latitude and longitude of the cisterns, the municipality and state, the type of technology used in the construction, and the start and end dates of the cistern’s construction. We carry out several steps to verify the registry’s data quality. First, we validated the geographic coordinates to verify that they were correctly associated with the indicated municipalities. After this procedure, 6,435 observations were excluded, resulting in a database of 171,329 cisterns. We then merge the cisterns to rural properties with the CAR dataset. This procedure allows us to identify the properties treated throughout our analysis period and creates four distinct scenarios: (i) cistern not linked to any property (46,948 cisterns); (ii) cistern linked to a single property (66,410 tanks); (iii) cistern linked to more than one property; and (iv) more than one cistern linked to the same property (57,971 cisterns in (iii) and (iv)).

Based on these scenarios, we define the criteria for constructing the analysis samples. Scenario (ii) was considered more appropriate for the main database, as a single cistern linked to each property, ensuring direct identification of the treatment and the year of the cistern’s construction. In turn, scenarios (iii) and (iv) present analytical limitations. In scenario (iii), the association of a cistern with several properties generates uncertainty about which properties were effectively treated, increasing the possibility of including untreated properties in the treatment group (Type I Error); in scenario (iv), although one knows the treatment status of each property, the presence of multiple cisterns prevented the precise determination of the year of construction, limiting the exact identification of the initial moment of treatment. Scenarios (ii), (iii), and (iv) are exemplified in Figure A.1. Given these limitations, the main sample was defined from the 63,802 properties linked to a single cistern, without duplication — case (ii).

Figure 3 depicts the spatial distribution of the main analysis sample. We allocate the cisterns from scenarios (iii) and (iv) to alternative samples to use in robustness exercises. The first alternative sample, containing 71,005 properties, considered the selection of duplicate cisterns (i.e., formed by cases (ii) and (iv)). The second, with 76,064 properties, incorporated properties formed by cases (ii) and (iii). Finally, the third alternative sample, with 85,241 properties, incorporated cisterns and properties in cases (ii), (iii), and (iv). In addition, the robustness analysis performs an analysis constructing buffers around each cistern to use the entire cistern sample.

Land-use datasets. We leverage satellite data from the MapBiomas dataset, which captures land use across properties in Brazil. MapBiomas processes high-resolution images (30-meter by 30-meter pixels) from the Landsat 8 satellite to create detailed land cover data. Specifically, we focus on the areas designated for natural forests, crop farming, and pasture land used for cattle-raising activities at the property-year level. This high-quality data collection spans our entire analysis period, providing a comprehensive view of land-use and environmental outcomes. We also use data on pasture quality from the Image Processing and Geoprocessing Laboratory of the Federal University of Goiás. Using vegetation indices obtained by remote sensing, Brazilian pastures were classified into three levels of degradation (Low, Medium, and High) for all the years of our analysis period. In this paper, we denote the medium and high degradation as "lower-quality" pasture, while the low degradation area is classified as "higher-quality" pasture.

FIGURE 3 Treated properties and Semiarid



Notes: This figure displays all properties in the main base with cisterns constructed between 2012 and 2023. The internal boundaries are the Brazilian semiarid.

4 | EMPIRICAL STRATEGY

In our context, rural properties receive cisterns at different times in a staggered rollout, after which the policy's effects persist. Since the treatment is irreversible and staggered, we use the estimator of Callaway and Sant'Anna (2021). Each property is part of a group G, whose value represents the initial year the property begins to benefit from the water resource for agricultural production.

Each property presents a vector of potential outcomes (e.g., forest cover, pasture area, and crop area) that varies depending on the year the cistern was installed and the calendar year. We denote $Y_t(0)$ as the potential outcome for a year t if the property did not receive the cistern during the analysis period and $Y_t(g)$ as the potential outcome in year t if the cistern was constructed in year $g \in \{2, \dots, T\}$.

Following Callaway and Sant'Anna (2021), the average group-time treatment effect is defined, which captures the average treatment effect in year t for properties in group g:

$$ATT(g,t) = \mathbb{E}\left[Y_t(g) - Y_t(0) \mid G = g\right]$$

for any $(g,t) \in \{2, \dots, T\} \times \{1, \dots, T\}$. This average group-time effect is aggregated into two main target parameters.

First, we examine the heterogeneity that arises from the duration of exposure to the treatment. We define $e = t - g$ as the time since the cistern was implemented. We calculate the average treatment effects for each period interval after adoption across all treated properties. We formally define the following:

$$\theta_{es}(e) := \sum_{g \in \{2,\dots,T\}} \mathbf{1}\{g + e \leqslant T\} \cdot \mathbb{P}\left[G = g \mid G + e \leqslant T\right] \cdot ATT\left(g, g + e\right) \tag{1}$$

for each $e \in \{0, \dots, T-2\}$. This parameter represents the average effect measured years after the cistern installation on the observed properties (“length of exposure").

Next, an aggregate parameter summarizes the group’s average treatment effects over time, as follows:

$$\theta := \sum_{g \in \{2,\dots,T\}} \left(\frac{1}{T - g + 1} \cdot \sum_{t=g}^{T} ATT(g,t) \right) \cdot \mathbb{P}\left[G = g \mid G \leqslant T\right] \tag{2}$$

This parameter captures the average treatment effect considering all properties that received cistern installation.

For identification, in addition to the assumptions of irreversibility and overlap, two main conditions are assumed: the absence of anticipation and unconditional parallel trends for the comparison group of not-yet-treated units. The “absence of anticipation" condition establishes that, before treatment, the potential outcomes of the properties that will receive the cistern are the same as those of the properties that have not yet been treated. This condition is plausible in our context since the families selected for the program are generally informed only a few months in advance, not having enough time to anticipate the effects of the additional water resources. Besides, the expansion of production (such as the increase in pasture and crop areas) depends on the effective presence of these water resources. The absence of anticipation condition implies that, in year t, the decisions of the properties reflect the resources available in that year.

The “unconditional parallel trends for a not-yet-treated group" condition assumes that, in the absence of treatment, the average outcomes of the farms that began receiving the cistern in year g and those that were not-yet-treated in year t would have followed parallel trajectories.

To estimate the parameters in Equations 1 and 2, the doubly robust estimator described in Callaway and Sant’Anna (2021) is used. This estimator integrates outcome regression and inverse probability weighting methods, so it requires modeling both the outcome expectation and the propensity score. However, the consistency of the estimator requires the correct specification of only one of these models. This estimator, therefore, presents greater robustness against specification errors compared to other traditional estimation methods. Standard errors are clustered at the farm level for inference. Confidence intervals for the target parameters are constructed using the multiplier bootstrap procedure, as detailed in Callaway and Sant’Anna (2021). In our analysis, we estimate placebo effects up to eight years before the delivery of the cistern and treatment effects up to five years after the event.

5 | RESULTS

In this section, we present the results for six outcome variables related to land use: agriculture area (that includes both crop farming and pasture), crop farming area, pasture area, forest cover, higher-quality pasture area, and lower-quality pasture area. All outcome variables are listed as a proportion of the total property area. Our estimates are then interpreted in terms of percentage change relative to the control group (farms that have not yet received cisterns). Section 5.1 shows the average effect result for all farms that received cisterns at some point (Equation 2). Section 5.2 shows the dynamic effects related to the length of exposure to cisterns (Equation 1).

5.1 | Average effect of cistern construction for all treated properties

Table 1 presents estimates of the average effect of cistern construction across all properties for six outcome variables: the proportion of area allocated to agriculture (column I), the proportion of area allocated to crop farming (column II), the proportion of area allocated to pasture (column III), the proportion of area allocated to forest cover (column IV), the proportion of pasture area classified as higher quality (column V), and the proportion of pasture area classified as lower quality (column VI). All estimates employ the doubly robust estimator proposed by Callaway and Sant'Anna (2021), with standard errors clustered at the property level. The analysis includes 63,802 observations across six groups.

The results show a decrease of 0.48 percentage points in the total area allocated to agriculture (0.80% relative to the baseline mean of 60.28%). The analysis of the other components of land use reveals the underlying mechanisms driving this change. While pasture area decreases by 0.70 percentage points (1.22% relative to the baseline mean of 57.39%), there are important compositional shifts. More precisely, higher-quality pasture area increases by 0.91 percentage points, representing a rise of 14.49%. Conversely, lower-quality pasture areas decreased by 1.62 percentage points (a drop of 3.17%). These results indicate internal substitution within pasture categories, with the final composition characterized by a greater proportion of higher-quality pasture. In addition, the area allocated to crop farming increased by 0.22 percentage points—representing a rise of 7.61% relative to the baseline mean of 2.89%. Forest area increased by 0.35 percentage points (a rise of 1.07% relative to the baseline mean of 32.56%).

TABLE 1 Main Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	Higher-quality Pasture (V)	Lower-quality Pasture (VI)
Treatment effect	-0.0048^{***} (0.00083)	0.0022^{***} (0.00047)	-0.0070^{***} (0.00093)	0.0035^{***} (0.00065)	0.0091^{***} (0.00134)	-0.0162^{***} (0.00147)
Baseline Mean	0.6028	0.0289	0.5739	0.3256	0.0628	0.5111
Effect Size	−0.80%	7.61%	−1.22%	1.07%	14.49%	−3.17%
# obs	63,802	63,802	63,802	63,802	63,802	63,802
# groups	6	6	6	6	6	6
# treated	63,802	63,802	63,802	63,802	63,802	63,802

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, higher-quality pasture, and lower-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$. The baseline mean considers information one year before cistern construction for each property.

The findings indicate that crop farming and higher-quality pasture expansion occurred primarily through the conversion of lower-quality pasture areas rather than impacting forest cover. This land-use transition has both economic and environmental implications. The increase in crop farming area contributes to household food security among beneficiary families. The simultaneous preservation and expansion of forest areas, combined with improvements in pasture quality composition, suggest that the intervention promotes higher-productivity land-use practices.

In sum, the results indicate that the construction of cisterns is associated with (i) a reduction in lower-productivity activities and an increase in higher-productivity land uses, (ii) a land-sparing effect (drop in total agriculture area) led by reductions in lower-quality pasture, and (iii) an increase in forest cover, which is consistent with the intervention being land-saving.

5.2 | Average effect of cistern construction: length of exposure

This section shows the average effect related to the length of exposure to the treatment (Equation 1), considering the period analyzed. This parameter is relevant for two reasons: (i) it allows us to test the null hypothesis that the trends between the treated and not-yet-treated groups are parallel in the period prior to the construction of the cisterns; and (ii) it allows us to assess whether the effect of the treatment varies over time, considering the possibility of increasing, decreasing or stable effect over time. This analysis is also relevant to understanding the persistence of the effects as a function of exposure time.

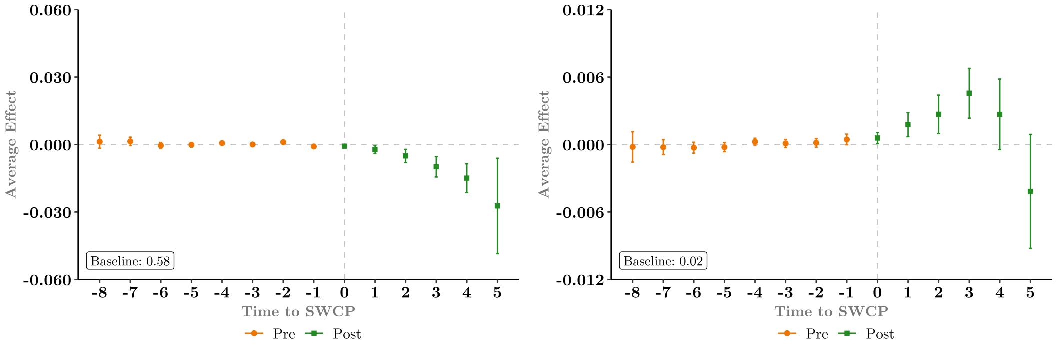
Figure 4 presents the estimates of the average effects of having a cistern in different periods after its construction (Equation 1). Outcome variables include the proportion of land devoted to agriculture (Figure 4a), the proportion of land dedicated to crop cultivation (Figure 4b), the proportion of land dedicated to pasture (Figure 4c), the proportion of land of forest cover (Figure 4d), the proportion of higher-quality pasture (Figure 4e), and the proportion of lower-quality pasture areas (Figure 4f). Vertical lines indicate 95% confidence intervals based on standard errors clustered at the farm level. Post-treatment effects are shown in square format, while placebo estimates for the pre-treatment period are shown in dot format. Estimates are based on the double-robust estimator proposed by Callaway and Sant'Anna (2021). Coefficients are shown in Appendix Table A.1.

Placebo effects up to eight years before treatment are small and generally statistically insignificant, supporting the parallel trends assumption. These results indicate the absence of significant anticipatory effects related to the construction of cisterns on land use, covering areas designated for agriculture, crop cultivation, pasture, and forest cover.

The length of exposure (“event-study") results support the findings from Section 5.1. The post-treatment estimates indicate significant effects for almost all periods and variables analyzed. In the case of the proportion of area designated for agriculture (Figure 4a), a negative and statistically significant effect is observed in all periods, with the effect intensifying as the time of exposure to the treatment increases. This pattern is strongly influenced by the reduction in pasture area (Figure 4c). The analysis of the proportion of higher-quality pasture (Figure 4e) reveals positive and statistically significant effects in all periods, with greater intensity in the extended periods of exposure. These results are consistent with the fact that, although there was a reduction in the total pasture area, the reduction was led predominantly by lower-quality pasture areas (see Figure 4f). The overall effect was a substitution in pasture composition, with an increase in the relative share of high-quality pasture and a reduction in low- and medium-quality areas.

The analysis of the proportion of area allocated to crops (Figure 4b) shows positive and significant effects in most periods, except for exposures longer than four years. However, the absolute effects observed in this variable were smaller than those related to the area allocated to pasture, which is consistent with the reduction in the total area allocated to agriculture. We also find a positive and significant effect observed in the proportion of area allocated to the forest (Figure 4d).

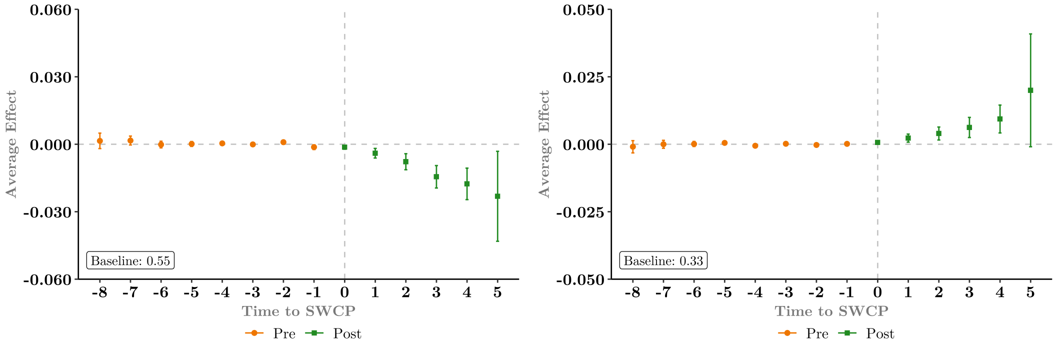
FIGURE 4 Baseline Results


(a) Agriculture Coverage

(b) Crop Farming Coverage

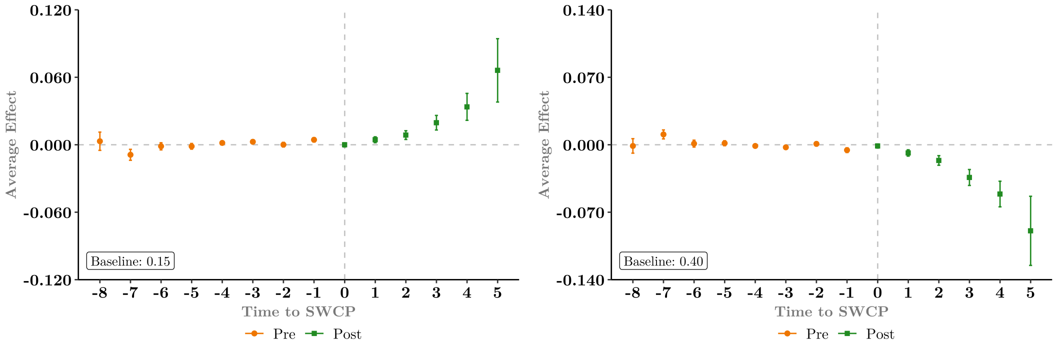
(c) Pasture Coverage

(d) Forest Coverage



(e) Higher-quality Pasture Coverage

(f) Lower-quality Pasture Coverage



Notes: All results are expressed in percentage points (0-1 scale). The figure shows the baseline results, where the agriculture variable equals the share of the area dedicated to crop farming and pasture (Panel 4a), crop farming variable equals the share of the area dedicated to crop farming (Panel 4b), pasture variable equals the share of the area dedicated to pasture (Panel 4c), forest variable equals the share of the area dedicated to forest (Panel 4d), higher-quality pasture variable equals the share of the pasture area with higher-quality (Panel 4e), and lower-quality pasture variable equals the share of the pasture area with low or medium quality pasture (Panel 4f). Coefficients are estimated from the empirical model in Section 4 for 63,802 properties. Data are provided at the property-year level. Vertical lines represent point-wise 95%-confidence intervals based on standard errors clusterized at the property level. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021) using a varying base period for the pre-treatment placebo estimates (in orange squares). Post-treatment estimates are reported in green dots. The baseline mean considers information one year before cistern construction for each property.

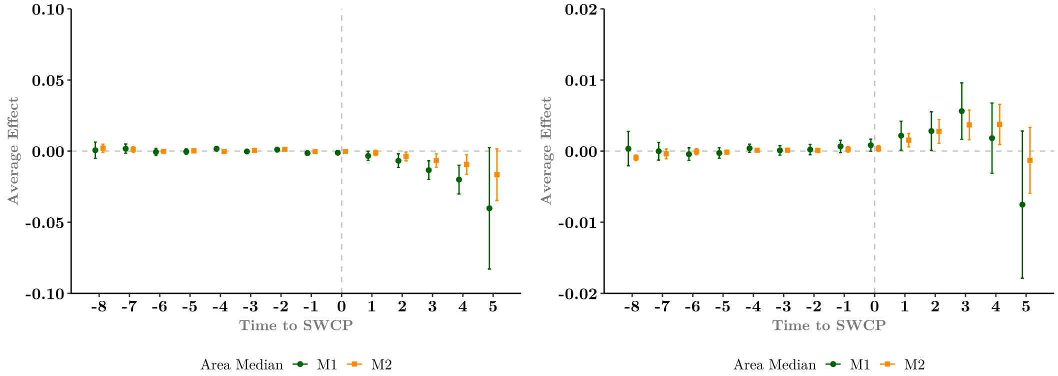
5.3 | Heterogeneity Analyses

The main results indicate a negative effect on the area allocated to pastures and a positive effect on areas dedicated to crops and forests. Initially, these results could be interpreted as environmentally positive due to the increase in vegetation areas and economically positive due to the rise in land allocated to higher-productivity uses. We now examine whether these effects vary across different categories of rural properties, particularly comparing larger and smaller properties.

To evaluate the heterogeneity of the effects, Figure 5 presents the impacts of cistern construction on the variables of interest: the proportion of area allocated to agriculture (Figure 5a), the proportion of area allocated to crop cultivation (Figure 5b), the proportion of area allocated to pastures (Figure 5c), the proportion of area allocated to forests (Figure 5d), the proportion of pasture areas of higher-quality (Figure 5e), and the proportion of lower-quality pasture area (Figure 5f). These results are derived from the methodology described in Equation 1, but splitting the sample into two distinct groups: the first group (M1) comprises rural properties with a total area below the median, while the second group (M2) includes properties above the median.

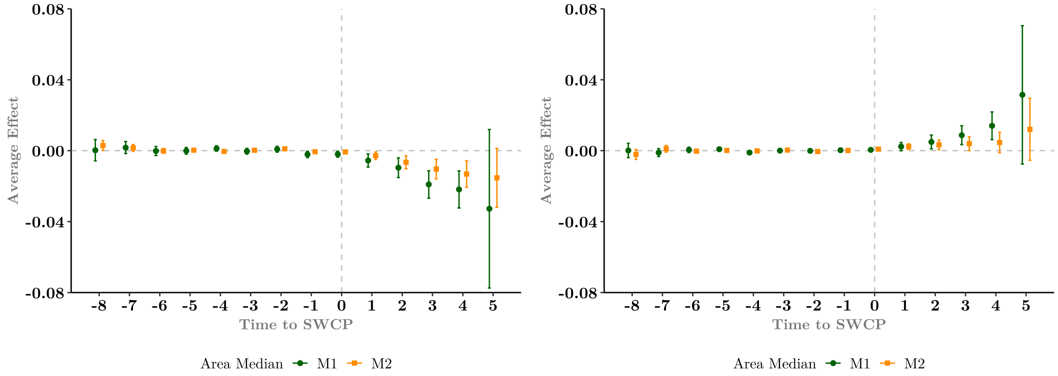
The results show that the effects are qualitatively similar between the two groups of properties. Smaller and larger properties have a negative effect on the total area allocated to agriculture, a positive effect on areas allocated to crop farming, and a negative effect on total pasture area. However, smaller properties display a slightly more significant average effect in absolute terms than those found in larger properties. When analyzing pasture categories, both higher-quality and lower-quality pastures show similar impact patterns across the two groups. The main difference is observed in the variable related to forest area (Figure 5d), where smaller properties exhibit a significantly more significant average effect than those of the larger properties. For the latter, the effects on forest area are not significant for most periods analyzed in the post-treatment interval (0 to 5 years of exposure).

FIGURE 5 Heterogeneity Results



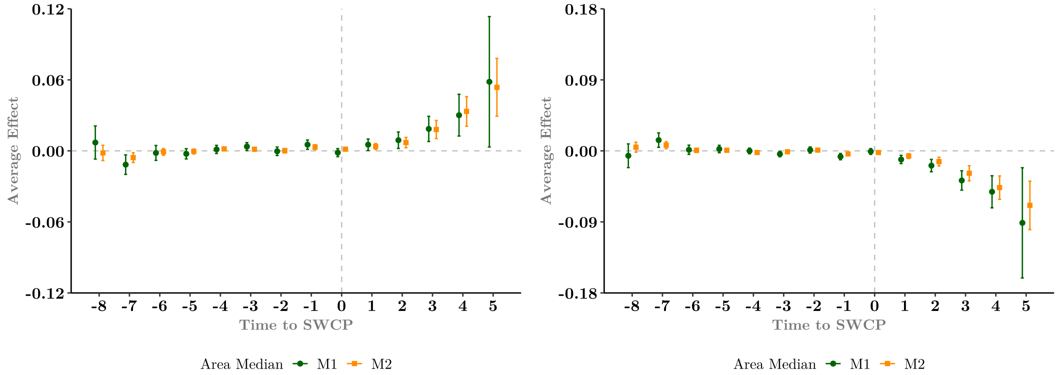
(a) Agriculture Coverage

(b) Crop Farming Coverage



(c) Pasture Coverage

(d) Forest Coverage



(e) Higher-quality Pasture Coverage

(f) Lower-quality Pasture Coverage

Notes: All results are expressed in percentage points (0-1 scale). The figure shows the heterogeneity results, where the agriculture variable equals the share of the area dedicated to farming and pasture (Panel 5a), farming variable equals the share of the area dedicated to farming (Panel 5b), pasture variable equals the share of the area dedicated to pasture (Panel 5c), forest variable equals the share of the area dedicated to forest (Panel 5d), high-quality pasture variable equals the share of higher-quality pasture (Panel 5e), and lower-quality pasture variable equals the share of the pasture area with low- or medium-quality (Panel 5f). Data are provided at the property-year level. Vertical lines represent point-wise 95%-confidence intervals based on standard errors clusterized at the property level. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021) using a varying base period for the pre-treatment placebo estimates (in orange squares). Post-treatment estimates are reported in green dots.

5.4 | Robustness and Specification Checks

This section presents six sets of robustness checks: (i) the inclusion of cisterns linked to multiple properties in the analysis sample, (ii) the inclusion of properties associated with multiple cisterns in the analysis sample, (iii) the simultaneous inclusion of both cases (i) and (ii) in the analysis sample, (iv) the analysis using a never-treated control group, (v) applying different estimator, and (iv) redefining the area of impact after the cistern construction. Detailed results of these analyses are provided in Appendix A.

In robustness check (i), which incorporates cisterns associated with multiple rural properties, the results remain consistent in magnitude (Appendix Table A.2) and persistence over time (Appendix Figure A.4). Similarly, in robustness check (ii), where properties linked to multiple cisterns are included, the findings align with the main results, demonstrating consistency in magnitude (Appendix Table A.3) and persistence of the effects over time (Appendix Figure A.5). In check (iii), encompassing both cistern duplication across properties and property duplication across cisterns, the results again remain largely unchanged in magnitude (Appendix Table A.4) and temporal persistence (Appendix Figure A.6).

When the control group is redefined from “not-yet-treated" (used in the principal analysis) to “never-treated", the findings remain robust relative to the main estimates. Note that in this exercise, treated properties in each period are compared exclusively with those that remained untreated throughout the analysis. Appendix Table A.5 indicates consistency in magnitude, while Appendix Figure A.7 illustrates comparable temporal persistence across all variables analyzed.

In addition to using the Callaway and Sant’Anna (2021) estimator in our primary analysis, we also employed the method proposed by De Chaisemartin and d’Haultfoeuille (2020) for conducting differences-in-differences with multiple periods. Both estimators address the issue of heterogeneity in effects within stepwise designs, each with its specific identification and aggregation procedures for group-time effects. Appendix Figure A.8 presents the comparative results for all relevant variables, including agriculture, crop farming, pasture, forest, higher-quality pasture, and lower-quality pasture. The analysis indicates that the point estimates and confidence intervals consistently overlap between the two methods, validating our conclusions regarding the impacts of the program on land-use and environmental outcomes.

Finally, as an additional robustness exercise, we implement an analysis based on buffers around constructed cisterns. More specifically, we define three buffers around each cistern with distances of 250m, 500m, and 1000m, with the 500m buffer established based on the median area of properties in the main base. This approach uses two datasets: the main base with 63,802 properties and an expanded base with 164,278 properties. Appendix Tables A.6 through A.11 present the point estimates of average effects for all outcome variables of interest, while Appendix Figures A.9 and A.10 illustrate the effects by treatment exposure time, comparing different buffer distances for both bases. The results demonstrate consistency between the main findings and the robustness exercises, maintaining the same direction of effects with comparable magnitudes. The stability of results across different spatial specifications reinforces the validity of the study’s main conclusions.

5.5 | Cost-Benefit Analysis

To evaluate the Cistern Program’s cost-benefit, we estimate the government expenditures related to cistern implementation and the environmental benefit from decreased greenhouse gas emissions resulting from reduced deforestation.

5.5.1 | Environmental Benefits

To assess the environmental impact of these water storage installations, we develop a framework that converts observed forest preservation into climate benefits:

1. **Establishing Emission-Forest Relationship**: We analyzed regional data from MapBiomas and SEEG datasets (in the period 2012-2018) to determine the relationship between forest loss and greenhouse gas emissions.[4] This yielded an annual conversion factor (θ_t) representing CO_2-equivalent tons emitted per hectare of cleared Caatinga vegetation (see Appendix Table A.12):

$$\theta_t = \frac{\text{GHG Emissions}_t}{\text{Deforested Area}_t} \tag{3}$$

   where t represents the year of analysis.
2. **Measuring Forest Preservation**: For each rural property, we compared actual forest coverage following installation ($F_{p,t}$) against projected coverage without intervention ($F'_{p,t}$). The aggregate difference across all treated properties in year t is calculated as:

$$\Delta F_t = \sum_{p \in \mathcal{P}_t} \frac{(F_{p,t} - F'_{p,t}) \cdot A_p}{|\mathcal{P}_t|} \tag{4}$$

   where $\mathcal{P}_t$ represents the set of properties with water storage systems installed in year t, $|\mathcal{P}_t|$ is the number of such properties, and A_p represents the property size in hectares.
3. **Calculating Climate Benefits**: The preserved forest area was converted to avoided emissions using our derived conversion factor:

$$\Delta E_t = \Delta F_t \cdot \theta_t \tag{5}$$

4. **Economic Valuation**: We assigned a monetary value to these climate benefits using carbon-valuation methods:

$$B_t^{\text{env}} = \text{SCC}_{2020} \cdot \varepsilon_{\text{exch}} \cdot \frac{P_{2023}}{P_{2020}} \cdot \Delta E_t \tag{6}$$

   where SCC_{2020} is the social cost of carbon emissions in 2020 based on the average estimate according to House (2021) with a 2.5% discount rate (we use the value of 76 dollars per ton of carbon dioxide equivalent), ε_{2020} is the exchange rate between Brazilian reais and US dollars in 2020, and $\frac{P_{2023}}{P_{2020}}$ represents the inflation adjustment factor according to the

---

[4] The *Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa* (SEEG) dataset follows the guidelines from the Intergovernmental Panel on Climate Change (IPCC) to provide emission estimates combining satellite and field-collected data. Greenhouse gases in the SEEG database include carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and other gases (e.g., perfluorocarbons, hydrofluorocarbons, sulfur hexafluoride, and nitrogen trifluoride). They are standardized into an emission metric known as carbon dioxide equivalent (CO_2-equivalent): a standard measure that transforms the amounts of other GHG gases to the equivalent amount of CO_2 based on their Global Warming Potential. See de Azevedo et al. (2018) for more details on SEEG methodology.

Brazil's consumer price index.[5]

5.5.2 | Program Costs

For the cost analysis, we focus solely on the installation costs of the program, using data obtained from official government records. The total program cost is calculated as:

$$C_t = \bar{c} * N_t \tag{7}$$

where $\bar{c}$ represents average installation cost per cistern (see Appendix Table A.13), and N_t is the total number of units installed across all regions in year t. For our analysis, we use this average cost of constructing a water storage unit with 52,000 liters capacity, as reported in official government expenditure records (Brazil, 2023).

5.5.3 | Net Benefit

For each year t in our analysis period, we calculate the net benefit (NB_t) as the difference between the benefits (B_t) and costs (C_t) in that year:

$$NB_t = B_t^{env} - C_t \tag{8}$$

The aggregate net benefit over the entire analysis period (2008-2018) is then calculated as the sum of annual net benefits:

$$NB_{total} = \sum_{t=2008}^{2018} NB_t \tag{9}$$

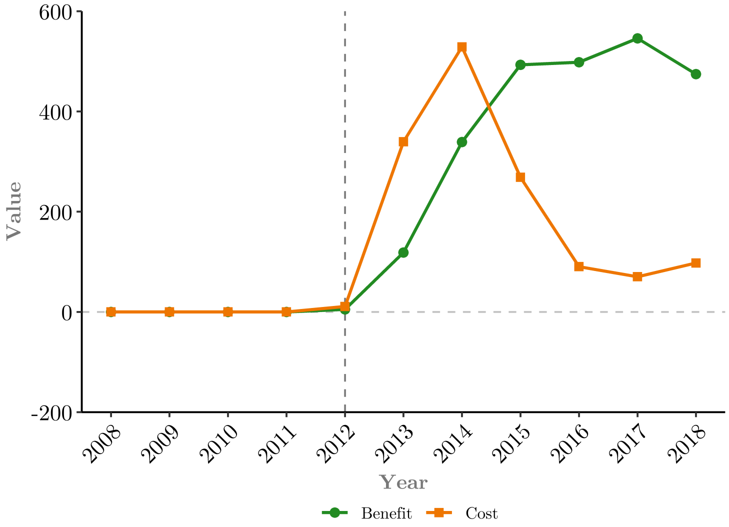
5.5.4 | Results and Policy Implications

Our empirical analysis reveals the evolution in the costs and benefits of the water storage program. Figure 6 depicts the evolution of program costs and benefits from 2008 to 2018, while Figure 7 displays the resulting net benefits over the same period.

---

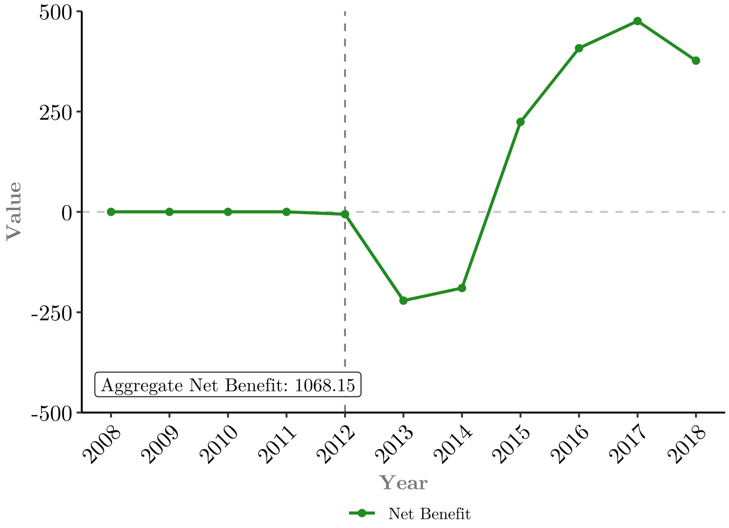
[5] The Social Cost of Carbon represents the monetary value of societal harm caused by adding one ton of carbon dioxide equivalent of greenhouse gases to the atmosphere. The Social Cost of Carbon accounts for diverse impacts ranging from agricultural productivity losses and health effects to property damage from floods, energy system disruptions, conflict risks, environmental migration, and ecosystem service degradation. Brazil's consumer price index is called IPCA ("Índice de Preços ao Consumidor Amplo").

FIGURE 6 Benefit and Cost



Notes: This figure presents the costs and benefits of cistern installation for the treated properties each year. The green circles show the estimated total benefit (Equation 6), and the orange squares show the estimated total cost of our target policy (Equation 7). All variables are measured in millions of Brazilian Reais of 2023.

FIGURE 7 Net Benefit



Notes: This figure depicts the net benefit of cistern installation for the treated properties each year. The green circles show the estimated total net benefit (Equation 9). The variable is measured in millions of Brazilian Reais of 2023.

Figure 7 depicts the net benefit trajectory and points out that the program initially generated negative returns during the initial phase (2012-2014). This negative return is due to the fact that the environmental benefits of the program only emerge a few years after the cistern's construction. However, starting in 2015, net benefits became positive and increased substantially. Over the entire study period, the program generated an aggregate net benefit of 1,062 million reais, confirming its economic viability when evaluated across the whole period.

We also calculate the Marginal Value of Public Funds (MVPF) to complement the welfare metrics presented above. The MVPF is the ratio of the benefits the policy provides its beneficiaries, divided by the net cost of the policy to the government. Building on Hendren and Sprung-Keyser (2020), we define the MVPF as:

$$\text{MVPF} = \frac{\text{Benefits}}{\text{Net Govt Cost}} = \frac{\Delta W}{\Delta E - \Delta C} \tag{10}$$

where ΔW denotes the benefits that the policy provides to individuals in the population, ΔE denotes the initial government spending on the policy, and ΔC denotes the long-term reduction in government costs due to the policy's effect.

In the case of the cisterns program, we calculate a benefit of R$ 2,473.79 million reais ($\Delta W = 2,473.79$) and an initial government spending of R$ 1,405.64 million reais ($\Delta E = 1,405.64$). Recall that the program's objective is to assist families in a state of vulnerability and guarantee only sufficient conditions for food subsistence. For simplicity, we assume that $\Delta C = 0$. Note that long-term benefits regarding government costs ($\Delta C > 0$) imply that the denominator we calculated is smaller than expected. Therefore, our estimate of the MVPF represents a lower bound of the true MVPF. Overall, we find an MVPF of 1.76, indicating that the Cistern Program generates R$ 1.76 in benefits for every real spent by the government, indicating a positive return on investment.

These findings highlight an important implication from the adaptation policy we study: interventions designed primarily for climate resilience may simultaneously contribute to mitigation goals. The water storage initiative demonstrates how properly designed rural infrastructure can address immediate community needs related to poverty alleviation while supporting broader climate objectives.

Policymakers should consider potential emission reduction co-benefits when evaluating climate adaptation measures, as these improve long-term cost-effectiveness ratios. Environmental programs often require time to realize their full economic value, with benefits accumulating even as implementation costs decline following the initial investment period. In regions lacking developed carbon markets to compensate rural communities directly for forest preservation services, government support for such programs is justified by their long-term, multifaceted benefits. By quantifying these combined impacts, we provide a more complete assessment of climate adaptation initiatives, potentially informing future policy design and implementation.

6 | CONCLUDING REMARKS

This study investigates the impact of climate adaptation policies on production and environmental outcomes in vulnerable regions. Analyzing the Cistern Program in Brazil's semiarid region reveals that improved water availability through cistern construction has generated significant changes in land-use patterns. While total agricultural area decreased, reductions were accompanied by increases in higher-quality pasture areas and forest coverage.

Expanded cropland occurred without corresponding deforestation, suggesting more efficient land-use practices. Farmers substituted lower-quality pastures with higher-quality ones, indicating gains in livestock productivity without environmental degradation. Water security enabled producers to intensify operations on existing agricultural land rather than expanding into forested areas. Effects remained consistent across different property sizes, with marginally larger magnitudes for smaller holdings, demonstrating successful targeting of vulnerable populations while generating broader benefits.

These results challenge the conventional view that climate adaptation and mitigation are competing policy priorities. Appropriately designed adaptation interventions can advance both objectives simultaneously, yielding three key implications for policy design.

First, economic evaluations must incorporate environmental co-benefits. Conventional cost-benefit analyses excluding forest preservation and avoided emissions systematically undervalue adaptation interventions, potentially leading to suboptimal resource allocation. Second, low-cost infrastructure investments can simultaneously address food security and environmental management among populations most vulnerable to climate impacts.

In contexts lacking developed carbon markets, where direct compensation mechanisms for ecosystem services remain absent, government investment in adaptation policies that yield measurable environmental co-benefits constitutes efficient climate action across both dimensions. Enhanced agricultural productivity, combined with reduced deforestation, demonstrates how policy design can explore complementarities between human resilience and environmental preservation, thereby avoiding the zero-sum resource allocation frameworks.

While our findings provide evidence for Brazil's semiarid context, several factors are informative to other contexts. The low-cost rainwater harvesting technology we study is scalable and relevant to other water-scarce regions worldwide, particularly in semiarid areas of sub-Saharan Africa, South Asia, and Latin America, where smallholder farmers face similar constraints, such limited credit. The mechanisms we identify (i.e., intensification on existing land rather than expansion into forests) may operate in contexts where water scarcity represents the binding constraint on agricultural productivity. However, generalization depends on contextual factors, including the strength of property rights and environmental regulations, which were relatively well-established in our setting. The effects may differ in contexts with weaker institutions or in which other constraints are more binding. Additionally, our findings apply to small-scale, targeted water technology rather than large-scale infrastructure projects. Future research should examine how these effects vary across institutional contexts and intervention scales to better understand when adaptation policies can simultaneously enhance productivity and environmental conservation.

ACKNOWLEDGEMENTS

We are grateful to Rafael Araujo, Adriana Camacho and participants at various seminars for their helpful comments and suggestions. We gratefully acknowledge financial support from CAF Development Bank. The usual disclaimer applies. Declarations of interest: none.

REFERENCES

Abajian, A. C., Carleton, T., Meng, K. C. and Deschenes, O. (2025) The climate adaptation feedback. *Working Paper 33531*, National Bureau of Economic Research.

AP1MC (2025) Associação programa um milhão de cisternas. URL: `https://ap1mc.org.br/p1mais2`. `https://ap1mc.org.br/p1mais2` [Accessed: 2025-11-05].

Aragón, F. M., Oteiza, F. and Rud, J. P. (2021) Climate change and agriculture: Subsistence farmers' response to extreme heat. *American Economic Journal: Economic Policy*, **13**, 1–35.

ASA Brasil (2025) Programa um milhão de cisternas (p1mc). URL: `https://asabrasil.org.br/projeto/p1mc/`. `https://asabrasil.org.br/projeto/p1mc/` [Accessed: 2025-11-05].

de Azevedo, T., Costa Junior, C., Brandão Junior, A., Cremer, M., Piatto, M., Tsai, D., Barreto, P., Martins, H., Sales, M., Galuchi, T., Rodrigues, A., Morgado, R., Ferreira, A., Barcellos e Silva, F., Viscondi, G., dos Santos, K., Cunha, K., Manetti, A., Coluna, I., Albuquerque, I., Junior, S., Leite, C. and Kishinami, R. (2018) SEEG Initiative Estimates of Brazilian Greenhouse Gas Emissions from 1970 to 2015. *Scientific Data*, **5**.

Barreca, A., Clay, K., Deschenes, O., Greenstone, M. and Shapiro, J. S. (2016) Adapting to climate change: The remarkable decline in the us temperature-mortality relationship over the twentieth century. *Journal of Political Economy*, **124**, 105–159.

Barreto, Y., Britto, G. C. D., Carrillo Bermúdez, B., Da Mata, D., Emanuel, L. and Sampaio, B. (2025) Cisterns for life: Climate adaptation policies for water provision and rural lives. URL: `https://ssrn.com/abstract=5571918`. Available at SSRN.

Berman, N., Couttenier, M., Leblois, A. and Soubeyran, R. (2023) Crop prices and deforestation in the tropics. *Journal of Environmental Economics and Management*, **119**, 102819. URL: `https://www.sciencedirect.com/science/article/pii/S0095069623000372`.

Blakeslee, D., Fishman, R. and Srinivasan, V. (2020) Way down in the hole: Adaptation to long-term water loss in rural india. *American Economic Review*, **110**, 200–224.

Bobonis, G. J., Gertler, P. J., Gonzalez-Navarro, M. and Nichter, S. (2022) Vulnerability and clientelism. *American Economic Review*, **112**, 3627–3659.

Brazil (2023) Instrução normativa sesan nº 10 - modelo da tecnologia social de acesso à Água nº 2: Cisterna calçadão de 52 mil litros.

Brazil (2023) Modelo de tecnologia social. `https://www.gov.br/mds/pt-br/acoes-e-programas/acesso-a-alimentos-e-a-agua/programa-cisternas/tecnologias-sociais`.

— (2024) Água para colher futuro.

Burke, M. and Emerick, K. (2016) Adaptation to climate change: Evidence from us agriculture. *American Economic Journal: Economic Policy*, **8**, 106–40.

Burney, J. A. and Naylor, R. L. (2012) Smallholder irrigation as a poverty alleviation tool in sub-saharan africa. *World Development*, **40**, 110–123.

Callaway, B. and Sant'Anna, P. H. (2021) Difference-in-differences with multiple time periods. *Journal of econometrics*, **225**, 200–230.

Carleton, T., Duflo, E., Jack, K. and Zappalà, G. (2024) Adaptation to climate change. *Working Paper 33264*, National Bureau of Economic Research.

Casagrande, D., Emanuel, L., Freitas, C. and Oliveira, F. (2024) Climate adaptation policies and rural income: Evidence from social technologies in brazil. *World Development*, **181**, 106683.

Cirilo, J. A. (2008) Políticas públicas de recursos hídricos para o semi-árido. *Estudos avançados*, **22**, 61–82.

Cust, J., Harding, T., Krings, H. and Rivera-Ballesteros, A. (2023) Public Governance versus Corporate Governance: Evidence from Oil Drilling in Forests. *Journal of Development Economics*, **163**, 103070.

Da Mata, D. and Dotta, M. (2024) Commodity Booms and The Environment. *Ssrn working paper*.

Da Mata, D., Emanuel, L., Pereira, V. and Sampaio, B. (2023) Climate adaptation policies and infant health: evidence from a water policy in brazil. *Journal of Public Economics*, **220**, 104835.

Da Mata, D. and Resende, G. (2020) Changing the climate for banking: the economic effects of credit in a climate-vulnerable area. *Journal of Development Economics*, **146**, 102459.

De Chaisemartin, C. and d'Haultfoeuille, X. (2020) Two-way fixed effects estimators with heterogeneous treatment effects. *American economic review*, **110**, 2964–2996.

Dell, M., Jones, B. F. and Olken, B. A. (2014) What do we learn from the weather? the new climate-economy literature. *Journal of Economic literature*, **52**, 740–798.

Devoto, F., Duflo, E., Dupas, P., Parienté, W. and Pons, V. (2012) Happiness on tap: Piped water adoption in urban morocco. *American Economic Journal: Economic Policy*, **4**, 68–99.

Duflo, E. and Pande, R. (2007) Dams. *The Quarterly Journal of Economics*, **122**, 601–646.

Dupas, P., Nhlema, B., Wagner, Z., Wolf, A. and Wroe, E. (2023) Expanding access to clean water for the rural poor: experimental evidence from malawi. *American Economic Journal: Economic Policy*, **15**, 272–305.

Dyer, J. and Shapiro, J. (2023) Pumps, prosperity and household power: Experimental evidence on irrigation pumps and smallholder farmers in kenya. *Journal of Development Economics*, **163**, 103034.

Embaye, T. G., Kahsay, G. H., Abadi, N., Kebede, M. M. and Dessie, D. T. (2020) Evaluation of water harvesting structures on agricultural productivity: the case of tigray region, ethiopia. *Sustainable Water Resources Management*, **6**.

Fankhauser, S. (2017) Adaptation to climate change. *Annual Review of Resource Economics*, **9**, 209–230.

Fund, U. N. C. and Organization, W. H. (2024) *Progress on household drinking water, sanitation and hygiene 2000-2022: Special focus on gender*. World Health Organization.

Gamper-Rabindran, S., Khan, S. and Timmins, C. (2010) The impact of piped water provision on infant mortality in brazil: A quantile panel data approach. *Journal of Development Economics*, **92**, 188–200.

Grum, B., Hessel, R., Kessler, A., Woldearegay, K., Yazew, E., Ritsema, C. and Geissen, V. (2016) A decision support approach for the selection and implementation of water harvesting techniques in arid and semi-arid regions. *Agricultural Water Management*, **173**, 35–47.

Hahn, R. W., Hendren, N., Metcalfe, R. D. and Sprung-Keyser, B. (2024) A welfare analysis of policies impacting climate change. *Tech. rep.*, National Bureau of Economic Research.

Harding, T., Herzberg, J. and Kuralbayeva, K. (2021) Commodity Prices and Robust Environmental Regulation: Evidence from Deforestation in Brazil. *Journal of Environmental Economics and Management*, **108**, 102452.

Hendren, N. and Sprung-Keyser, B. (2020) A unified welfare analysis of government policies. *The Quarterly journal of economics*, **135**, 1209–1318.

Hornbeck, R. and Keskin, P. (2014) The historically evolving impact of the ogallala aquifer: Agricultural adaptation to groundwater and drought. *American Economic Journal: Applied Economics*, **6**, 190–219.

House, W. (2021) Social cost of carbon, methane, and nitrous oxide-interim estimates under executive order 13990. *Technical support document, Interagency Working Group on Social Cost of Greenhouse Gases, United States Government., Washington DC, USA*.

IPCC (2022) *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. URL: `https://doi.org/10.1017/9781009325844`.

Jack, W., Kremer, M., De Laat, J. and Suri, T. (2023) Credit access, selection, and incentives in a market for asset-collateralized loans: Evidence from kenya. *Review of Economic Studies*, **90**, 3153–3185.

Jalan, J. and Ravallion, M. (2003) Does piped water reduce diarrhea for children in rural india? *Journal of econometrics*, **112**, 153–173.

Jayachandran, S. (2022) How Economic Development Influences the Environment. *Annual Review of Economics*, **14**, 229–252.

Kahn, M. E. (2016) The climate change adaptation literature. *Review of Environmental Economics and Policy*, **10**, 166–178.

Kremer, M., Leino, J., Miguel, E. and Zwane, A. P. (2011) Spring cleaning: Rural water impacts, valuation, and property rights institutions. *The Quarterly Journal of Economics*, **126**, 145–205.

Lima, J. R. and Magalhaes, A. R. (2018) Secas no nordeste: Registros históricos das catástrofes econômicas e humanas do século 16 ao século 21. *Parcerias Estrategicas*, **23**, 191–212.

Rocha, R., Gandour, C. and Assunção, J. (2015) Deforestation Slowdown in the Brazilian Amazon: Prices or Policies? *Environment and Development Economics*, **20**, 697–722.

Rocha, R. and Soares, R. R. (2015) Water scarcity and birth outcomes in the brazilian semiarid. *Journal of Development Economics*, **112**, 72–91.

Santana, V. L. and Rahal, L. d. S. (2020) Tecnologias sociais como impulso para o acesso à água e o desenvolvimento sustentável no meio rural brasileiro: a experiência do programa cisternas.

Seddon, A. W., Macias-Fauria, M., Long, P. R., Benz, D. and Willis, K. J. (2016) Sensitivity of global terrestrial ecosystems to climate variability. *Nature*, **531**, 229–232.

Sekhri, S. (2014) Wells, water, and welfare: the impact of access to groundwater on rural poverty and conflict. *American Economic Journal: Applied Economics*, **6**, 76–102.

Villa, M. A. (2000) *Vida e morte no sertão: história das secas no Nordeste nos séculos XIX e XX*. Ática.

Yosef, B. A. and Asmamaw, D. K. (2015) Rainwater harvesting: An option for dry land agriculture in arid and semi-arid ethiopia. *International Journal of Water Resources and Environmental Engineering*, **7**, 17–28.

A | EXTRA TABLES AND FIGURES

A.1 | Tables

TABLE A.1 Models Results

Time to SWCP	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
-8	0.0013	-0.0002	0.0015	-0.0009	0.0031	-0.0012
	(0.00107)	(0.00048)	(0.00121)	(0.00082)	(0.00293)	(0.00278)
-7	0.0014	-0.0002	0.0016*	0.0000	-0.0089***	0.0107***
	(0.00068)	(0.00025)	(0.00067)	(0.00053)	(0.00159)	(0.00174)
-6	-0.0004	-0.0003	-0.0001	0.0001	-0.0014	0.0012
	(0.00048)	(0.00017)	(0.00046)	(0.00031)	(0.00122)	(0.00119)
-5	-0.0001	-0.0002	0.0001	0.0005	-0.0014	0.0016
	(0.00034)	(0.00014)	(0.00037)	(0.00024)	(0.00082)	(0.00086)
-4	0.0006	0.0002	0.0004	-0.0006*	0.0016	-0.0013
	(0.00026)	(0.00010)	(0.00030)	(0.00021)	(0.00070)	(0.00071)
-3	0.0000	0.0001	-0.0001	0.0002	0.0026***	-0.0027***
	(0.00028)	(0.00013)	(0.00032)	(0.00019)	(0.00066)	(0.00067)
-2	0.0011***	0.0002	0.0009**	-0.0003	0.0001	0.0009
	(0.00028)	(0.00015)	(0.00029)	(0.00021)	(0.00071)	(0.00075)
-1	-0.0008*	0.0004	-0.0013***	0.0001	0.0044***	-0.0056***
	(0.00033)	(0.00017)	(0.00037)	(0.00025)	(0.00079)	(0.00077)
0	-0.0007	0.0006***	-0.0013***	0.0007**	-0.0001	-0.0013
	(0.00029)	(0.00017)	(0.00032)	(0.00023)	(0.00068)	(0.00075)
1	-0.0022***	0.0018***	-0.0040***	0.0023***	0.0045***	-0.0085***
	(0.00059)	(0.00041)	(0.00069)	(0.00049)	(0.00096)	(0.00113)
2	-0.0051***	0.0027***	-0.0078***	0.0040***	0.0086***	-0.0163***
	(0.00107)	(0.00063)	(0.00116)	(0.00080)	(0.00138)	(0.00177)
3	-0.0099***	0.0046***	-0.0145***	0.0062***	0.0196***	-0.0340***
	(0.00147)	(0.00086)	(0.00177)	(0.00116)	(0.00250)	(0.00285)
4	-0.0150***	0.0027	-0.0176***	0.0094***	0.0337***	-0.0512***
	(0.00241)	(0.00116)	(0.00240)	(0.00181)	(0.00403)	(0.00443)
5	-0.0273***	-0.0042	-0.0232**	0.0200*	0.0661***	-0.0894***
	(0.00723)	(0.00186)	(0.00697)	(0.00694)	(0.00960)	(0.01182)

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.2 Cisterns Base - Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
Treatment Effect	-0.0048^{***} (0.00086)	0.0019^{***} (0.00042)	-0.0067^{***} (0.00085)	0.0037^{***} (0.00058)	0.0096^{***} (0.00120)	-0.0163^{***} (0.00147)
# obs	71,005	71,005	71,005	71,005	71,005	71,005
# groups	6	6	6	6	6	6
# treated	71,005	71,005	71,005	71,005	71,005	71,005

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.3 Properties Base - Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
Treatment Effect	-0.0045^{***} (0.00073)	0.0019^{***} (4e-04)	-0.0064^{***} (0.00079)	0.0034^{***} (0.00059)	0.0090^{***} (0.00121)	-0.0154^{***} (0.00136)
# obs	76,064	76,064	76,064	76,064	76,064	76,064
# groups	6	6	6	6	6	6
# treated	76,064	76,064	76,064	76,064	76,064	76,064

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.4 All Base - Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
Treatment Effect	-0.0046^{***} (0.00065)	0.0017^{***} (0.00037)	-0.0062^{***} (0.00082)	0.0037^{***} (0.00058)	0.0094^{***} (0.00113)	-0.0156^{***} (0.00128)
# obs	85,241	85,241	85,241	85,241	85,241	85,241
# groups	6	6	6	6	6	6
# treated	85,241	85,241	85,241	85,241	85,241	85,241

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.5 Never Treated Base - Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
Treatment Effect	-0.0028^{***}	0.0016^{***}	-0.0044^{***}	0.0019^{***}	0.0090^{***}	-0.0134^{***}
	(0.00078)	(0.00043)	(0.00077)	(0.00056)	(0.00126)	(0.00136)
# obs	66,410	66,410	66,410	66,410	66,410	66,410
# groups	5	5	5	5	5	5
# treated	56,185	56,185	56,185	56,185	56,185	56,185

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.6 Buffer 250m Distance - Main Base - Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
Treatment Effect	-0.0032^{***}	0.0022^{***}	-0.0054^{***}	0.0025^{***}	0.0089^{***}	-0.0143^{***}
	(0.00066)	(0.00040)	(0.00078)	(0.00053)	(0.00124)	(0.00143)
# obs	63,802	63,802	63,802	63,802	63,802	63,802
# groups	6	6	6	6	6	6
# treated	63,802	63,802	63,802	63,802	63,802	63,802

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.7 Buffer 500m Distance - Main Base - Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
Treatment Effect	-0.0021^{***}	0.0016^{***}	-0.0037^{***}	0.0018^{***}	0.0088^{***}	-0.0125^{***}
	(0.00054)	(0.00030)	(0.00056)	(0.00040)	(0.00095)	(0.00116)
# obs	63,802	63,802	63,802	63,802	63,802	63,802
# groups	6	6	6	6	6	6
# treated	63,802	63,802	63,802	63,802	63,802	63,802

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.8 Buffer 1000m Distance - Main Base - Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
Treatment	-0.0015^{***}	0.0011^{***}	-0.0026^{***}	0.0015^{***}	0.0086^{***}	-0.0112^{***}
Effect	(0.00040)	(0.00026)	(0.00042)	(0.00031)	(0.00089)	(0.00090)
# obs	63,802	63,802	63,802	63,802	63,802	63,802
# groups	6	6	6	6	6	6
# treated	63,802	63,802	63,802	63,802	63,802	63,802

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.9 Buffer 250m Distance - Total Base - Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
Treatment	-0.0025^{***}	0.0015^{***}	-0.0040^{***}	0.0026^{***}	0.0084^{***}	-0.0123^{***}
Effect	(0.00041)	(0.00025)	(0.00046)	(0.00036)	(0.00066)	(0.00073)
# obs	164,278	164,278	164,278	164,278	164,278	164,278
# groups	6	6	6	6	6	6
# treated	164,278	164,278	164,278	164,278	164,278	164,278

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.10 Buffer 500m Distance - Total Base - Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
Treatment	-0.0017^{***}	0.0011^{***}	-0.0028^{***}	0.0021^{***}	0.0083^{***}	-0.0110^{***}
Effect	(0.00033)	(0.00020)	(0.00036)	(0.00026)	(0.00059)	(0.00067)
# obs	164,278	164,278	164,278	164,278	164,278	164,278
# groups	6	6	6	6	6	6
# treated	164,278	164,278	164,278	164,278	164,278	164,278

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.11 Buffer 1000m Distance - Total Base - Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-quality Pasture (VI)
Treatment Effect	-0.0014^{***} (0.00024)	0.0007^{***} (0.00016)	-0.0021^{***} (0.00028)	0.0017^{***} (0.00021)	0.0081^{***} (0.00049)	-0.0102^{***} (0.00056)
# obs	164,278	164,278	164,278	164,278	164,278	164,278
# groups	6	6	6	6	6	6
# treated	164,278	164,278	164,278	164,278	164,278	164,278

Notes: This table presents the estimates of the average effect of constructing cisterns. The outcome variables are the proportion of area dedicated to agriculture, farming, pasture, forest, and high-quality pasture. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021). Standard errors are reported in parenthesis and are clustered at the property level. Significance levels are denoted as follows: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

TABLE A.12 Deforestation and Emissions Relationship (2012-2018)

Year	**Deforestation (ha)**	**Emissions (tCO_2eq)**	**Ratio (θ_t)**
2012	525,082	60,388,743	115.01
2013	537,906	63,525,604	118.10
2014	605,015	70,353,319	116.28
2015	563,247	68,361,576	121.37
2016	571,923	64,302,502	112.43
2017	499,317	58,335,362	116.83
2018	646,444	61,334,835	94.88

Note: The data presents annual deforestation in the Brazilian Caatinga biome and corresponding carbon emissions from 2012-2018. Deforestation data (in hectares) is sourced from MapBiomas satellite monitoring initiative. Emissions data (measured in tons of CO_2 equivalent) is sourced from the System for Greenhouse Gas Emissions and Removals Estimates (SEEG) and pertains solely to emissions resulting from deforestation. The ratio (θ_t) represents tons of CO_2eq emissions per hectare of deforested land.

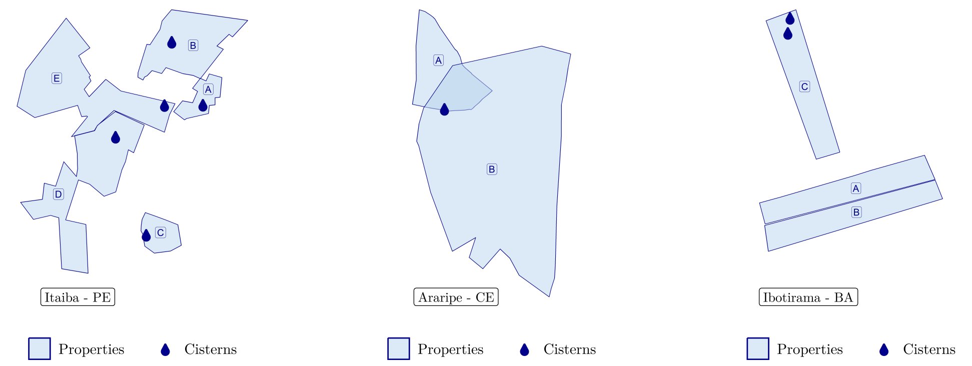
TABLE A.13 Mean Cistern Costs by State

State	Mean Cost
Alagoas	21,590.24
Bahia	21,942.22
Ceará	22,075.97
Maranhão	21,638.06
Minas Gerais	22,427.42
Paraíba	21,867.46
Pernambuco	22,128.22
Piauí	22,976.50
Rio Grande do Norte	22,147.69
Sergipe	21,519.00
Mean ($\bar{c}$)	**22,031.28**

Note: Data represents average cistern construction costs across different Brazilian states in 2023. Costs include materials, labor, and installation expenses for 52,000 liter cisterns. Values are presented in Brazilian Reais (R$) of 2023.

A.2 | Figures

FIGURE A.1 Cases of cisterns distributions



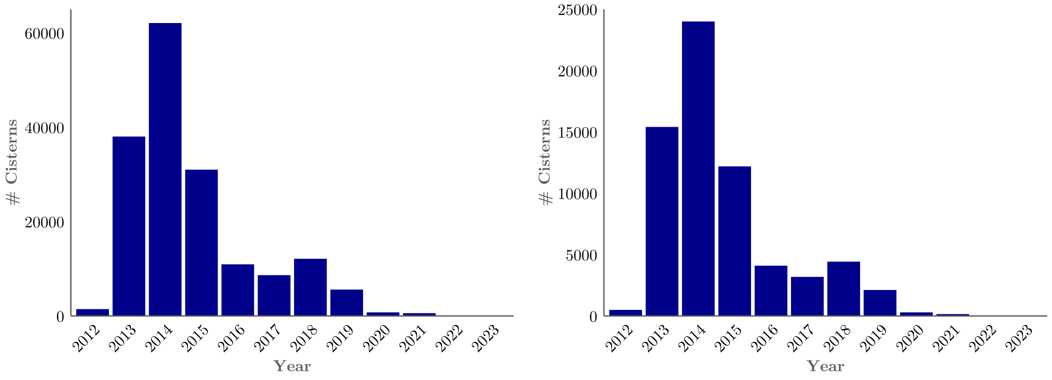
(a) 1 cistern : 1 property (b) 1 cistern : N properties (c) N cisterns : 1 property

Notes: Cases of cistern distributions after geographical attachment to rural properties. Panel (A.1a) shows the desired case, in which a single cistern is assigned to a single rural property. Panel (A.1b) shows the case in which a cistern is assigned to more than one property. Panel (A.1c) shows the case where several cisterns are assigned to a single property.

FIGURE A.2 Cistern in the Brazilian Semi-arid

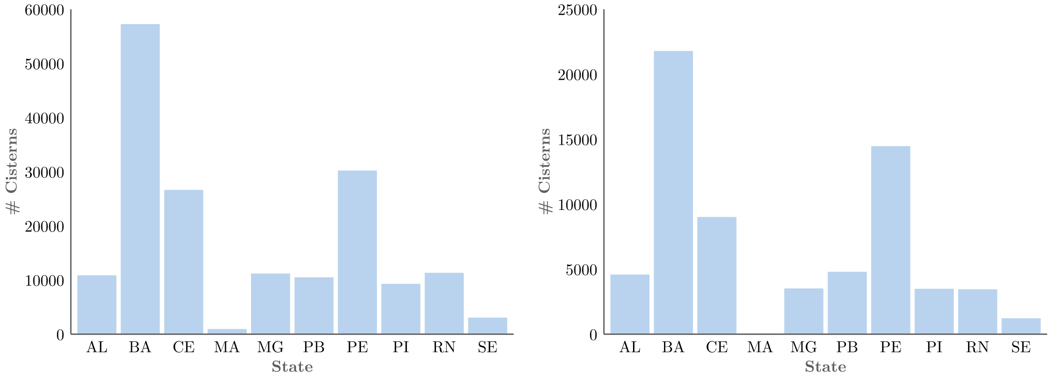
Notes: The pictures display typical cisterns distributed through the Second Water Cistern Program. Photo provided by the Brazilian Semi-arid Articulation — ASA Brazil.

FIGURE A.3 Cisterns Distributions by year and state, considering initial and final bases



(a) Number of Cisterns in initial base by year (2012-2023)

(b) Number of Cisterns in final base by year (2012-2023)

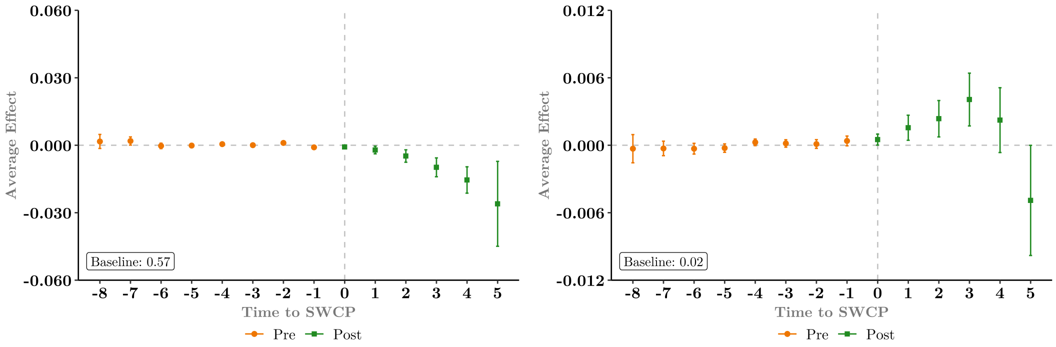


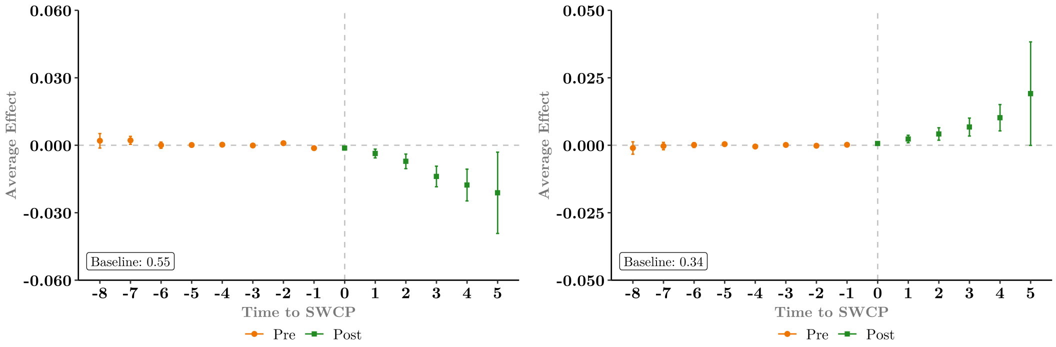
(c) Number of Cisterns in initial base by state

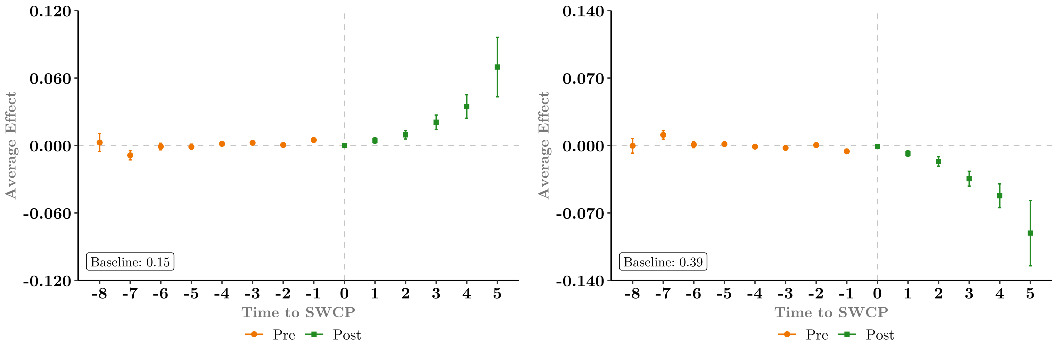
(d) Number of Cisterns in final base by state

Notes: Cisterns distributions by year and state, considering initial and final bases. Panel (A.3a) shows the distribution of cisterns by year, considering the initial base. Panel (A.3b) shows the distribution of cisterns by year, considering the final base. Panel (A.3c) shows the distribution of cisterns by state, considering the initial base. Panel (A.3d) shows the distribution of cisterns by state, considering the final base.

FIGURE A.4 Cistern Base - Results

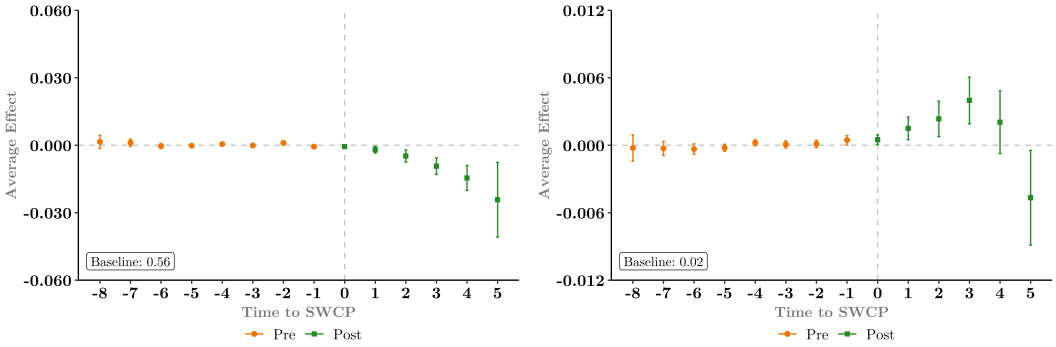

(a) Agriculture Coverage (b) Farming Coverage


(c) Pasture Coverage (d) Forest Coverage


(e) High-quality Pasture Coverage (f) Low/Medium-quality Pasture Coverage

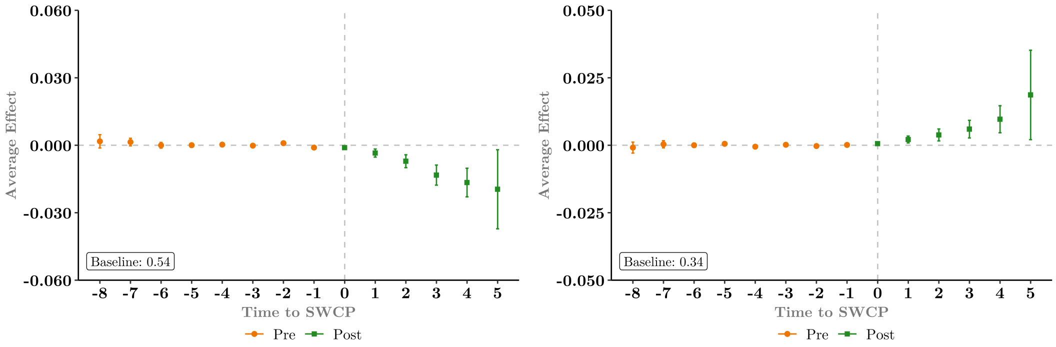
Notes: All results are expressed in percentage points (0-1 scale). The figure shows the results, where the agriculture variable equals the share of the area dedicated to farming and pasture (Panel A.4a), farming variable equals the share of the area dedicated to farming (Panel A.4b), pasture variable equals the share of the area dedicated to pasture (Panel A.4c), forest variable equals the share of the area dedicated to forest (Panel A.4d), high-quality pasture variable equals the share of the pasture area with high quality (Panel A.4e), and low/medium-quality pasture variable equals the share of the pasture area with low or medium quality (Panel A.4f). Coefficients are estimated from the empirical model in Section IV for 71,005 properties. Data are provided at the property-year level. Vertical lines represent point-wise 95%-confidence intervals based on standard errors clusterized at the property level. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021) using a varying base period for the pre-treatment placebo estimates (in orange). Post-treatment estimates are reported in green. The baseline mean considers information one year before cistern construction for each property.

FIGURE A.5 Property Base - Results



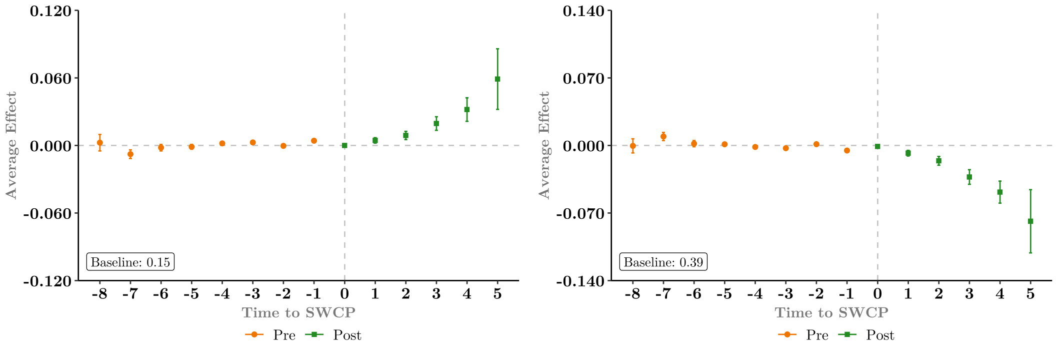
(a) Agriculture Coverage

(b) Farming Coverage



(c) Pasture Coverage

(d) Forest Coverage



(e) High-quality Pasture Coverage

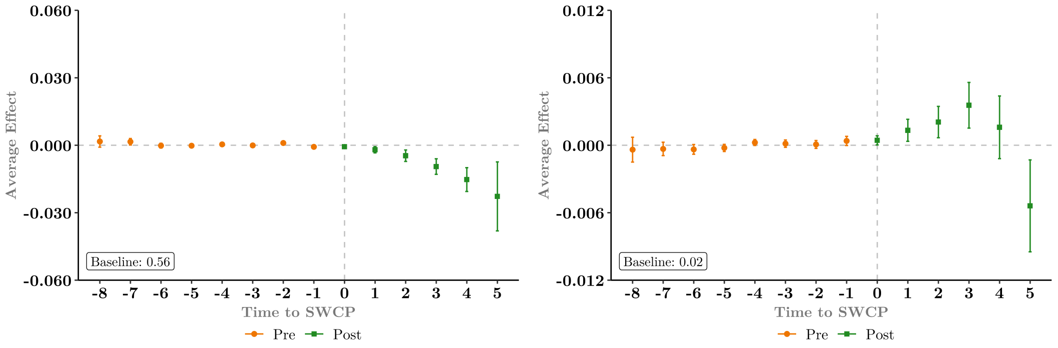
(f) Low/Medium-quality Pasture Coverage

Notes: All results are expressed in percentage points (0-1 scale). The figure shows the results, where the agriculture variable equals the share of the area dedicated to farming and pasture (Panel A.5a), farming variable equals the share of the area dedicated to farming (Panel A.5b), pasture variable equals the share of the area dedicated to pasture (Panel A.5c), forest variable equals the share of the area dedicated to forest (Panel A.5d), high-quality pasture variable equals the share of the pasture area with high quality (Panel A.5e), and low/medium-quality pasture variable equals the share of the pasture area with low or medium quality (Panel A.5f). Coefficients are estimated from the empirical model in Section IV for 76,064 properties. Data are provided at the property-year level. Vertical lines represent point-wise 95%-confidence intervals based on standard errors clusterized at the property level. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021) using a varying base period for the pre-treatment placebo estimates (in orange). Post-treatment estimates are reported in green. The baseline mean considers information one year before cistern construction for each property.

FIGURE A.6 All Base - Results

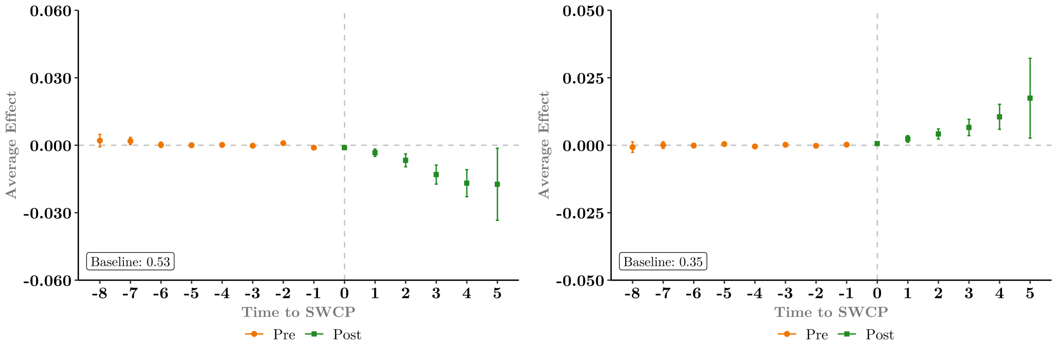
(a) Agriculture Coverage

(b) Farming Coverage



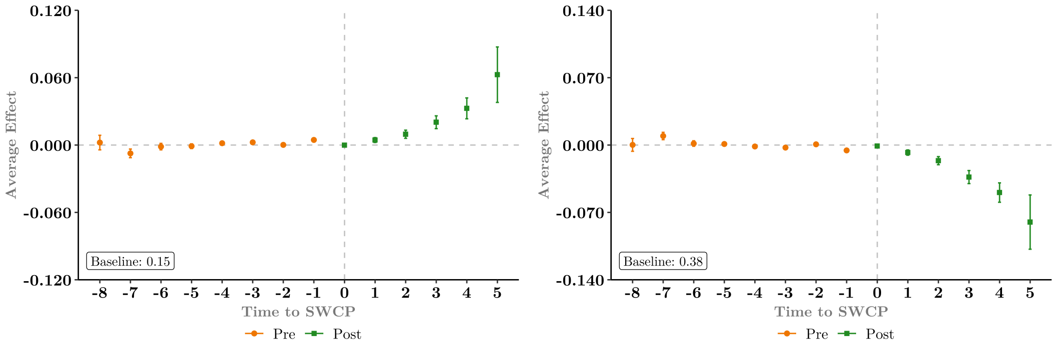
(c) Pasture Coverage

(d) Forest Coverage



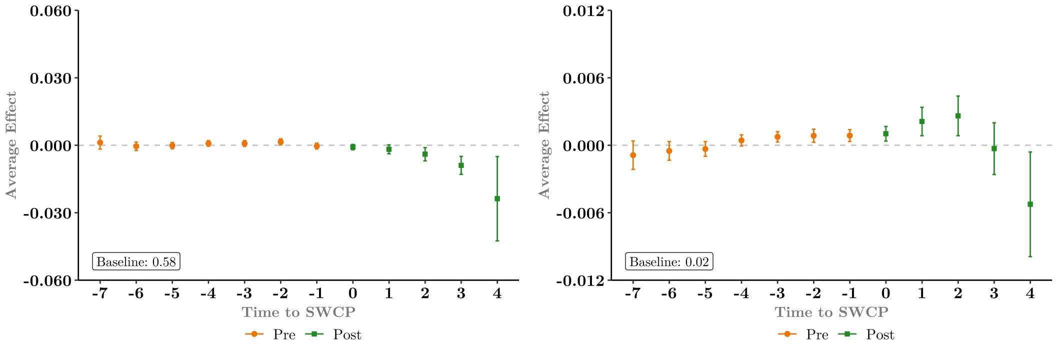
(e) High-quality Pasture Coverage

(f) Low/Medium-quality Pasture Coverage



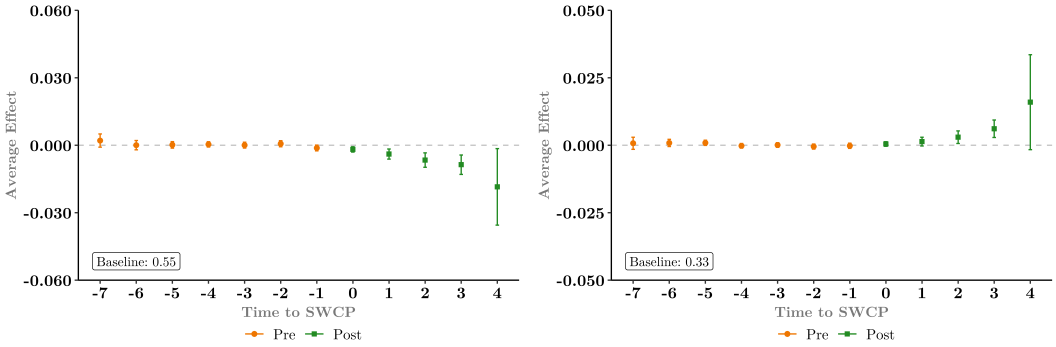
Notes: All results are expressed in percentage points (0-1 scale). The figure shows the results, where the agriculture variable equals the share of the area dedicated to farming and pasture (Panel A.6a), farming variable equals the share of the area dedicated to farming (Panel A.6b), pasture variable equals the share of the area dedicated to pasture (Panel A.6c), forest variable equals the share of the area dedicated to forest (Panel A.6d), high-quality pasture variable equals the share of the pasture area with high quality (Panel A.6e), and low/medium-quality pasture variable equals the share of the pasture area with low or medium quality (Panel A.6f). Coefficients are estimated from the empirical model in Section IV for 85,241 properties. Data are provided at the property-year level. Vertical lines represent point-wise 95%-confidence intervals based on standard errors clusterized at the property level. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021) using a varying base period for the pre-treatment placebo estimates (in orange). Post-treatment estimates are reported in green. The baseline mean considers information one year before cistern construction for each property.

FIGURE A.7 Never Treated - Results



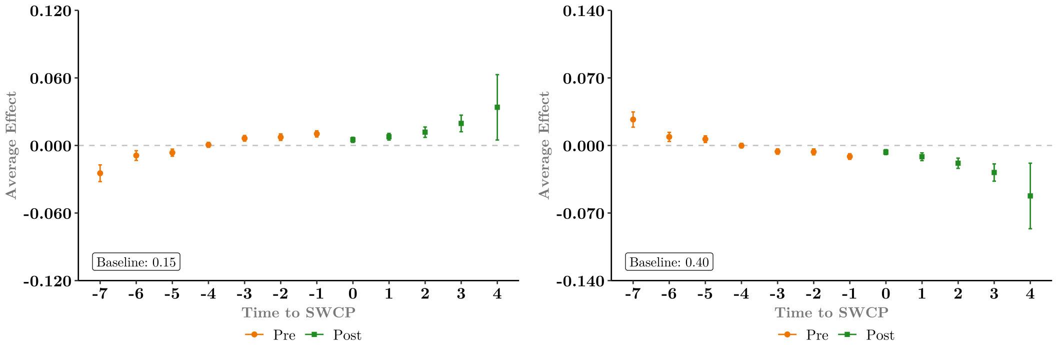
(a) Agriculture Coverage

(b) Farming Coverage



(c) Pasture Coverage

(d) Forest Coverage

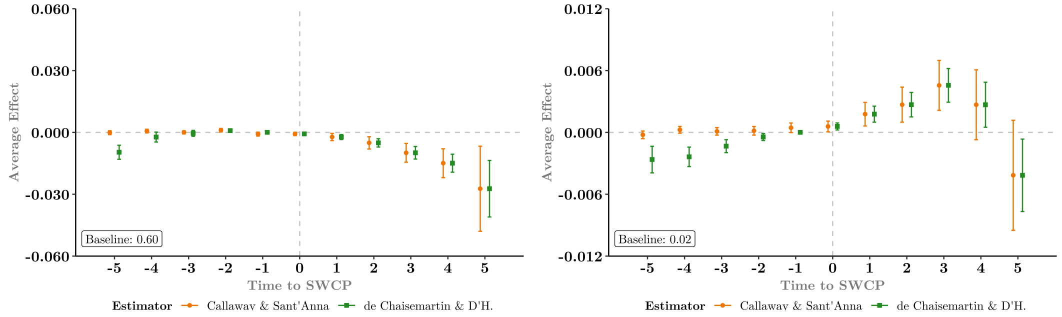


(e) High-quality Pasture Coverage

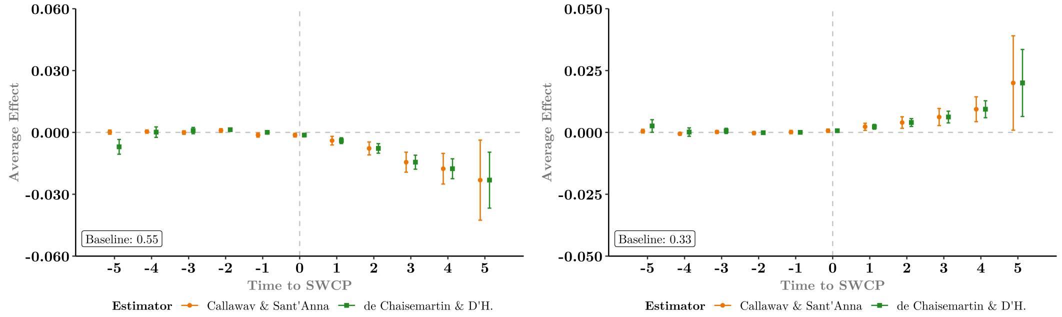
(f) Low/Medium-quality Pasture Coverage

Notes: All results are expressed in percentage points (0-1 scale). The figure shows the baseline results, where the agriculture variable equals the share of the area dedicated to farming and pasture (Panel A.7a), farming variable equals the share of the area dedicated to farming (Panel A.7b), pasture variable equals the share of the area dedicated to pasture (Panel A.7c), forest variable equals the share of the area dedicated to forest (Panel A.7d), high-quality pasture variable equals the share of the pasture area with high quality (Panel A.7e), and low/medium-quality pasture variable equals the share of the pasture area with low or medium quality (Panel A.7f). Coefficients are estimated from the empirical model in Section IV for 63,802 properties. Data are provided at the property-year level. Vertical lines represent point-wise 95%-confidence intervals based on standard errors clusterized at the property level. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021) using a varying base period for the pre-treatment placebo estimates (in orange). Post-treatment estimates are reported in green. The baseline mean considers information one year before cistern construction for each property.

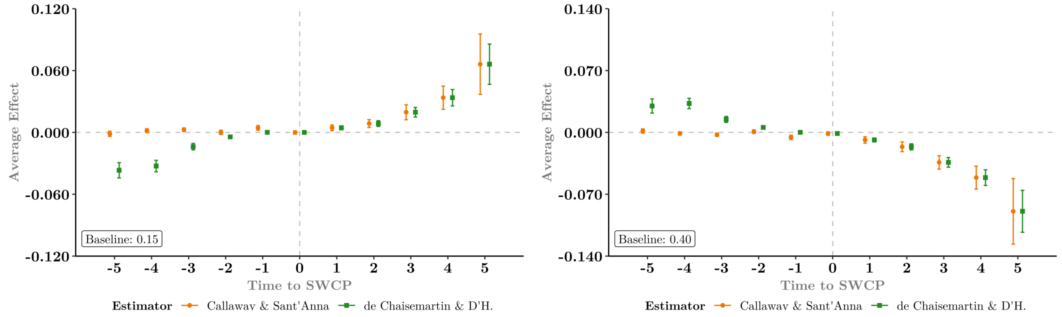
FIGURE A.8 Alternative Estimator - Results - Main Base


(a) Agriculture Coverage

(b) Farming Coverage


(c) Pasture Coverage

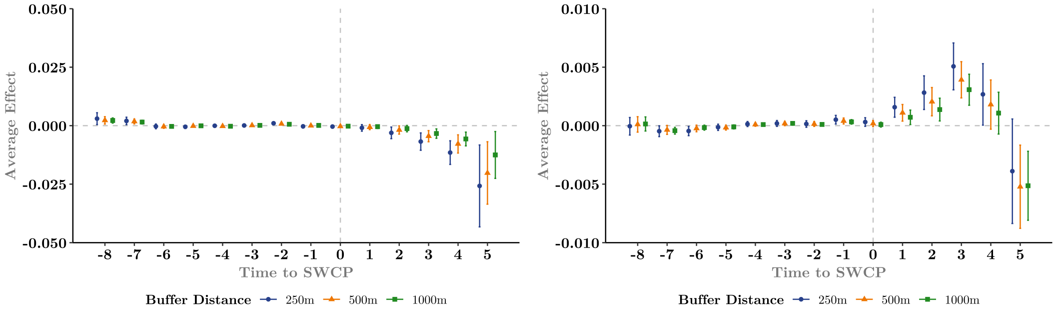
(d) Forest Coverage


(e) High-quality Pasture Coverage

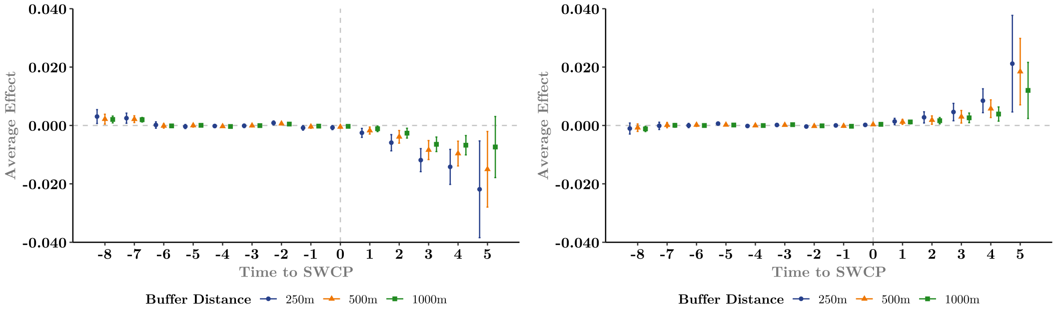
(f) Low/Medium-quality Pasture Coverage

Notes: All results are expressed in percentage points (0-1 scale). The figure shows the results, where the agriculture variable equals the share of the area dedicated to farming and pasture (Panel A.8a), farming variable equals the share of the area dedicated to farming (Panel A.8b), pasture variable equals the share of the area dedicated to pasture (Panel A.8c), forest variable equals the share of the area dedicated to forest (Panel A.8d), high-quality pasture variable equals the share of the pasture area with high quality (Panel A.8e), and low/medium-quality pasture variable equals the share of the pasture area with low or medium quality (Panel A.8f). Coefficients are estimated from the empirical model in Section IV for 63,802 cisterns. Data are provided at the cistern-year level. Vertical lines represent point-wise 95%-confidence intervals based on standard errors clusterized at the property level. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021) using a varying base period for the pre-treatment placebo estimates and estimator proposed by De Chaisemartin and d'Haultfoeuille (2020) using -1 as base period for the pre-treatment placebo estimates. The baseline mean considers information one year before cistern construction for each property.

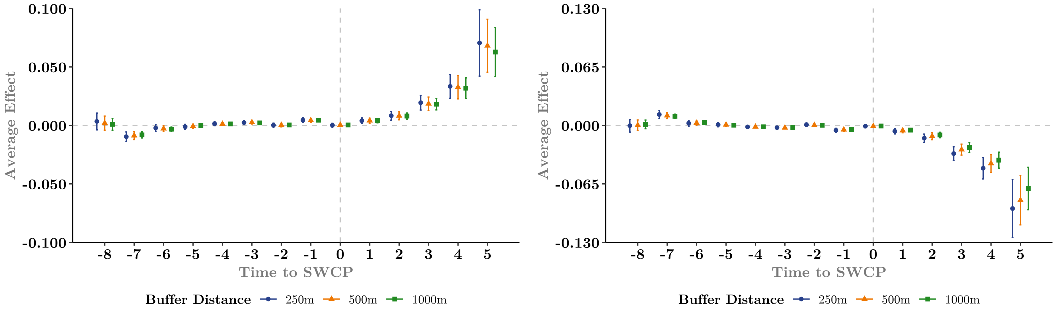
FIGURE A.9 Buffers - Results - Main Base


(a) Agriculture Coverage

(b) Farming Coverage


(c) Pasture Coverage

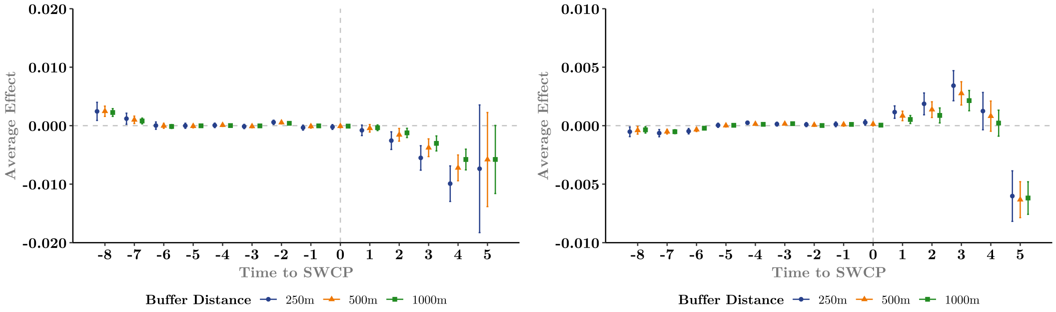
(d) Forest Coverage


(e) High-quality Pasture Coverage

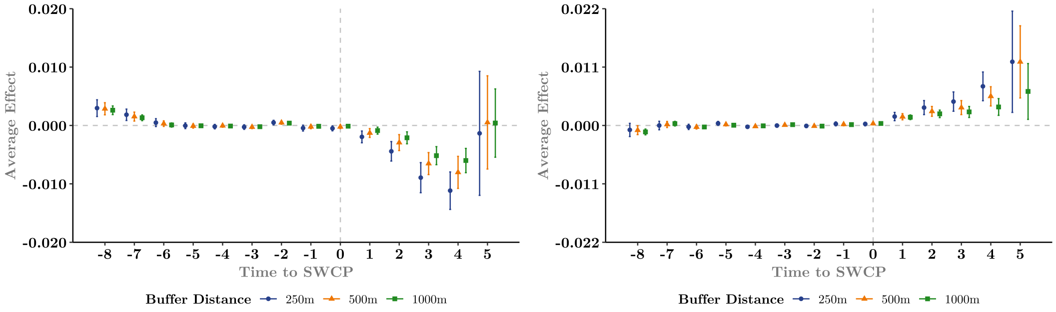
(f) Low/Medium-quality Pasture Coverage

Notes: All results are expressed in percentage points (0-1 scale). The figure shows the buffers results, where the agriculture variable equals the share of the area dedicated to farming and pasture (Panel A.9a), farming variable equals the share of the area dedicated to farming (Panel A.9b), pasture variable equals the share of the area dedicated to pasture (Panel A.9c), forest variable equals the share of the area dedicated to forest (Panel A.9d), high-quality pasture variable equals the share of the pasture area with high quality (Panel A.9e), and low/medium-quality pasture variable equals the share of the pasture area with low or medium quality (Panel A.9f). Coefficients are estimated from the empirical model in Section IV for 63,802 cisterns. Data are provided at the cistern-year level. Vertical lines represent point-wise 95%-confidence intervals based on standard errors clusterized at the property level. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021) using a varying base period for the pre-treatment placebo estimates.

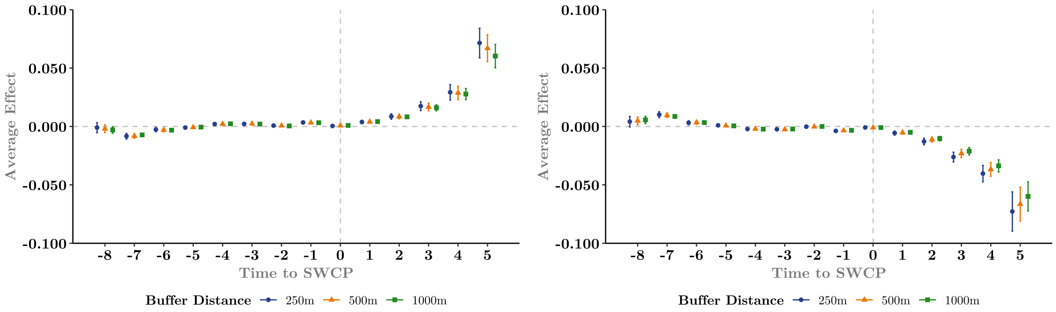
FIGURE A.10 Buffers - Results - Total Base


(a) Agriculture Coverage

(b) Farming Coverage


(c) Pasture Coverage

(d) Forest Coverage


(e) High-quality Pasture Coverage

(f) Low/Medium-quality Pasture Coverage

Notes: All results are expressed in percentage points (0-1 scale). The figure shows the buffers results, where the agriculture variable equals the share of the area dedicated to farming and pasture (Panel A.10a), farming variable equals the share of the area dedicated to farming (Panel A.10b), pasture variable equals the share of the area dedicated to pasture (Panel A.10c), forest variable equals the share of the area dedicated to forest (Panel A.10d), high-quality pasture variable equals the share of the pasture area with high quality (Panel A.10e), and low/medium-quality pasture variable equals the share of the pasture area with low or medium quality (Panel A.10f). Coefficients are estimated from the empirical model in Section IV for 164,278 cisterns. Data are provided at the cistern-year level. Vertical lines represent point-wise 95%-confidence intervals based on standard errors clusterized at the property level. These results are based on the doubly-robust estimator proposed by Callaway and Sant'Anna (2021) using a varying base period for the pre-treatment placebo estimates.