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Preferences for Sustainable Production Practices in Extensive Livestock Systems

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How Do Climate Adaptation Policies Affect Production and Environmental Outcomes? Evidence from a Water Policy[*]

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Abstract

This paper examines the effects of a climate adaptation policy on production and environmental outcomes in Brazil's semiarid region. The water policy builds rainwater reservoirs designed to boost production and strengthen rural producers' resilience. Using individual-level administrative data from the program combined with high-resolution satellite data on land use and coverage, we find that cistern construction led to increased high-quality pasture areas and forest coverage (+0.35 percentage points) while also expanding cultivation area (+0.22 percentage points). These effects were consistent across property sizes, though slightly larger for smaller properties. Our cost-benefit analysis reveals a positive aggregate return with each invested monetary unit generating 1.76 units of benefits, demonstrating that adaptation policies can simultaneously advance mitigation goals.

JEL Classification: O13, O18, Q15, Q18, Q24, Q25

Keywords: Climate Change Adaptation, Water Policy, Agricultural Production, Land Use, Deforestation, Environmental Conservation

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1 Introduction

The implications of climate change are at the forefront of current political debates. Climate dynamics, influenced by a prolonged period of greenhouse gas emissions, project a scenario of more frequent and intense extreme events, disproportionately affecting vulnerable communities and increasing social inequality (Dell et al., 2014). In response, governments worldwide have developed climate adaptation policies. These policies are configured as an integrative approach to neutralize the adverse effects of climate change. While adaptation policies aim to increase well-being by altering behavioral responses, these policies may have unintended effects. In particular, less is known about how adaptation policies may (unintentionally) affect environmental outcomes. For instance, interventions designed to increase energy resilience may inadvertently raise overall energy demand and greenhouse-gas emissions, while measures supporting agricultural production may end up promoting cropland expansion and generate loss of forest cover.

How do climate adaptation policies affect production and environmental outcomes? We examine this question in the context of a water policy in Brazil that aims to boost production and strengthen the resilience of rural producers. More specifically, we evaluate the effects of the Cisterns Program on the economic and environmental impacts of rural establishments. The Cisterns 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.[1] The program focuses on low-income rural producers in the Brazilian semiarid region who do not have a water supply. Together, the program aims to mitigate the semiarid climate's impacts, support agriculture and livestock, and improve the well-being of the rural population (Santana and Rahal, 2020).

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). Occupying 12% of the national territory, the Brazilian semiarid region houses about 28 million inhabitants and is populated by small rural landowners dedicated to agriculture (Da Mata and Resende, 2020a). For most of these families, the primary water sources are intermittent rivers and small community reservoirs — which fill during the rainy season. 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.

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[1] The Cistern Program builds smaller cisterns for domestic use (First Water Cistern Program, see Da Mata et al., 2023) and larger cisterns for production (Second Water Cistern Program, focus of this paper).

Note that 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).

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 occurs in one or two 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, 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 investigate the program's effects, we combine individual-level administrative data with satellite data. We have access to the Cisterns Program microdata between 2012 and 2023 with each cistern's latitude and longitude coordinates, allowing us to merge with satellite data. We also have access to land cover and use data from MapBiomas, covering data from 1985 to 2023. MapBiomas processes LandSat-8 satellite images of 30 meters by 30 meters to document and classify changes in Brazil's land use and coverage MapBiomas (2024). In particular, we collect annual farm-level data on natural forest stock, pastures, and agricultural areas. The natural forest area corresponds to land covered by forests and native vegetation. Pasture and agricultural areas refer to areas covered by agriculture and pastures (planted or natural).[2] Additionally, we also use data on pasture quality. These are satellite-derived data on pasture quality with a resolution of 30 meters by 30 meters from the Pasture Atlas—an initiative of LAPIG-UFG. The data are collected for the years 2008 to 2022 and contain a three-level granularity on pasture degradation: (i) severely degraded areas, (ii) intermediately degraded areas, and (iii) non-degraded areas (Huete et al., 2002; LAPIG, 2022). The production area and environmental outcomes of deforestation and soil degradation are constructed using satellite images, which minimizes concerns about measurement errors of self-reported income and production data — commonly used in work scopes similar to ours.

The adaptation policy under study aims to increase agricultural production, making evaluating the program's impact on cultivated areas important. Water capture techniques improve water availability, an essential factor for crop cultivation, especially in arid and semiarid regions (Grum et al., 2016). Next, we evaluate the impact on forest coverage. An increase in the area allocated to agriculture can occur through a reduction in forest or degraded area, which could have been recovered for produc-

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[2] See Baeza et al. (2022) and Souza Jr et al. (2020) for works on the remote sensing literature using these data.

tion. For example, the observed increase in production can occur through (i) no deforestation and less land degradation or (ii) increased deforestation and more land degradation. Therefore, the ex-ante impact on forest coverage and land degradation is conceptually ambiguous. We also evaluate heterogeneous effects regarding farm size to assess whether the program is relevant for producers or only for a subgroup of farms.

While there is evidence of the need for water storage policies for adaptation 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) — intensified by climate change —, it is important to consider their potential environmental impacts. Adaptation policies, while reducing the adverse effects of climate change, may inadvertently 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 (or lead to higher energy consumption in cases of energy-related adaptation policies). In the context of the analyzed policy, this dynamic can manifest as follows: since the water storage program's objective is to promote agricultural production, beneficiaries may expand their cultivation areas toward forest regions, resulting in increased deforestation and, consequently, an increase in GHG emissions.

To assess the program's effects, 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. The results indicate that the construction of cisterns generated significant changes in the proportion of land use, with a reduction in the area destined for agriculture (-0.48 percentage points) and pasture (-0.70 percentage points), accompanied by an increase in high-quality pasture area and forest areas (+0.35 percentage points). Replacing low-quality pastures with high-quality pastures suggests potential gains in livestock productivity. Simultaneously, there was an increase in the proportion of areas destined for crops (+0.22 percentage points) without negative impacts on forest areas. These results indicate greater land use efficiency, with forest coverage maintenance and increased agricultural productivity.

Furthermore, we analyze the policy's heterogeneous effects to shed light on the contexts where it was most effective economically and environmentally. The impacts may vary according to property size, revealing differences between small and large production units. The heterogeneity analysis reveals that the effects are consistent between small and large properties, with slightly larger impacts on smaller properties. Small properties showed a greater relative increase in the proportion of forests, while the effects on other land use categories were similar between the two groups. The robustness exercises corroborated the validity of the main results, showing consistency in magnitude and persistence, even when including different categories of cisterns and redefining the control group to never treated.

Our cost-benefit analysis reveals that the cistern program generates significant environmental benefits. We estimate the program's climate benefits by converting observed forest preservation into avoided greenhouse gas emissions using derived conversion factors from regional data. Over 2012-2018, the program generated an aggregate net benefit with a Marginal Value of Public Funds (MVPF) of 1.76, indicating that each monetary spent by the government generated 1.76 units in benefits. While the program initially showed negative returns over 2012-2014, benefits substantially increased from 2015 onward.

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 case there is a market to compensate producers for mitigation results—adaptation policies may 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.

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 economics literature has extensively studied production responses to climate variation (Dell et al., 2014). However, adaptation policies' environmental and production consequences have been studied less. This paper contributes to the literature by providing new empirical facts about how adaptation policies affect environmental outcomes. In particular, we contribute by evaluating whether adaptation policies are carbon-intensive by 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 and land-use adaptive behavior.

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 studied how an adaptation policy affects deforestation, highlighting the interaction between adaptation and mitigation efforts.

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 the dam 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, Da Mata et al. (2023) found that access to cisterns for domestic consumption during pregnancy improved birth outcomes. 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 Cisterns 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.

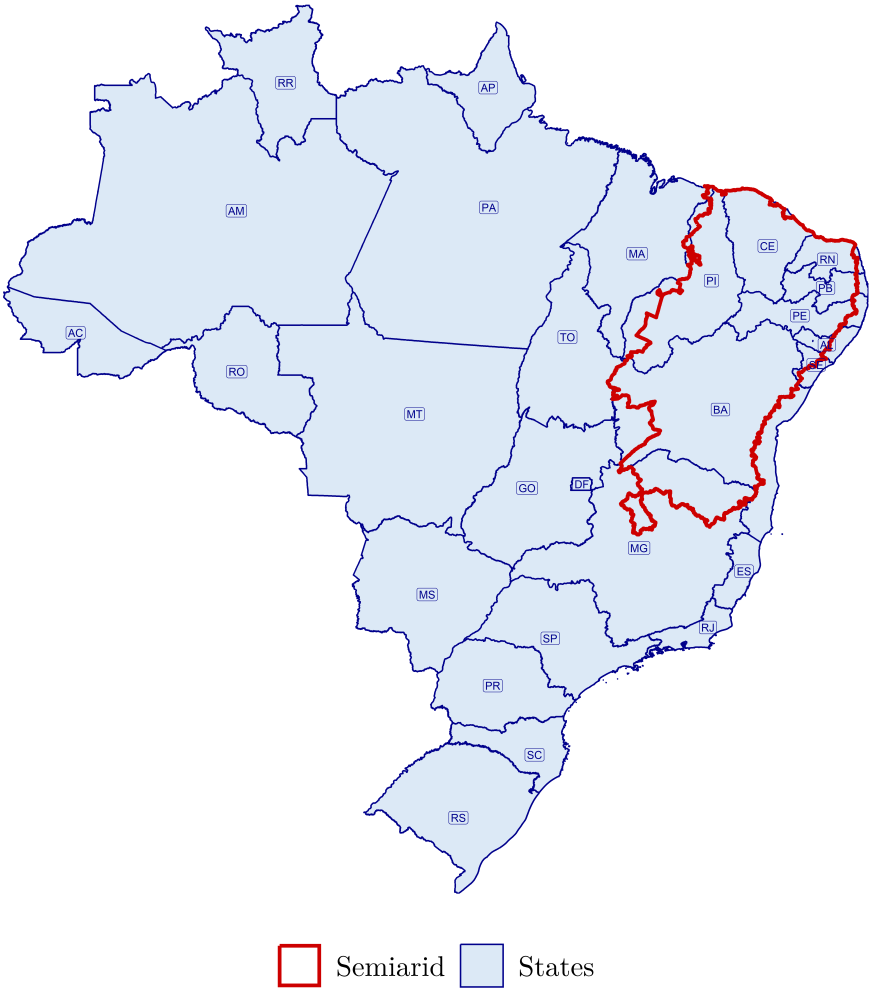
2 Background

2.1 Semiarid

The Brazilian semiarid region is located in the Northeast region of the country. It covers nine states in the region, including the northern part of the state of Minas Gerais – Figure 1. It corresponds to the region with the lowest water availability in the country and has the largest population living in arid areas with a tropical climate, with around 22 million inhabitants — approximately 12% of the Brazilian population. This region is marked by irregular rainfall, low soil capacity to retain water, and recurrent droughts. Composed of 1,262 predominantly small municipalities focused on agriculture (Da Mata and Resende, 2020b), the area has social indicators, such as health and education, that are lower than those of other regions of Brazil, concentrating 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).

The region is predominantly inhabited by small rural landowners involved in agricultural practices highly dependent on rainfall. For most families, intermittent streams and community dams at the foot of the hills, which fill during the rainy season, serve as their primary water sources. Vulnerability to drought is exceptionally high, 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, 2020b). Water scarcity represents a central vulnerability factor (Bobonis et al., 2022). 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, which is 1,550 mm and was characterized by a heterogeneous temporal distribution. The region has experienced droughts since the 16th century, events 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, high evapotranspiration, and regional geology, with predominantly shallow and rocky soils, restrict water retention. Groundwater wells do not satisfactorily meet local demands, as the extracted water often has a high salinity content ((Cirilo, 2008)). Approximately 66% of rural homes lack access to public water supply systems (Brazil (2024)).

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).

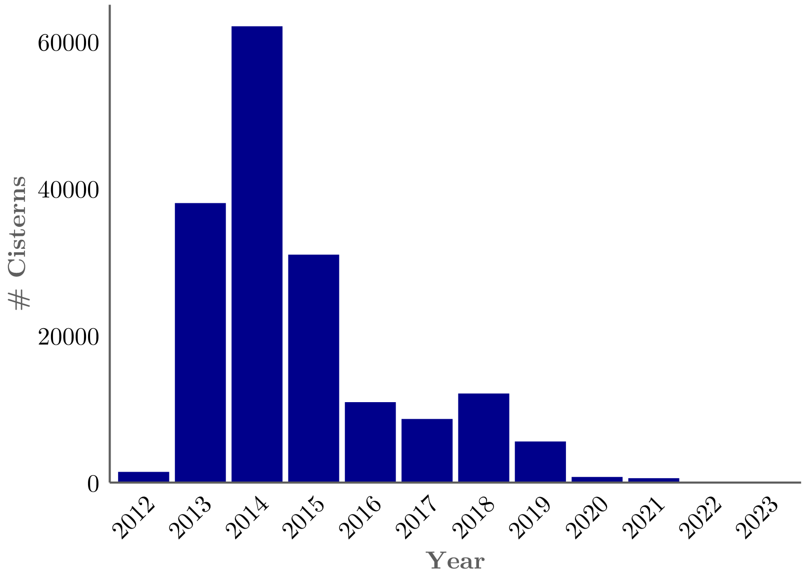
2.2 Second Water Cistern Program

The SWCP is an initiative of the Brazilian government to promote the economic inclusion of families in vulnerable situations, focusing on the semiarid region. In 2011, the government expanded the rainwater collection cistern program, initially intended for human consumption, to include larger cisterns — with a capacity of up to 52 thousand liters to support agricultural production and raise small animals.

This new model, 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.

In recent years, the SWCP has become part of sustainable development in the semiarid region. In addition to 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). 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 benefited over time. 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 their near-disappearance from 2020 onwards, despite the benefits recorded. Administrative data indicate 980 municipalities were served, especially in the Brazilian semiarid region. The high concentration of cisterns in this area reflects the adverse climate conditions, marked by high temperatures and irregular rainfall, with long periods of drought — on average 8 months, interspersed with concentrated rainfall.

Figure 2: Number of Cisterns (2012-2023)



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

2.3 Water Availability, Rural Land Use, and Environmental Outcomes

In this section, we theoretically discuss how water availability policies may affect environmental outcomes and land use patterns in rural areas. To test the effects on environmental outcomes, we hypothesize that water availability policies can influence environmental impacts via land use optimization, agricultural intensification, and resource substitution effects.

Water scarcity constrains agricultural productivity and often forces producers to expand cultivation across larger areas to maintain output levels. Policies that alleviate this constraint can alter the land allocation decisions of rural households. Under improved water security, farmers may shift from extensive to intensive cultivation strategies. The mechanism operates as follows: reliable water access increases the productivity of existing plots, potentially reducing the incentive to bring additional land into production.

This substitution between intensive and extensive margins has implications for deforestation and changes in land cover. Consider a farmer who maximizes profits, subject to constraints on land and water availability. Under scarcity, the farmer may expand the area to maintain output. When interventions increase availability, the enhanced productivity of existing plots may reduce the optimal cultivation area, potentially releasing land for forest recovery. The net environmental effect depends on whether interventions enhance productivity on existing plots or reduce the costs of bringing new land into cultivation.

Water interventions can also transform production systems with environmental implications. In pastoral systems, reliable access enables the maintenance of higher-quality grazing areas, which support more animals per unit area and potentially reduce greenhouse gas emissions per unit of output. This quality upgrading operates through several pathways. Security allows farmers to invest in pasture improvement, soil conservation, and grazing management practices. These investments typically require long-term planning that is only feasible under resource stability.

The resulting improvements in land quality can generate spillover effects, including carbon sequestration, reduced soil erosion, and enhanced biodiversity outcomes. The intensification process may also facilitate the adoption of environmentally beneficial technologies. Stability provides farmers with the foundation to invest in precision techniques, integrated pest management, and climate-adaptive crop varieties, thereby enhancing their ability to produce sustainable yields.

Additionally, water interventions generate benefits through resource substitution that reduces pressure on natural systems and ecosystems. In water-scarce environments, households and farmers often resort to environmentally costly strategies, including groundwater extraction, deforestation around natural sources, and long-distance transport. By providing alternative sources, these interventions can help replace or supplement harmful procurement strategies. Rainwater harvesting systems, for instance, reduce dependence on surface water and groundwater resources, potentially preserving ecological flows and aquifer sustainability.

Interventions may also generate indirect benefits through labor reallocation. When programs reduce the time and labor requirements for water procurement, they may free up household labor for alternative activities, potentially including stewardship or off-farm income generation, which can help reduce pressure on natural resources.

The impacts of water interventions vary across different rural areas depending on baseline ecological conditions, cultivation systems, and demographic characteristics. In regions with high deforestation pressure, programs may yield larger benefits by reducing incentives for expansion. In areas where cultivation is already intensive, interventions may affect production practices rather than land use patterns. Farm size introduces complexity in outcomes. Smaller units may respond more to availability improvements due to their constraints and limited access to infrastructure.

If smallholder farms are more likely to clear forest for subsistence cultivation under stress, programs that enhance their security could generate conservation benefits. Geographic factors, including proximity to natural sources, soil quality, precipitation patterns, and market access, mediate the relationship between interventions and outcomes. Regions with seasonal rainfall variability may exhibit different responses compared to chronically arid areas, as storage becomes important for bridging temporal gaps in availability.

As a result of all three channels, the potential mechanisms indicate that the effects of water availability policies on environmental outcomes are conceptually ambiguous. The theoretical analysis reveals that the net impact depends on the relative magnitudes of competing mechanisms. While access can promote land-use efficiency and reduce ecosystem pressure, it may also lower the costs of expansion in specific contexts.

The outcome depends on several factors: the initial level of stress and productivity, the availability and opportunity cost of potential expansion areas, market incentives for production, and the presence of complementary institutional arrangements such as forest protection regulations or payments for ecosystem services. This theoretical indeterminacy requires empirical investigation to establish the consequences of interventions in specific contexts.

3 Data

Our analysis period covers 11 years, from 2008 to 2018, and the spatial unit of analysis is the property. We work with several publicly available datasets to build a panel at the property-year level. To describe the data, we classify each dataset into two categories: (i) cisterns base and (ii) environmental and output outcomes.

3.1 Cisterns base

CAR base. The Rural Environmental Registry (CAR) is an electronic public registry, mandatory for all rural properties, whose purpose is to integrate environmental information regarding the status of permanent preservation areas (APP), legal reserve areas, forests and remnants of native vegetation, restricted use areas and consolidated areas of rural properties and possessions in the country. Legally established by the Forest Code within the scope of the National Environmental Information System (Sinima) 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. Through the CAR, we have important information about rural properties in the semiarid region, such as the municipality and state to which they belong, the size of the area, legal status, and the geographic limit of each one.

SWCP. We began the analysis with a database of 177,764 cisterns built in the states that make up the Brazilian semiarid region. The database contained information on the latitude and longitude of the cisterns, the city code, the state, the name of the beneficiary, the type of technology used in the construction, and the start and end dates of the works. As an initial step, 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.

With the database validated, we cross-referenced the cisterns to rural properties with the Rural Environmental Registry (CAR) database. This procedure allowed us to identify the properties treated throughout the period analyzed and generated four distinct scenarios: (i) cistern not linked to any property; (ii) cistern linked to a single property; (iii) cistern linked to more than one property; and (iv) more than one cistern linked to the same property. The distribution of observations between the scenarios was as follows: 46,948 cisterns in scenario (i), 66,410 in scenario (ii), and 57,971 distributed between scenarios (iii) and (iv).

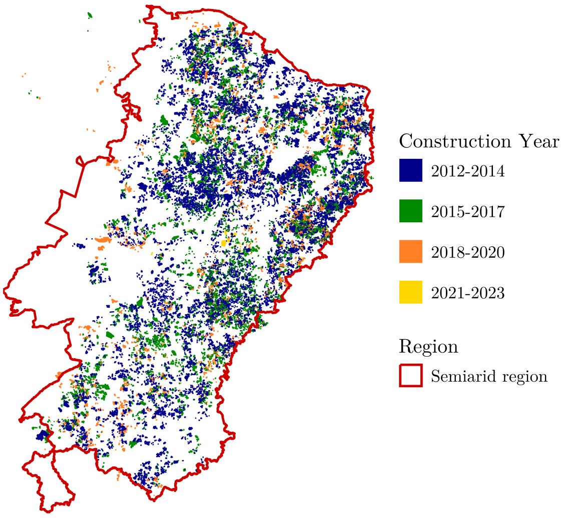
Based on these scenarios, we define the criteria for constructing the samples. Scenario (ii) was considered more appropriate for the main database because it involves a single cistern linked to each property, ensuring clarity in the identification of the treatment and the year of construction. On the other hand, scenarios (iii) and (iv) presented analytical limitations. In scenario (iii), the association of a cistern with several properties generated uncertainty about which properties were effectively treated, increasing the possibility of including untreated properties in the treatment group; in scenario (iv), although it was possible to confirm the treatment status of each property, the presence of multiple cisterns prevented the precise determination of the year of construction, compromising the exact identification of the initial moment of treatment. Scenarios (ii), (iii), and (iv) are exemplified in Figure 1. Given these limitations, the main sample was defined from the 66,410 properties linked to a single cistern, without duplication — case (ii); the distribution of the main base is exemplified in Figure 3. The observations from scenarios (iii) and (iv) were allocated to alternative samples and used in robustness exercises. The first alternative sample, containing 73,937 properties, considered the selection of duplicate cisterns — formed by cases (ii) and (iv). The second, with 79,287 properties, incorporated duplicate properties — formed by cases (ii) and (iii). Finally, the most comprehensive sample, with 88,881 properties, incorporated duplicates of both cisterns and properties — formed by cases (ii), (iii), and (iv).

3.2 Environmental and output outcomes

Land use. We leverage the precision of satellite data from the MapBiomas dataset, which captures land use across semiarid 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, farming, and pasture land used for cattle-raising activities at the property-year level. This high-quality data collection spans from 2008 to 2018, providing a comprehensive view of environmental outcomes.

Pasture Quality. We used data on pasture quality prepared by the Image Processing and Geoprocessing Laboratory (Lapig) of the Federal University of Goiás (UFG). Using vegetation indices obtained by remote sensing, Brazilian pastures were classified into three levels of degradation, Low, Medium, and High, for the years 2000 to 2022.

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 the methodological approach used, rural properties start to have cisterns at different times over time, permanently maintaining the benefits derived from the policy. This treatment occurs in an irreversible and staggered manner, as described in Callaway and Sant'Anna (2021), which allows each property to be associated with a G group, representing the initial year the property begins to benefit from the water resource for agricultural production.

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

Based on the work of 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 parameters.

First, we examine the heterogeneity that arises from the duration of exposure to the treatment. To do this, 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:

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

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

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

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

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

The scenario in question is suitable for the scaled difference-in-differences model, and the approach proposed by Callaway and Sant'Anna (2021) was chosen for its flexibility in the face of different sources of heterogeneity.

For identification, in addition to the assumptions of irreversibility and overlap, two main conditions are adopted: the absence of anticipation and unconditional parallel trends for the group that has not yet been treated. The "absence of anticipation" condition establishes that, before treatment, the potential results 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 the context studied since the families selected for the program are generally informed less than a year in advance, not having enough time to anticipate the effects of the additional water resources. From a practical perspective, the expansion of production (such as the increase in pasture and crop areas) depends on the effective presence of these 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 never-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 adjusted at the farm level for inferences. Confidence intervals for the target parameters are constructed using the multiplier bootstrap procedure, as detailed in Callaway and Sant'Anna (2021).

5 Results

In this section, we present the two sets of average effects of cistern construction for the five outcome variables: agriculture, farm, pasture, forest, and high-quality pasture. Section 5.1 shows the average effect result for all farms that received cisterns at some point (Equation 2). Section 5.2 shows the average effects for each possible time interval size of exposure to the amenities provided by cisterns (Equation 1). All outcome variables are listed as a proportion of the area devoted to that use. Our estimates are interpreted as percentage change relative to the control group (farms that have not yet received cisterns).

5.1 Average effect of cistern construction for all treated properties

The main aim of this study is to summarize the average effect of the treatment across all time groups. The parameter illustrated in equation 2 reflects the average effect of cistern construction across all properties that benefited from the intervention at some point. Table 1 presents the estimates of this parameter for five outcome variables: the proportion of area allocated to agriculture (column I), the proportion of area allocated to farmland (column II), the proportion of area allocated to pasture (column III), the proportion of area allocated to forest (column IV), the proportion of pasture area of high quality (column V), and the proportion of pasture area of low- or medium-quality (column VI). All estimates are based on the double-robust method proposed by Callaway and Sant'Anna (2021), with standard errors clustered at the farm level.

The results indicate a significant decrease of 0.48 percentage points in the total area allocated to agriculture, defined as the sum of farm and pasture areas. Although this decrease may suggest a possible reduction in agricultural production, a disaggregated analysis provides greater detail.

About pasture, a significant reduction of 0.7 percentage points is observed. However, this effect's magnitude is relatively small compared to the proportion of area allocated to pasture in the initial period, which was 55%. This decrease is equivalent to only 1.27% of the pasture area in the baseline. Furthermore, the reduction in pasture extension does not necessarily imply decreased livestock production, considering that productivity is associated mainly with pasture quality. The results show an absolute increase in the proportion of high-quality pasture greater than the decrease observed in total pasture. These results suggest internal substitution, with the final composition showing a more significant share of high-quality pasture, which may indicate a potential gain in livestock productivity.

Concerning crops, the area allocated to plantations increased by 0.22 percentage points, possibly reflecting an increase in total food production. This increase does not appear to have occurred at the expense of forest areas since the average effect of cistern construction on forest areas was positive and significant, estimated at 0.35 percentage points.

These findings indicate that the area used for crops grew primarily in pasture areas, not forest areas. This dynamic has economic and environmental implications. On the one hand, the agricultural area increased, contributing to the food security of the families benefiting from it. On the other hand, maintaining forest areas reduces potential adverse environmental impacts since agricultural expansion on pasture areas—an activity that emits the most greenhouse gases—represents a more environmentally sustainable alternative.

Table 1: Main Results

	Agriculture (I)	Farming (II)	Pasture (III)	Forest (IV)	High-quality Pasture (V)	Low/Medium-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)
# obs	63802	63802	63802	63802	63802	63802
# groups	6	6	6	6	6	6
# treated	63802	63802	63802	63802	63802	63802

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: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

5.2 Average effect of cistern construction for each exposure size

This section shows the average effect for each possible exposure size to the treatment (Equation 1), considering the period analyzed. This parameter is helpful for two reasons: (i) it allows us to test the null hypothesis that the temporal trends between the "eventually 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 increase, decrease or stability. This analysis is also relevant to understand the persistence of the effects as a function of the exposure time.

Figure 4a to Figure 4e present the estimates of the average effects of having a cistern in different periods after its construction, considering all rural properties benefited from the SWCP program for exactly x periods (Equation 1). Outcome variables include the proportion of land devoted to agriculture (Figure 4a), the proportion of land dedicated to crops (Figure 4b), the proportion of land dedicated to pasture (Figure 4c), the proportion of land dedicated to forest (Figure 4d), the proportion of pasture of high-quality (Figure 4e), and the proportion of pasture areas of low- or medium-quality (Figure 4f). Vertical lines indicate 95% confidence intervals based on standard errors clustered at the farm level. Post-treatment effects are shown in green, while placebo estimates for the pre-treatment period are shown in orange. Estimates are based on the double-robust estimator proposed by Callaway and Sant'Anna (2021).

Estimates for the pre-treatment period (orange dots) suggest that effects are statistically insignificant for most variables analyzed, including the estimate just before treatment's start (orange dot in the period -1). These results indicate the absence of significant anticipatory effects related to the construction of cisterns on land use, covering areas designated for agriculture, cultivation, pasture, and forestry. Furthermore, almost all placebo estimates are statistically insignificant, corroborating the plausibility of the assumption of parallel trends in the pre-treatment period for the variables analyzed (point values are in Table A.1 of the Appendix).

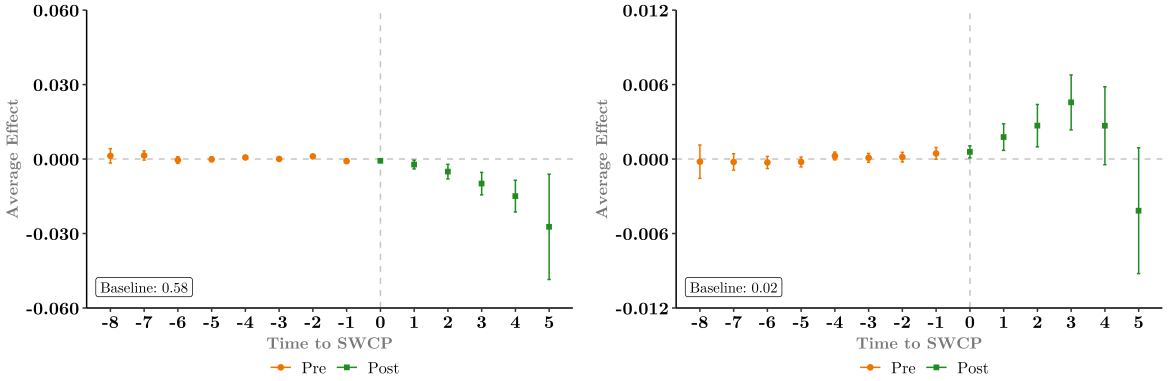
The post-treatment estimates (green dots) indicate significant effects for almost all periods and variables analyzed. In the case of the proportion of area designated for agriculture (Figure 4a), a negative and statistically significant effect is observed in all periods, with the effect intensifying as the time of exposure to the treatment increases. This pattern is strongly influenced by the reduction in pasture area (Figure 4c).

However, the analysis of the proportion of high-quality pasture (Figure 4e) reveals positive and statistically significant effects in all periods, with greater intensity in the extended periods of exposure. These results suggest that, although there was a reduction in the total pasture area, this reduction was predominantly concentrated in low-quality pasture areas. 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.

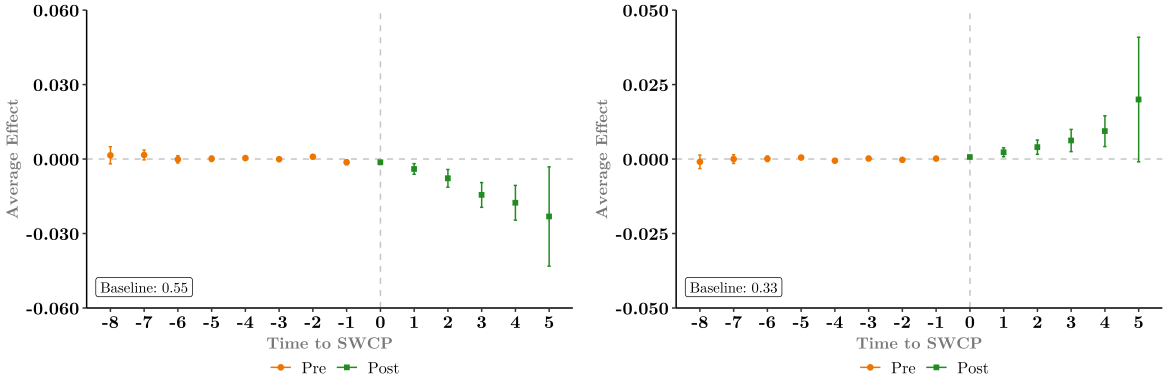
The analysis of the proportion of area allocated to crops (Figure 4b) shows positive and significant effects in most periods, except for exposures longer than four years. However, the absolute effects observed in this variable were smaller than those related to the area allocated to pasture, which is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

The logic underlying these results may be associated with the benefits of water availability from cisterns. The increase in water availability would have made it possible to maintain agricultural productivity during drought, reducing the need to expand crop areas to the detriment of forest areas. This dynamic has promoted greater efficiency in land use, reducing pressure on agricultural and forestry areas.

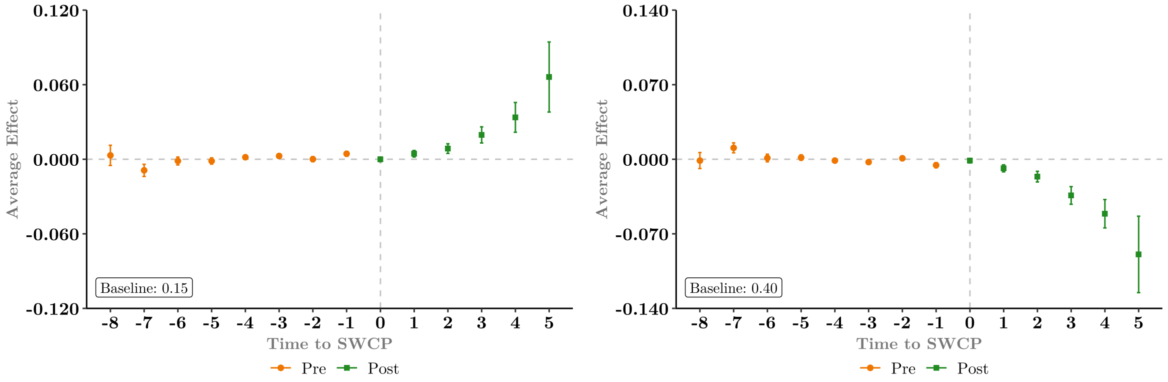
Figure 4: Baseline Results


(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 4a), farming variable equals the share of the area dedicated to 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), high-quality pasture variable equals the share of the pasture area with high quality (Panel 4e), and low/medium-quality pasture variable equals the share of the pasture area with low or medium quality (Panel 4f). 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.

5.3 Heterogeneity Analyses

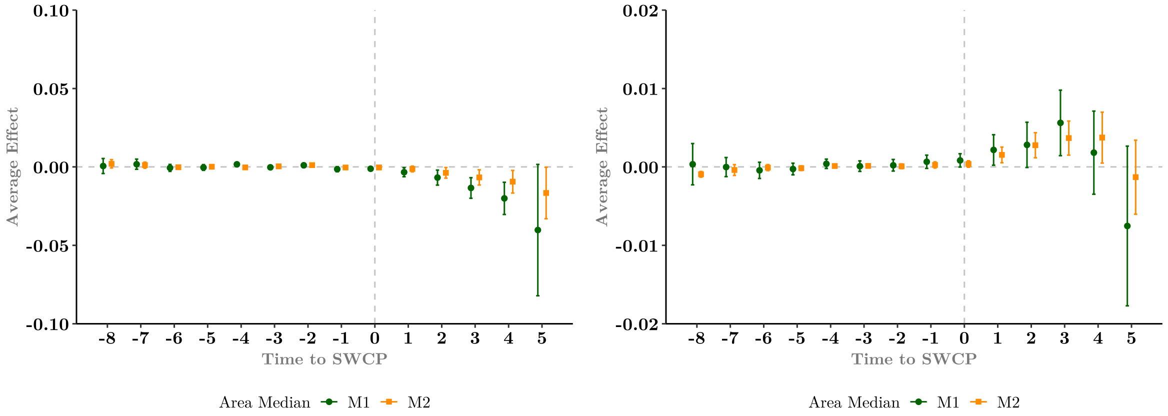
The results indicate a negative effect on the area allocated to pastures and a positive effect on areas dedicated to crops and forests. Initially, these results could be interpreted as environmentally positive due to the increase in vegetation areas and economically harmful due to the reduction in pasture areas. However, it is observed that the reduction in pasture areas occurs exclusively in low-quality pastures. At the same time, there is a net increase in the area of high-quality pastures, which is relevant for the potential productivity of these areas. Nevertheless, an aspect that remains open is the significance of these effects across different categories of rural properties, particularly when comparing larger and smaller properties.

To evaluate the heterogeneity of 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 crops (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 high-quality (Figure 5e), and the proportion of pasture areas of low- and medium-quality (Figure 5f). These results are derived from the methodology described in Equation 1, supplemented by analyzing effects in 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.

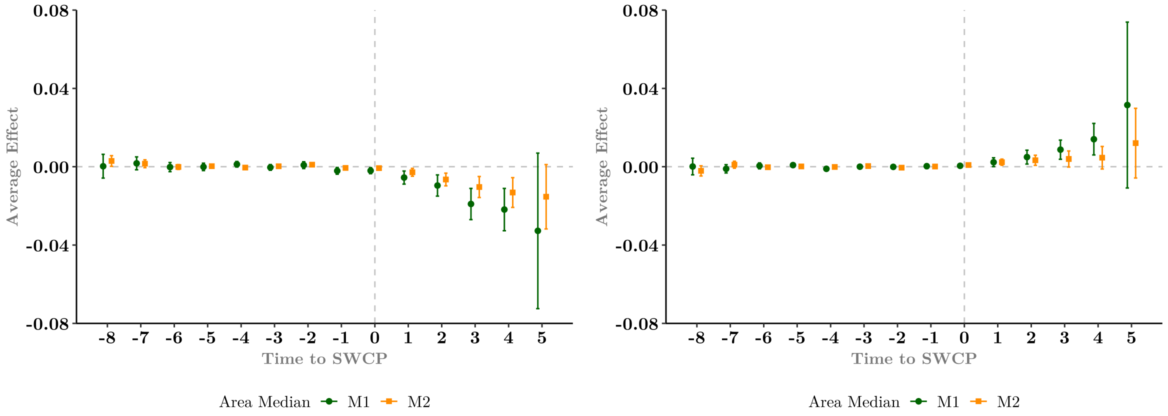
The results show that the effects are generally similar between the two groups of properties. Smaller and larger properties have a negative effect on the total area allocated to agriculture, a positive effect on areas allocated to crops, and a negative effect on pasture areas. However, smaller properties display a slightly more significant average effect in absolute terms than larger ones. When analyzing pasture categories, both high-quality and low- or medium-quality pastures show similar impact patterns across the two groups (M1 and M2). 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 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

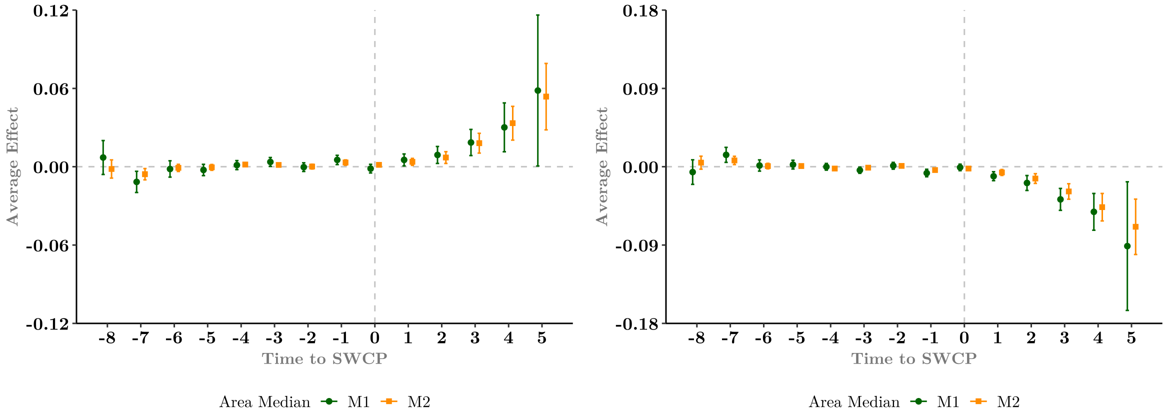
(a) Agriculture Coverage **(b)** Farming Coverage



(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 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 the pasture area with high quality (Panel 5e), and low/medium-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). Post-treatment estimates are reported in green.

5.4 Robustness and Specification Checks

This section presents four sets of robustness checks: the inclusion of cisterns linked to multiple properties, the inclusion of properties associated with multiple cisterns, the simultaneous inclusion of both anterior cases, and the analysis of results using a never-treated control group. In the latter case, treated properties in each period are compared exclusively with those that remained untreated throughout the analysis. Detailed results of these analyses are provided in Appendix A.

In the first scenario, incorporating cisterns associated with multiple rural properties, the results remain consistent in magnitude (Table A.2) and temporal persistence (A.5). Similarly, in the second scenario, where properties linked to multiple cisterns are included, the findings align with the main results, demonstrating consistency in magnitude (Table A.3) and persistence of effects over time (Figure A.6). When a more comprehensive dataset is employed, encompassing both cases—cistern duplication across properties and property duplication across cisterns—the results maintain robustness in magnitude (Table A.4) and temporal persistence (Figure A.7).

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. Table A.5 confirms consistency in magnitude, while Figure A.8 illustrates comparable temporal persistence across all variables analyzed.

Finally, as an additional robustness exercise, we implement an analysis based on buffers around constructed cisterns. This approach utilizes two databases: the main base with 63,802 properties and an expanded base with 164,278 properties. For each base, we define three buffers with distances of 250m, 500m, and 1000m, with the 500m buffer established based on the median area of properties in the main base. Tables A.6 through A.11 present the point estimates of average effects for all outcome variables of interest, while 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 SWCP's cost-benefit in the Caatinga biome, we estimate (i) the government expenditures related to cistern implementation and (ii) the environmental benefit from decreased greenhouse gas emissions resulting from reduced deforestation.

5.5.A Environmental Benefits

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

1. **Establishing Emission-Forest Relationship**: We analyzed regional data from MapBiomas and SEEG databases (2012-2018) to determine the relationship between forest loss and greenhouse gas emissions. 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 participating 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 current 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 Brazil's consumer price index.[3]

5.5.B Program Costs

For our 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). This approach ensures that our cost estimates accurately reflect the actual public investment in the program.

5.5.C 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:

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

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

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

These metrics provide complementary perspectives on the program's economic efficiency over its lifecycle.

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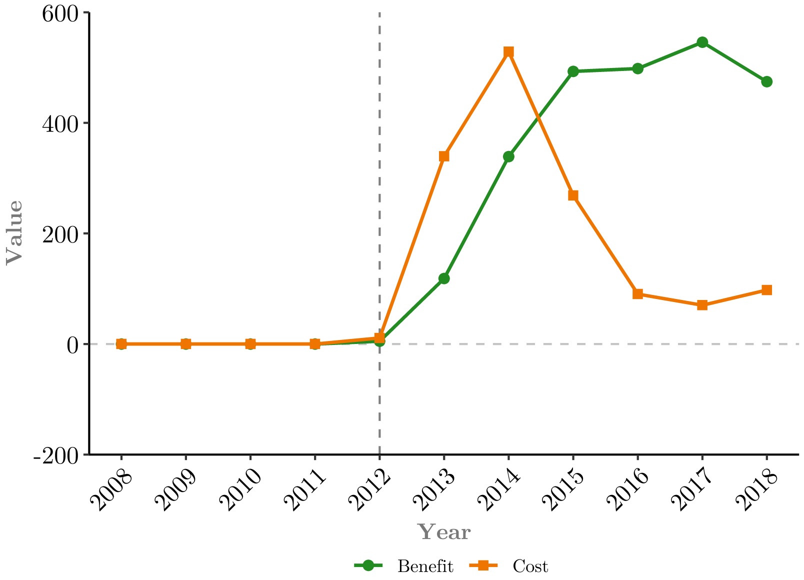
[3] The Social Cost of Carbon represents the monetary value of societal harm caused by adding one ton of carbon dioxide (CO_2) equivalent of greenhouse gases to the atmosphere. The Social Cost of Carbon accounts for diverse impacts ranging from agricultural productivity losses and health effects to property damage from floods, energy system disruptions, conflict risks, environmental migration, and ecosystem service degradation. CO_2 equivalent consists of a common measure in which the amounts of all greenhouse gases are converted to the equivalent amount of CO_2 based on their Global Warming Potential (GWP). Brazil's consumer price index is called IPCA ("Índice de Preços ao Consumidor Amplo").

5.5.D Results and Policy Implications

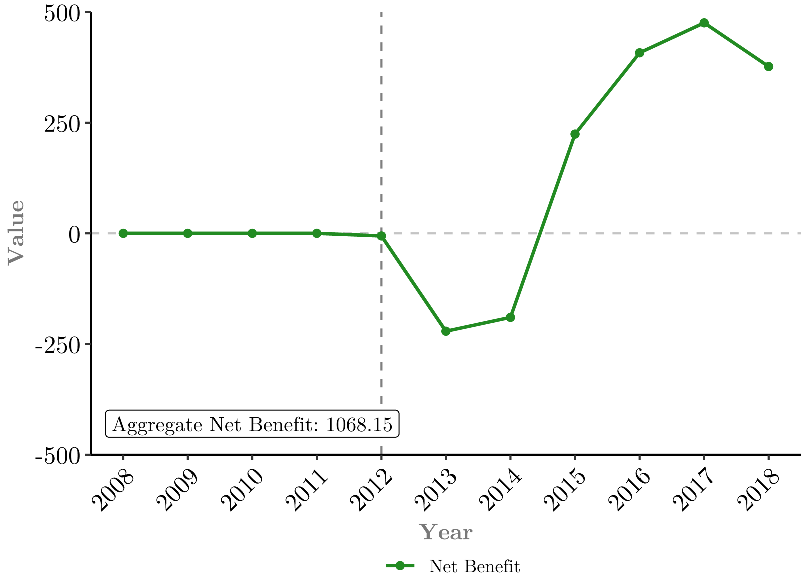
Our empirical analysis reveals a clear temporal pattern in the costs and benefits of the water storage program. Figure 6 illustrates the evolution of program costs and benefits from 2008 to 2018, while Figure 7 displays the resulting net benefits over the same period.

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 circles 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 presents 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). However, starting in 2015, net benefits became strongly positive and increased substantially. Over the entire study period, the program generated an aggregate net benefit of 1,062.08 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. Hendren and Sprung-Keyser (2020) define the MVPF as:

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

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 causal effect of the policy.

In the case of the cisterns program, we have 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 this reason, we adopted $\Delta C = 0$. Even if there are some long-term benefits regarding government costs ($\Delta C > 0$), this suggests 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 Second Water Cistern Program (SWCP) 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 emissions reduction. 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. The positive net returns observed in our analysis confirm the program's economic viability.

This study demonstrates the value of comprehensive cost-benefit analyses that capture both direct program benefits and environmental co-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 examines how climate adaptation policies affect production and environmental outcomes in vulnerable regions. Analyzing Brazil's Second Water Cistern Program in the semiarid region, we find that improved water availability through cistern construction generated significant changes in land use patterns and agricultural practices.

Our empirical findings reveal several important dynamics in agricultural land use. While total agricultural area decreased, this reduction was accompanied by increases in high-quality pasture areas and forest coverage. The analysis demonstrates expanded cropland without corresponding deforestation, suggesting more efficient land use practices. The substitution of low-quality pastures with high-quality ones indicates potential gains in livestock productivity without environmental degradation. This pattern suggests that water security can enable farmers to intensify production on existing agricultural land rather than expanding into forested areas.

The impacts were generally consistent across property sizes, though slightly more pronounced for smaller properties, indicating that the program successfully reached its target population while generating broader benefits. This finding is particularly relevant given the program's focus on supporting small-scale farmers in vulnerable conditions. The consistency of effects across different property sizes suggests that water availability constraints affect agricultural productivity regardless of farm scale. However, smaller producers may face more significant limitations in adapting to water scarcity.

The results demonstrate that well-designed water security interventions can simultaneously enhance agricultural productivity while preserving natural resources, offering a path toward sustainable adaptation to climate change. This finding challenges the common assumption that agricultural development in water-stressed regions necessarily comes at the expense of environmental conservation. Instead, our evidence suggests that addressing water security constraints can lead to more sustainable land use practices.

This research contributes to understanding how adaptation measures affect mitigation efforts through land use changes, addressing an important gap in the climate policy literature. The findings have implications for policy design in other regions facing similar challenges. Adaptation policies can be designed to avoid potential conflicts with environmental goals, particularly when they enable more efficient resource use.

Future research could explore several important dimensions: the long-term sustainability of these effects, their replicability in other arid and semiarid regions, and the specific mechanisms through which water security enables more sustainable land use practices. Additionally, investigating the program's cost-effectiveness and potential for scaling could provide valuable insights for policymakers in other regions facing similar climate adaptation challenges.

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Online Appendix to "How Do Climate Adaptation Policies Affect Production and Environmental Outcomes? Evidence from a Water Policy"

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A Extra Tables and Figures

A.1 Tables

Table A.1: Models Results

Time to SWCP	Agriculture	Farming	Pasture	Forest	High-quality Pasture	Low/Medium-quality Pasture
	(I)	(II)	(III)	(IV)	(V)	(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	-0.0046^{***}	0.0017^{***}	-0.0062^{***}	0.0037^{***}	0.0094^{***}	-0.0156^{***}
Effect	(0.00065)	(0.00037)	(0.00082)	(0.00058)	(0.00113)	(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	-0.0028^{***}	0.0016^{***}	-0.0044^{***}	0.0019^{***}	0.0090^{***}	-0.0134^{***}
Effect	(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	-0.0032^{***}	0.0022^{***}	-0.0054^{***}	0.0025^{***}	0.0089^{***}	-0.0143^{***}
Effect	(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	-0.0021^{***}	0.0016^{***}	-0.0037^{***}	0.0018^{***}	0.0088^{***}	-0.0125^{***}
Effect	(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	-0.0014^{***}	0.0007^{***}	-0.0021^{***}	0.0017^{***}	0.0081^{***}	-0.0102^{***}
Effect	(0.00024)	(0.00016)	(0.00028)	(0.00021)	(0.00049)	(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.

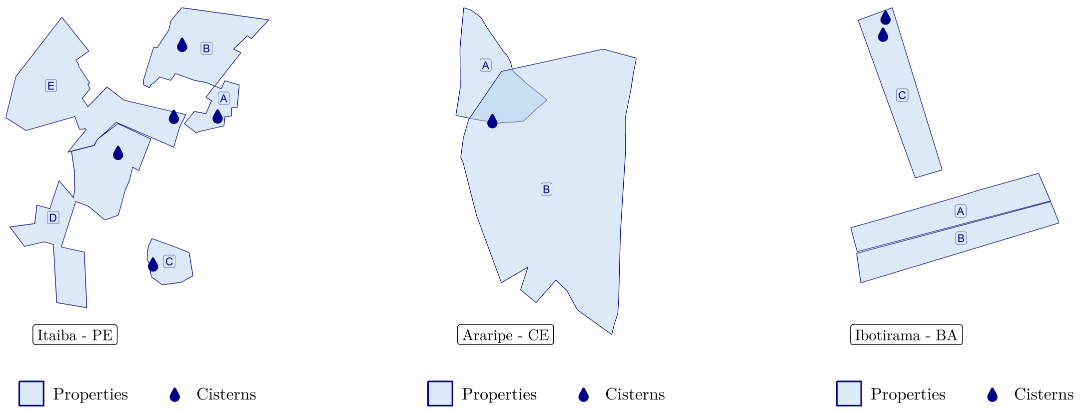
Table A.13: Mean Cistern Costs by State

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



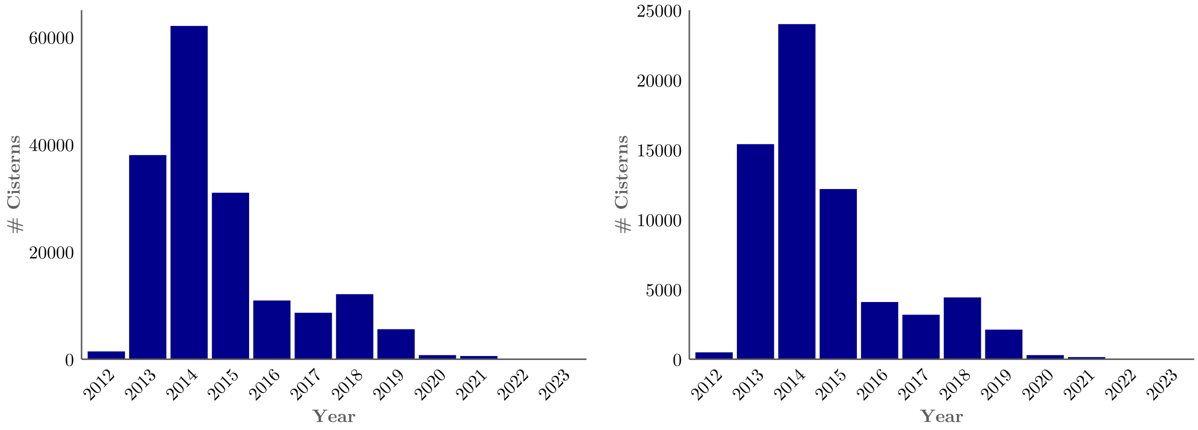
(a) 1 cistern : 1 property

(b) 1 cistern : N properties

(c) N cisterns : 1 property

Notes: Cases of cistern distributions after geographical attachment to rural properties. Panel (A.2a) shows the desired case, in which a single cistern is assigned to a single rural property. Panel (A.2b) shows the case in which a cistern is assigned to more than one property. Panel (A.2c) shows the case where several cisterns are assigned to a single property.

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

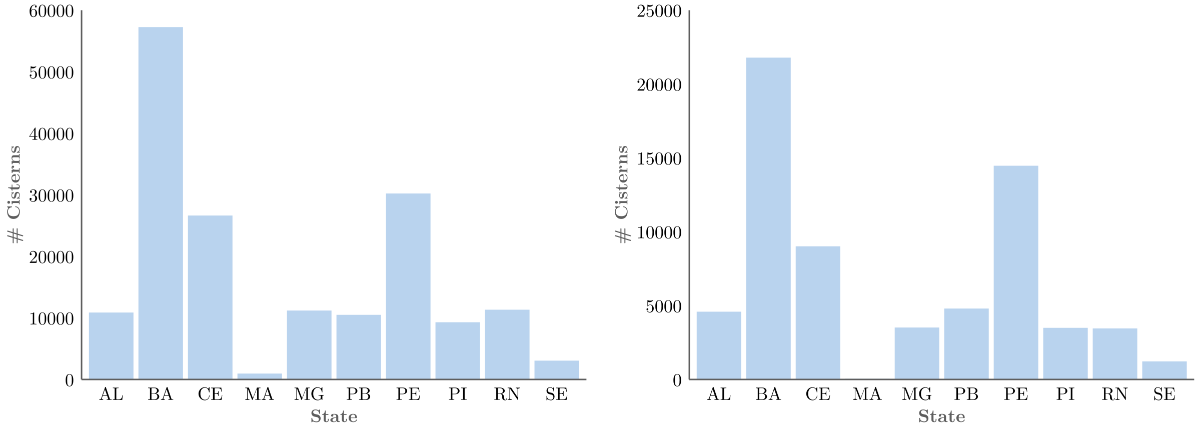


(a) Number of Cisterns in initial base by year (2012-2023)

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

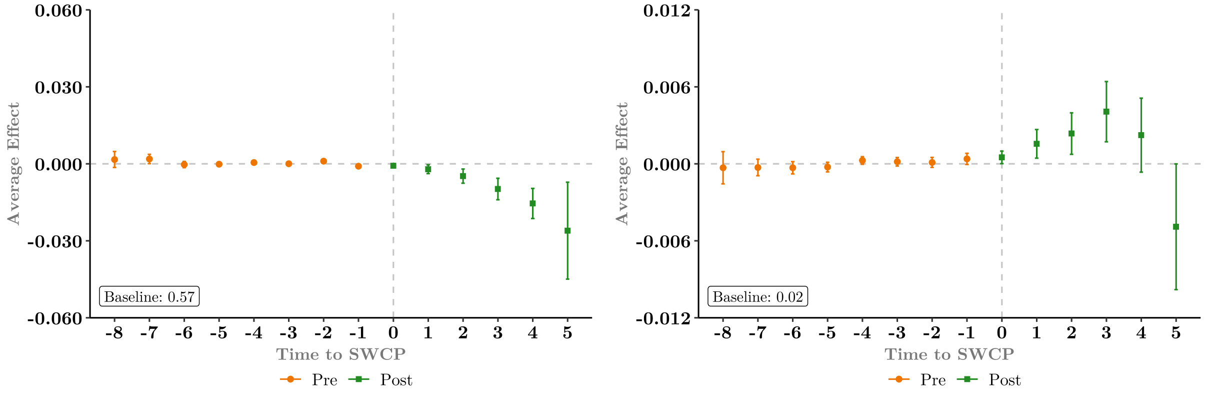
(c) Number of Cisterns in initial base by state

(d) Number of Cisterns in final base by state



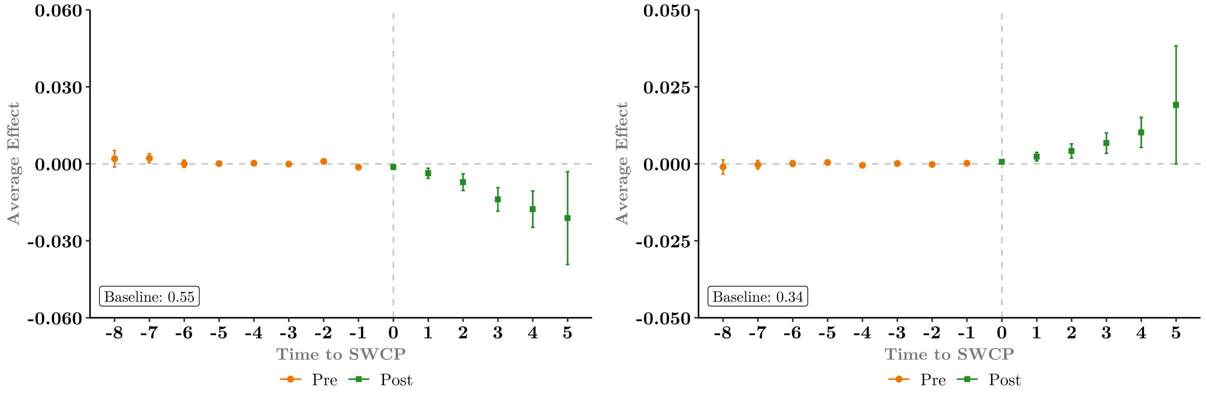
Notes: Cisterns distributions by year and state, considering initial and final bases. Panel (A.4a) shows the distribution of cisterns by year, considering the initial base. Panel (A.4b) shows the distribution of cisterns by year, considering the final base. Panel (A.4c) shows the distribution of cisterns by state, considering the initial base. Panel (A.4d) shows the distribution of cisterns by state, considering the final base.

Figure A.5: Cistern Base - Results



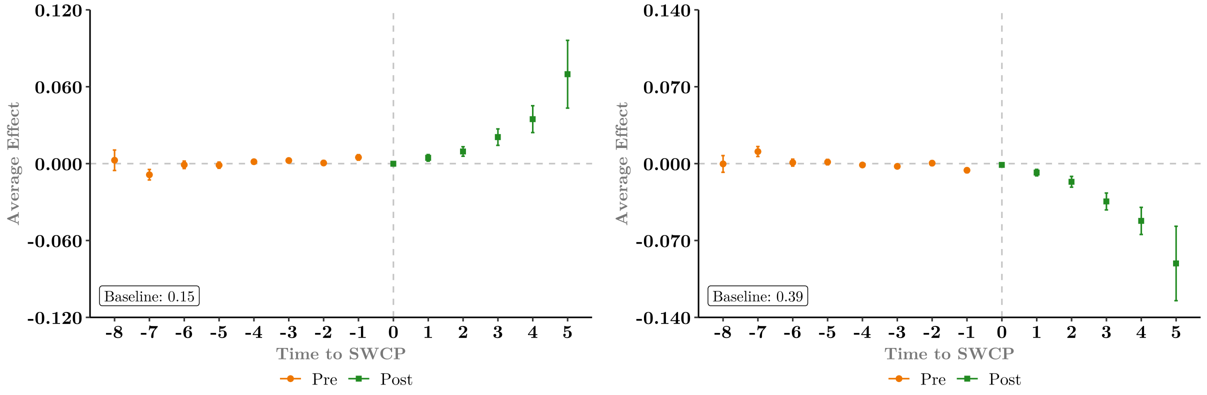
(a) Agriculture Coverage

(b) Farming Coverage



(c) Pasture Coverage

(d) Forest Coverage

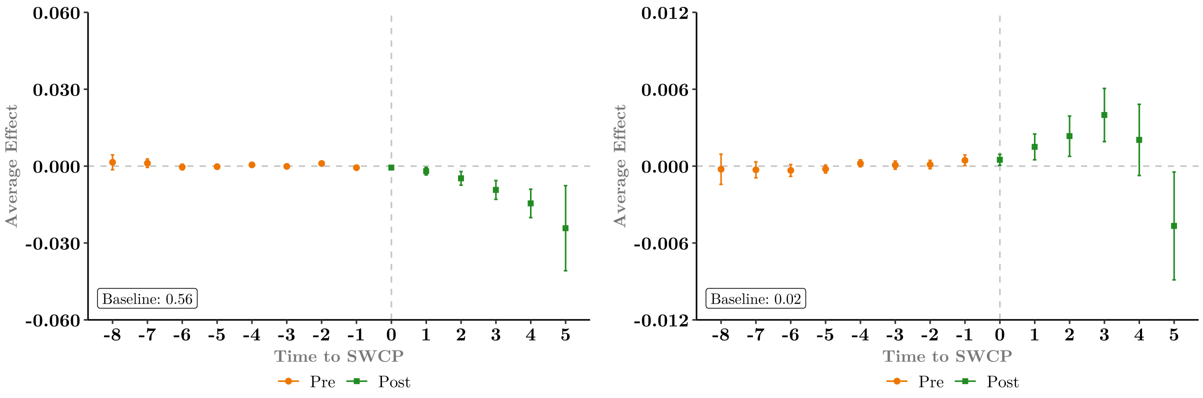


(e) High-quality Pasture Coverage

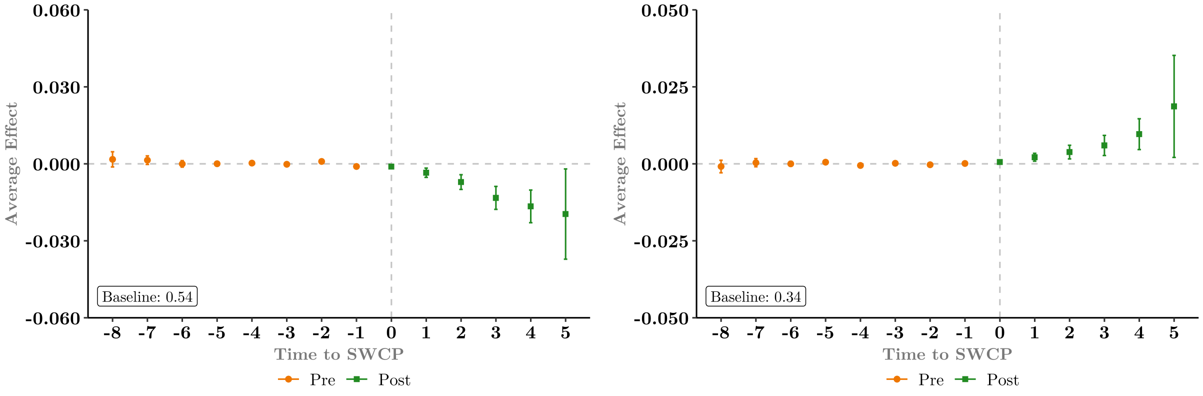
(f) Low/Medium-quality Pasture Coverage

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 **??**), 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 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.

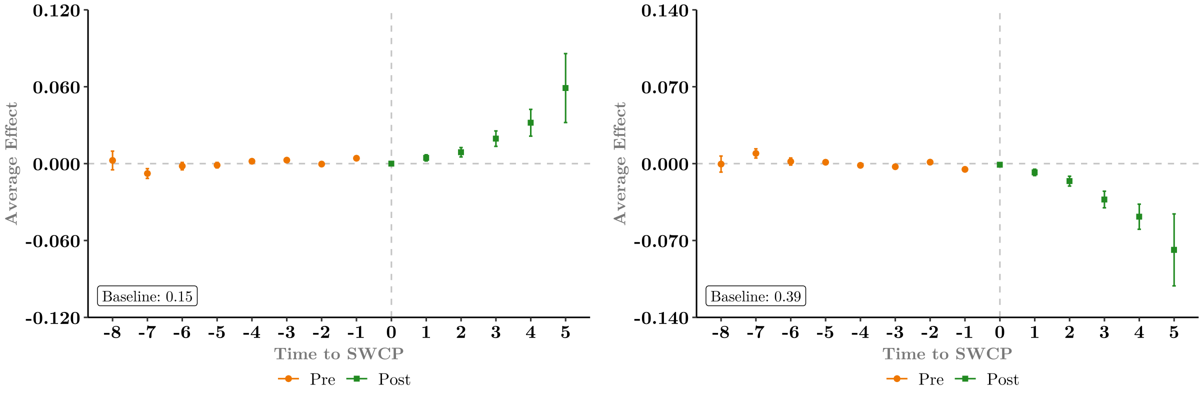
Figure A.6: Property Base - Results



(a) Agriculture Coverage **(b)** Farming Coverage



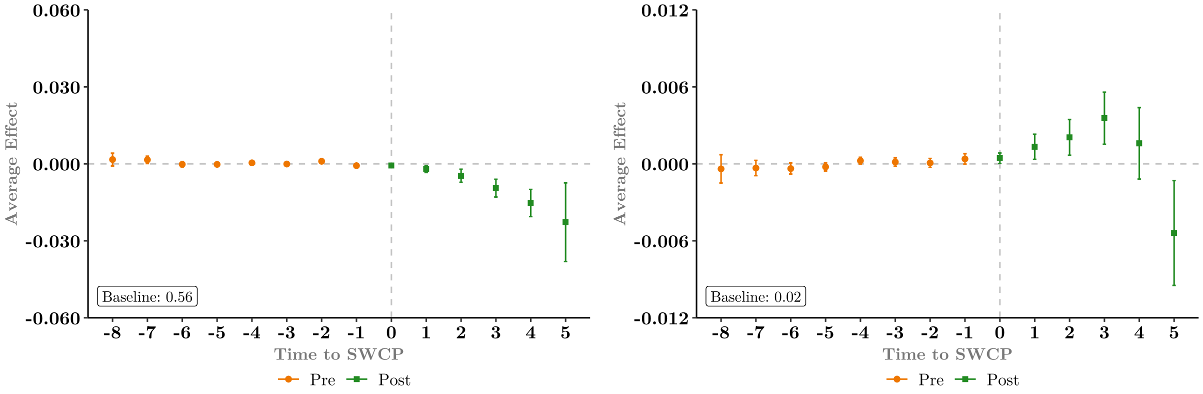
(c) Pasture Coverage **(d)** Forest Coverage



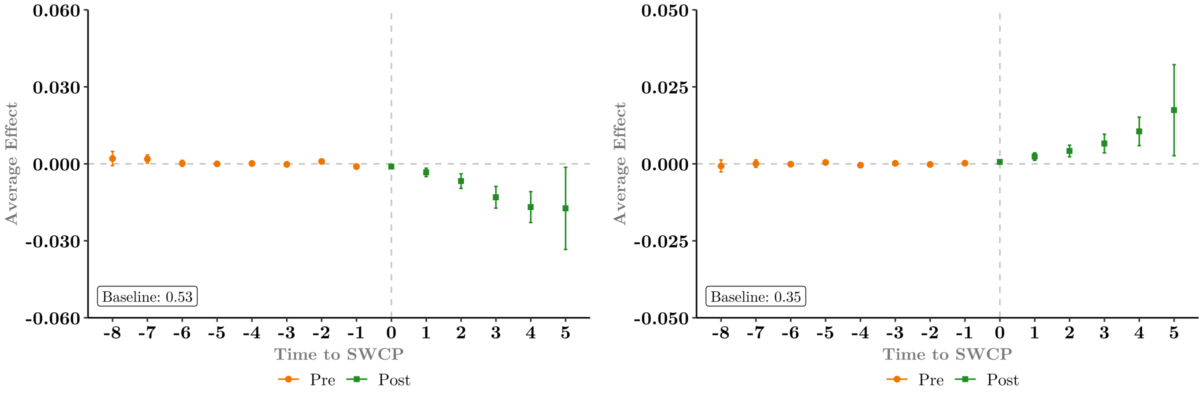
(e) High-quality Pasture Coverage **(f)** Low/Medium-quality Pasture Coverage

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.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 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.

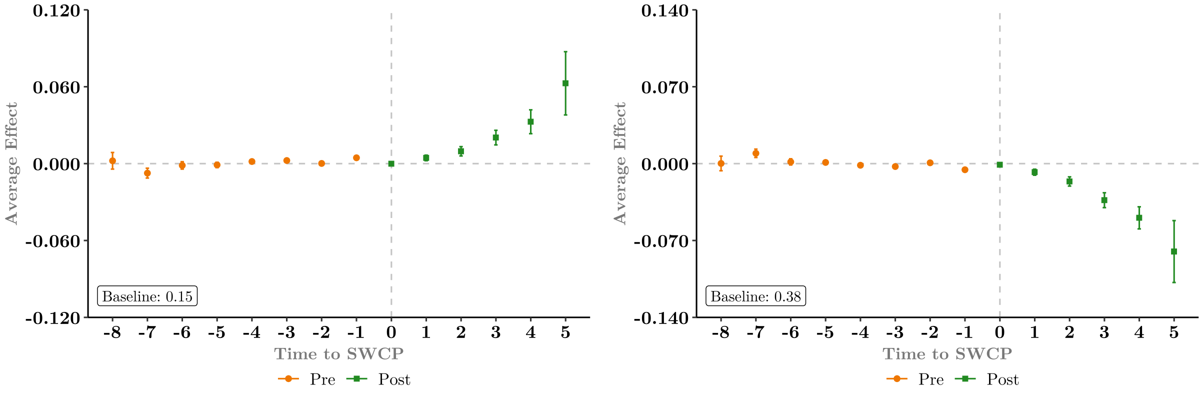
Figure A.7: All Base - Results



(a) Agriculture Coverage **(b)** Farming Coverage



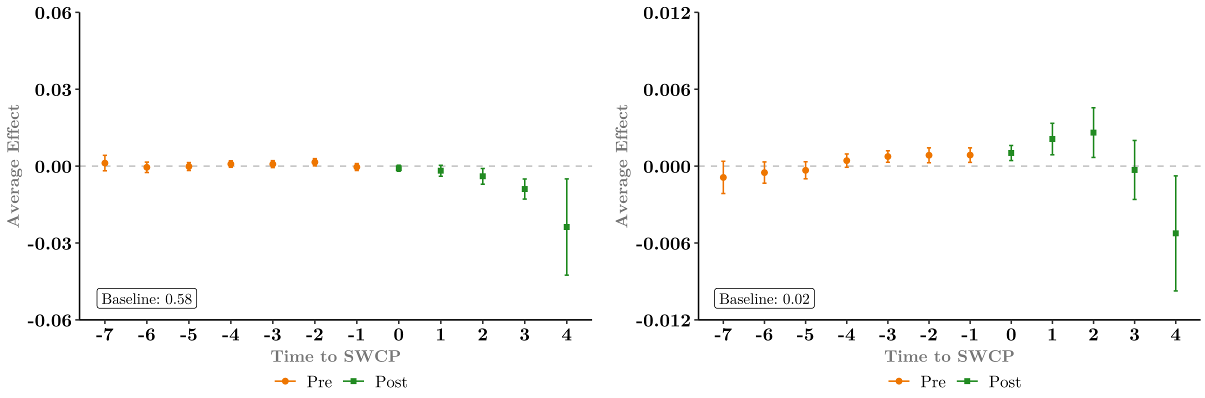
(c) Pasture Coverage **(d)** Forest Coverage



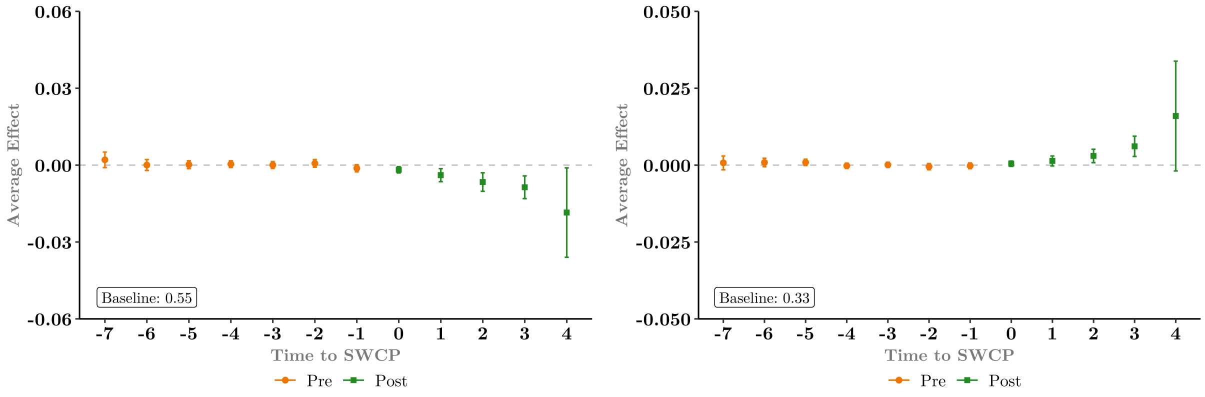
(e) High-quality Pasture Coverage **(f)** Low/Medium-quality Pasture Coverage

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.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 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.

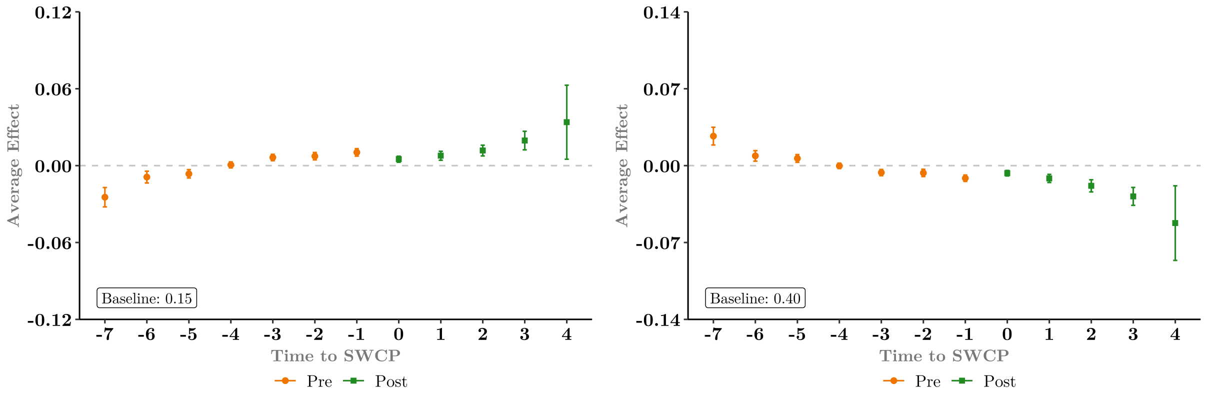
Figure A.8: Never Treated - Results



(a) Agriculture Coverage **(b)** Farming Coverage



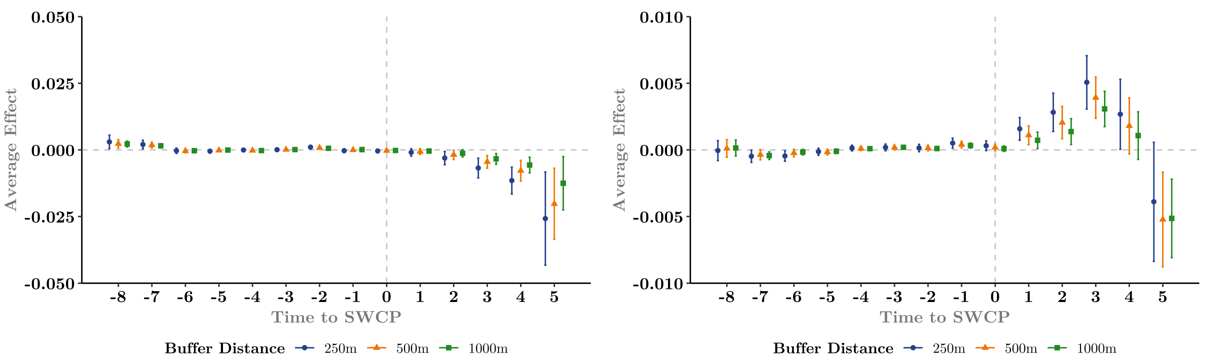
(c) Pasture Coverage **(d)** Forest Coverage



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

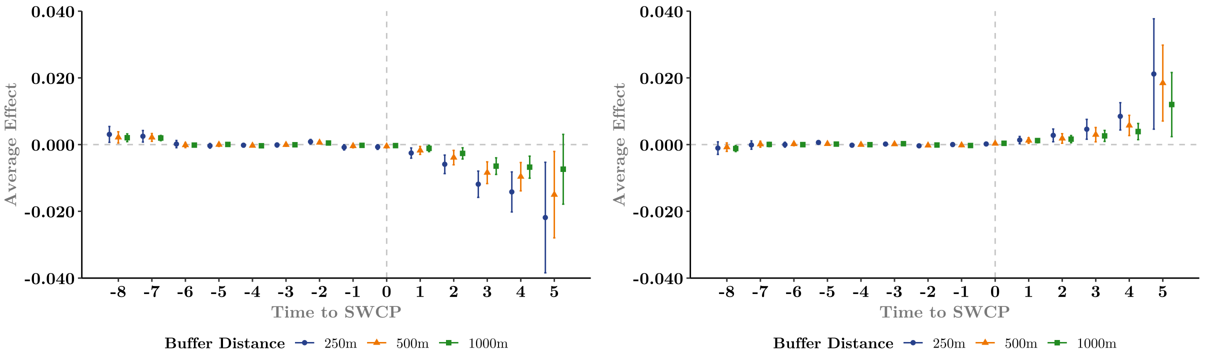
Notes: All results are expressed in percentage points (0-1 scale). The figure shows the baseline results, where the agriculture variable equals the share of the area dedicated to farming and pasture (Panel A.8a), farming variable equals the share of the area dedicated to farming (Panel A.8b), pasture 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 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.

Figure A.9: Buffers - Results - Main Base



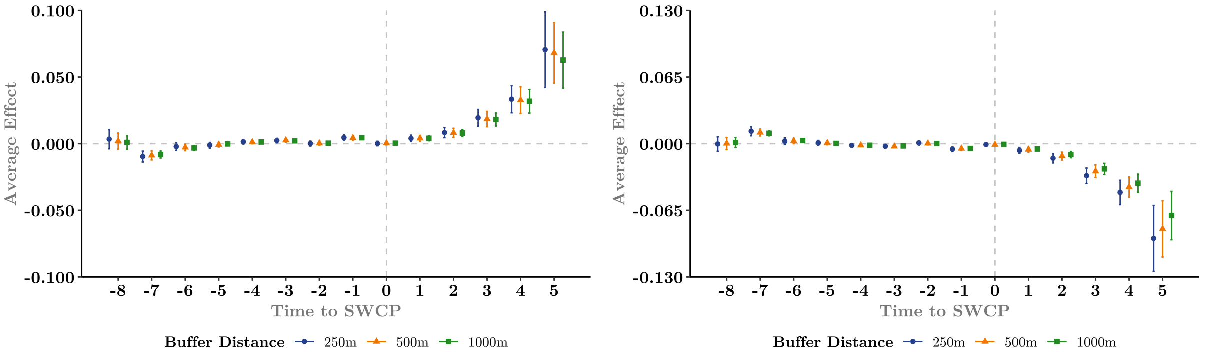
(a) Agriculture Coverage

(b) Farming Coverage



(c) Pasture Coverage

(d) Forest Coverage

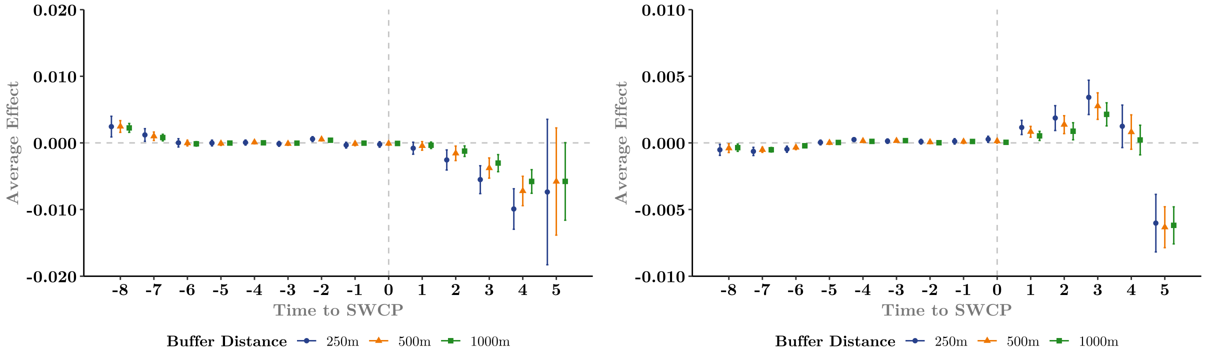


(e) High-quality Pasture Coverage

(f) Low/Medium-quality Pasture Coverage

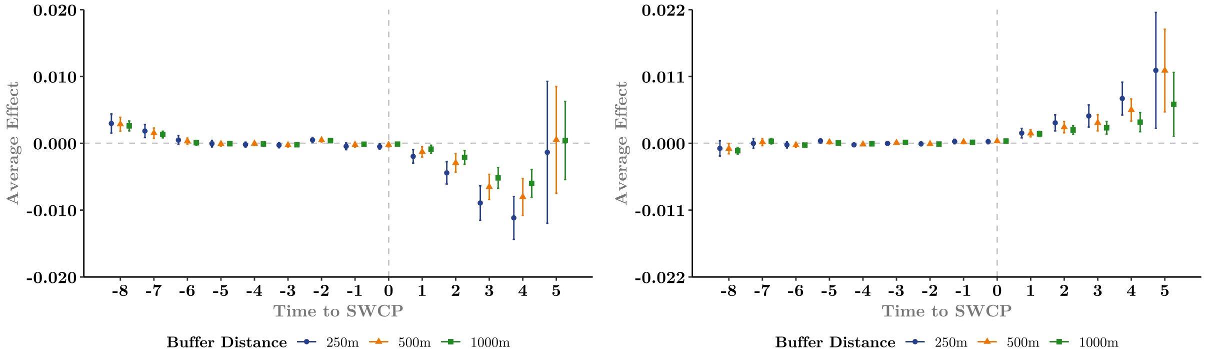
Notes: All results are expressed in percentage points (0-1 scale). The figure shows the buffers results, where the agriculture variable equals the share of the area dedicated to farming and pasture (Panel A.9a), farming variable equals the share of the area dedicated to farming (Panel A.9b), pasture 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



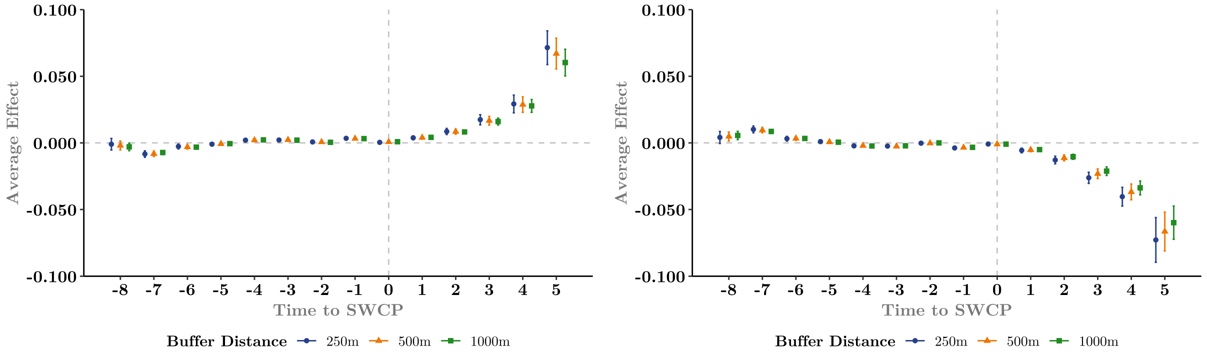
(a) Agriculture Coverage

(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.