TECHNICAL REPORT

Impacts of Water Bunds on Vegetation and Soil Moisture in Pastoral Land in Kenya

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Front cover photo: People drawing water from Itare River. (*photo*: Sande Murunga/CIFOR)
Back cover photo: Maasai father and son tend to their cattle in their paddock in Kitengela, Kenya (*photo*: Stevie Mann/ILRI).

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1. Introduction

Arid and semi-arid lands (ASALs) cover over 80% of Kenya's lands, and are home to around 30% of Kenya's population whose livelihood depends on a mix of pastoralism and small-scale agriculture (International Union for Conservation of Nature 2024). These regions are among the most severely affected by land degradation in the country: nearly 80% of Kenya's landmass is affected by land degradation, and approximately 30–40% of the arid and semi-arid lands are rapidly being lost through degradation, with an additional 2% already completely degraded (Mganga 2023). These lands have been degraded by deforestation, overgrazing, droughts and floods, poor rainfed and irrigation practices, population pressure, and mineral mining activities (International Union for Conservation of Nature 2024; Mganga 2023), making them increasingly vulnerable to desertification. Land degradation has resulted in salinization, soil compacting, degradation of vegetation, and soil erosion (Mganga 2023). Although these threats have persisted for generations, climate change has intensified land degradation in these environments (Downing and Olago 2024). It has been estimated that between 2001 and 2009, the total economic value of land degradation in Kenya was about 1.3 billion USD annually (Mulinge et al. 2016). Such large-scale land degradation threatens the livelihoods of the roughly 16 million marginalized people who reside in these fragile landscapes.

Given the scale of degradation and the limited financial resources available to communities and governments across the ASALs, nature-based solutions (NbS) have gained recognition as a low-cost, gender-responsive and locally grounded approach to restoring degraded land (Downing and Olago 2024). Among the various nature-based restoration techniques promoted in drylands, water bunds, also known as semi-circular bunds, demi-lunes, or half-moons, have become one important intervention to enhance the establishment of native perennial grasses (Kimiti et al. 2017; Mganga et al. 2015, 2019). These bunds are rainwater harvesting structures consisting of digging semi-circular holes on the ground with the opening perpendicular to the flow of water. These structures primarily serve to slow down and retain runoff, ensuring that the plants inside them receive necessary water (Itabari et al. 2011). Anecdotal evidence suggests that water bunds have the potential to improve both environmental and socioeconomic outcomes across a range of dryland settings. However, robust empirical evidence establishing the causal effects of water bund construction on environmental outcomes remains limited. This study addresses this gap by evaluating the environmental impacts of water bunds implemented by a non-governmental organization engaged in restoring degraded dryland ecosystems through nature-based solutions in Kenya.

The remainder of the report is organized as follows: Section 2 provides the study context, and Section 3 presents the theory of change. Sections 4 and 5 describe the data and empirical strategy, respectively. Section 6 presents the descriptive statistics, the estimated Average Treatment Effects on the Treated (ATT), and the dynamic treatment effects. Section 7 concludes.

2. Context of the Study

In this study, we evaluate the environmental impacts of water bunds implemented by Justdiggit, a non-governmental organization working to restore degraded dryland ecosystems through nature-based solutions. The description of the intervention presented in this section draws on discussions with Justdiggit staff, project documentation, and insights gathered during a scoping field visit in June 2026 to an intervention site in Kajiado County. During the field visit, we engaged with a range of stakeholders, including programme managers, community leaders, members of grazing committees, women's Grass Seed Bank groups, and pastoral households who are direct beneficiaries of the intervention.

Justdiggit's primary objective is to regenerate degraded landscapes by improving rainwater infiltration and restoring vegetation; and strengthening the resilience of pastoral communities to climate variability. Between 2016 and 2025, the organization constructed more than 746,000 water bunds across 33 project sites in Kenya, covering the Amboseli, South Rift, Chyulu, Mid-Tana, and Northern landscapes. The intervention is currently being implemented across 30 sites in Kajiado County, two in Samburu County, and one in Taita Taveta County. These project sites are located within Kenya's arid and semi-arid lands (ASALs), where rainfall is highly variable and water scarcity is a major constraint to ecosystem productivity and rural livelihoods. These landscapes are characterized by recurrent droughts, land degradation, and declining vegetation cover, which reduce the availability of forage for livestock and increase the vulnerability of pastoral households. The subdivision of former group ranches into individual landholdings has compounded the problem, shrunken communal grazing areas and thus further limiting access to forage. Furthermore, rapid urbanization, population growth, and ongoing structural transformation are accelerating the conversion of rangelands to residential and commercial uses, prompting many pastoral households to sell their land. These factors have fragmented traditional grazing landscapes, restricted livestock mobility, and intensified pressure on the remaining communal pastures. From a socio-economic perspective, declining access to forage has important implications for pastoral households. As grazing resources become increasingly scarce, men often migrate with livestock to distant grazing areas in search of pasture and water, leaving women and children behind. Women consequently assume sole responsibility for household management and caregiving while also experiencing reduced access to milk and other livestock-derived products, which are critical for household nutrition and income. To address these complex problems associated with degraded and fragmented land, Justdiggit's restoration approach utilizes two complementary interventions: (i) the construction of water bunds on degraded communal rangelands to improve water retention and soil moisture, and (ii) the Grass Seed Bank (GSB) Programme, which promotes grassland restoration through the production and dissemination of native grass seeds via women's groups.

Water Bunds are small semi-circular earth embankments constructed by hand to capture rainfall runoff, increase soil moisture infiltration, to restore degraded dryland landscapes. They are 3-5 meters wide and 20-40 cm high, spaced across hillslopes with the 'closed' side of the earth smile directing downwards to capture water running downhill. It is estimated by Justdiggit that a single bund can help green an area of about 124 m^2 and can collect and store 2,100 litres of water (Just Diggit 2024; JustDiggit 2025). Water bunds can also create micro-environments suitable for fodder production, vegetable cultivation, and dry-season feed reserve. To facilitate vegetation recovery, restored areas are typically protected from livestock grazing for two to five years following water bund construction. During this recovery period, community grazing committees establish and enforce local by-laws that restrict grazing until sufficient vegetation has regenerated. This temporary exclusion allows native grass and other vegetation to be established, reducing the risk of overgrazing and increasing the likelihood of long-term success of landscape restoration. Once adequate vegetation cover has been restored, the land is gradually reopened for controlled grazing, increasing the availability of forage for pastoral communities while improving the resilience of rangelands to drought. An important feature of the intervention is that water bunds are constructed entirely by hand rather than using heavy machinery, making the program highly labor-intensive and generating local employment opportunities during implementation. Construction employs both men and women from surrounding communities, providing an additional source of income alongside the environmental benefits of the intervention. Just Diggit sets an upper limit for each worker on the number of bunds they can construct. On average a worker can construct a maximum of six water bunds per day and receives around KES 200 per bund (~ USD 1.5), creating short-term employment while simultaneously investing in long-term ecosystem restoration. The cap of six bunds per worker per day is applied to safeguard construction quality and discourage workers from prioritizing volume over proper construction to maximize their daily earnings. This labor-intensive approach not only lowers construction costs and enables restoration in remote landscapes but also ensures that local communities directly benefit through wage employment and active participation in restoring their natural resource base.

The Grass Seed Bank (GSB) Program complements water bund construction by promoting community-led restoration while creating livelihood opportunities, particularly for women. Under the program, women's groups comprising approximately 20 members are established across intervention sites to cultivate indigenous grass species that are well adapted to local ecological conditions. The harvested products, including grass seed and hay, are sold to Justdiggit and other local buyers, generating an independent source of income for women in pastoral communities where ownership of land and livestock is often limited. Income earned through the program is commonly invested in children's education, house construction, household assets, and small businesses, thereby potentially strengthening women's economic empowerment and decision-making within the household. Ecologically, the program increases the local availability of native grass seeds, which are used to reseed newly constructed water bunds and accelerate vegetation recovery. Increased grass production also expands the availability of forage for surrounding communities, with the potential to improve livestock productivity, increase herd sizes, and strengthen household resilience to drought. By linking ecological restoration with income generation, the GSB program reinforces the long-term sustainability of landscape restoration efforts while delivering both environmental and socio-economic benefits.

Against this background, this study focuses on evaluating whether the large-scale rollout of water bunds has achieved its intended environmental objectives. Using satellite-derived measures of vegetation, soil moisture, and radar backscatter, we estimate the causal effects of water bund construction on ecosystem recovery across treated landscapes. These biophysical outcomes represent the first stages of the intervention's theory of change and provide evidence on whether water bunds create the ecological conditions necessary for longer-term livelihood improvements.

3. Theory of Change

Small-scale rainwater harvesting interventions, such as water bunds, are expected to generate a range of hydrological, ecological, and socio-economic impacts. From a hydrological and ecological perspective, water bunds intercept and slow the flow of surface runoff during rainfall events, allowing more water to infiltrate into the soil while reducing runoff losses and soil erosion (van der Vliet et al. 2024; Jemberu et al. 2017). As a result, such structures could potentially capture rainfall and retain it within the landscape rather than being lost downstream. The immediate consequence of this process could be an increase in both surface and subsurface soil moisture. Improved soil water availability could also create favorable conditions for seed germination and enhance plant growth. Over a longer period, such changes are expected to increase vegetation greenness, above-ground biomass, and overall rangeland productivity, while also improving ecosystem resilience to drought and climate variability.

Moreover, the ecological improvements generated by water bunds are expected to extend beyond environmental restoration and generate important socio-economic benefits for local communities. The manual construction of water bunds has the potential to increase local employment opportunities for both men and women, which could provide additional source of income. Furthermore, improved vegetation cover and increased biomass could also enhance the availability of forage, which can in turn improve livestock productivity, increase milk production, reduce livestock mortality during dry periods, and strengthen household incomes. Greater availability of pasture within local rangelands is also expected to reduce the need for men to undertake long-distance seasonal migration with livestock in search of grazing resources. As a result, families can remain together for longer periods, reducing the burden on women who often manage households alone during migration and increasing household access to milk and other livestock products. By increasing the capacity of landscapes to retain rainfall and sustain vegetation, water bunds also enhance resilience to drought and climate variability while contributing to long-term land restoration. Collectively, these environmental and livelihood improvements have the potential to reduce vulnerability to climate shocks, strengthen food and nutrition security, promote women's well-being, and improve the overall resilience and welfare of rural pastoral households.

Figure 1 summarizes the theory of change. While this report's empirical analysis focuses on hydrological and ecological pathways, the broader livelihood and social outcomes, expected to emerge over the longer term through improved ecosystem functioning, are being examined through a separate household-level survey of pastoral communities and will be presented in a subsequent study.

Figure 1. Theory of Change for Water Bund Interventions: Pathways through which water bunds influence hydrological and ecological processes and, in turn, contribute to socio-economic outcomes and longer-term development goals.

4. Data

To examine the causal impact of water bunds on vegetation dynamics and soil moisture, we use multiple remotely sensed Earth observation datasets. All geospatial datasets were processed and extracted using Google Earth Engine (GEE), which enabled consistent preprocessing, temporal aggregation, and spatial harmonization across datasets. Temporal aggregation was performed to generate annual measures from the native temporal resolutions (daily, 8-day, 16-day, or monthly), while spatial harmonization involved resampling all variables to a common 1 km grid.

i. **Vegetation:** Vegetation outcomes are measured using the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD13Q1 Version 6.1 product. The dataset provides 16-day composite vegetation indices, including the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), at a spatial resolution of 250 m. Annual averages were computed from the 16-day composites for the period 2014–2025, after which the data were averaged to a common 1 km spatial resolution to ensure consistency with the analytical framework.

ii. **Soil Moisture:** Soil moisture information is obtained from the ERA5-Land reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Monthly observations were aggregated to annual averages and resampled from the native 9 km spatial resolution to 1 km. Two soil moisture layers are used in the analysis: topsoil moisture (0–7 cm) and subsurface soil moisture (7–28 cm). The data covers the period 2014 to April 2023. Since ERA5-Land provides relatively coarse spatial resolution, as a robustness check, we also use Sentinel-1 Synthetic Aperture Radar (SAR) observations, which provide independent, high-resolution measures of soil and vegetation conditions. Sentinel-1 Ground Range Detected (GRD) imagery provides VV (Vertical–Vertical) and VH (Vertical–Horizontal) polarization backscatter coefficients at approximately 10 m spatial resolution. Annual composites of both polarization bands were generated in GEE. The VV backscatter is sensitive to changes in the dielectric properties of the soil and is therefore used as a proxy for near-surface soil moisture, complementing the coarser-resolution ERA5-Land soil moisture estimates. The VH backscatter is primarily sensitive to volume scattering from vegetation and is used as an indicator of above-ground biomass, vegetation structure, and crop growth (Singh and Gaurav 2023; Zhang et al. 2024). Together, these measures provide an independent assessment of surface moisture and vegetation conditions at a much finer spatial resolution, allowing us to test the robustness of our results obtained using ERA5-Land data.

iii. **Rainfall:** Annual rainfall is measured using the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) dataset. CHIRPS provides quasi-global daily precipitation estimates at approximately 0.05° (~5 km) spatial resolution by combining satellite observations with in-situ rain gauge measurements. Daily rainfall observations were aggregated into annual totals and subsequently resampled to the common 1 km analysis grid.

iv. **Land Surface Temperature:** Land Surface Temperature (LST) is obtained from the MODIS MOD11A2 Version 6.1 product, which provides 8-day composite daytime and nighttime land surface temperature estimates at approximately 1 km spatial resolution. Annual mean LST was calculated from the 8-day composites, and temperature values were converted from Kelvin to degrees Celsius before inclusion in the analysis.

v. **Night-time Lights:** Economic activity and human settlement intensity are proxied using the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) monthly cloud-free composites (NOAA/VIIRS/DNB/MONTHLY_V1/VCMSLCFG). The dataset is available at approximately 500 m spatial resolution. Monthly observations were aggregated to annual averages and spatially aligned to the common 1 km grid.

5. Methodology

5.1 Empirical Strategy

To estimate the causal impact of water bund construction on vegetation and soil moisture outcomes, we use a staggered Difference-in-Difference (DiD) approach. Water bunds were constructed across different locations over the years between 2016 and 2025, resulting in variation in treatment timing. A conventional two-way fixed effects (TWFE) estimator may produce biased estimates in such settings because treatment effects can vary over time and across treatment cohorts (de Chaisemartin and D'Haultfœuille 2020; Goodman-Bacon 2021; Sun and Abraham 2021). To address this concern, we adopt the group-time average treatment effect estimator proposed by Callaway and Sant'Anna (2021), which provides unbiased estimate under staggered treatment adoption and heterogenous treatment effects.

Let $Y_{it}(0)$ denote the potential outcome (vegetation or soil moisture) for grid i in year t if no water bund had been constructed. Similarly, $Y_{it}(g)$ represents the potential outcome for grid i in year t if it received a water bund in year g. Let G_i denote the year in which a grid first becomes treated (i.e., the year a water bund is constructed), while C_i identifies grids that are never treated during the study period. The treatment indicator D_{it} equals one if a grid has received a water bund by year t and zero otherwise. The observed outcome Y_{it} corresponds to the actual vegetation or soil moisture observed for each grid in each year. For grids that never receive a water bund, the observed outcome is always equal to the untreated potential outcome $Y_{it}(0)$ in all time periods. For treated grids, we observe the untreated outcome before water bund construction and the treated outcome after construction.

The staggered DiD approach relies on two key assumptions. First, staggered treatment adoption assumes that once a water bund is constructed in a grid, the grid remains treated for all subsequent years. Second, the parallel trends assumption states that, in the absence of water bund construction, vegetation and soil moisture in treated and never-treated grids would have followed similar trends over time. Under these assumptions, differences in post-treatment outcomes between treated and comparison grids can be interpreted as the causal effect of water bund construction. A related assumption is that treatment begins in the recorded year of water bund construction. In practice, however, restoration activities such as community engagement, site preparation, or voluntary grazing exclusion may commence before physical construction. If these pre-construction activities influence vegetation or soil moisture, the estimated treatment effects may partly capture the impacts of the broader restoration process rather than the engineering intervention alone. While our event-study estimates show no evidence of statistically significant pre-treatment trends, suggesting that anticipation effects are limited, they cannot be ruled out entirely and should be considered when interpreting the estimated treatment effects.

Following the framework of Callaway and Sant'Anna (2021), we estimate the group-time average treatment effects on the treated (ATT) defined as:

$$ATT(g,t) = E[Y_t(g) - Y_t(0)|G = g]$$

The $ATT(g,t)$ measures the average causal effect of water bund construction for grids that first received treatment in year g, evaluated in year t. It compares the observed post-treatment outcomes of treated grids with counterfactual outcomes that would have been observed in the absence of water bund construction. Estimating treatment effects separately for each treatment cohort and time period allows the impacts of water bunds to vary across cohorts and over time, rather than imposing a constant treatment effect. The cohort-specific estimates are subsequently aggregated to obtain the overall average treatment effect of water bund construction on vegetation and soil moisture outcomes.

In addition to estimating the average treatment effects, we examine the dynamic effects of water bund construction using an event-study specification. The event study estimates treatment effects relative to the year of water bund construction, where event time is defined as the number of years before or after treatment. This allows us to assess whether vegetation and soil moisture exhibit any differential trends prior to treatment, thereby providing evidence on the validity of the parallel trends' assumption. It also illustrates how the effects of water bunds evolve over time, indicating whether impacts emerge immediately after construction or accumulate gradually in the subsequent years.

5.2 Construction of Matched Sample

To improve the comparability of treated and control grids, we implement Propensity Score Matching (PSM) before estimating the staggered Difference-in-Differences model. Because water bunds are not randomly located, treated grids may systematically differ from untreated grids in their initial biophysical and environmental characteristics.

Matching helps reduce this selection bias by constructing a comparison group with characteristics similar to those of treated grids prior to treatment. Prior to matching, we restrict the sample to grid cells relevant for the evaluation. Grids located within water bodies and protected areas (national parks) are excluded, as these areas are not suitable for water bund construction. To define the study area, we further retain only grids located within a 20 km buffer of water bund project sites, to ensure that treated and comparison grids are drawn from similar agro-climatic and geographical settings while avoiding comparisons with distant areas that are unlikely to be comparable.

The propensity scores are estimated using pre-treatment characteristics averaged over the baseline period 2014–2015, before the implementation of water bunds. The matching covariates include average vegetation condition (NDVI), annual rainfall, night-time light intensity, land surface temperature, and average soil moisture. Using the estimated propensity scores, each treated grid is matched to its three nearest untreated neighbors based on the nearest-neighbors matching algorithm. This procedure creates a balanced sample in which treated and control grids have similar observable pre-treatment characteristics while retaining multiple comparable control observations for each treated grid. In total we have 852 grids in our sample of which 239 are treated grids and 613 control grids (Figure 2).

The matched sample is subsequently used to estimate the causal effects of water bund construction using the staggered Difference-in-Differences estimator of Callaway and Sant'Anna (2021). The approach of combining propensity score matching with the staggered Difference-in-Differences strengthens the identification strategy by ensuring that treatment effects are estimated from observationally similar treated and comparison grids while accounting for the staggered timing of water bund construction.

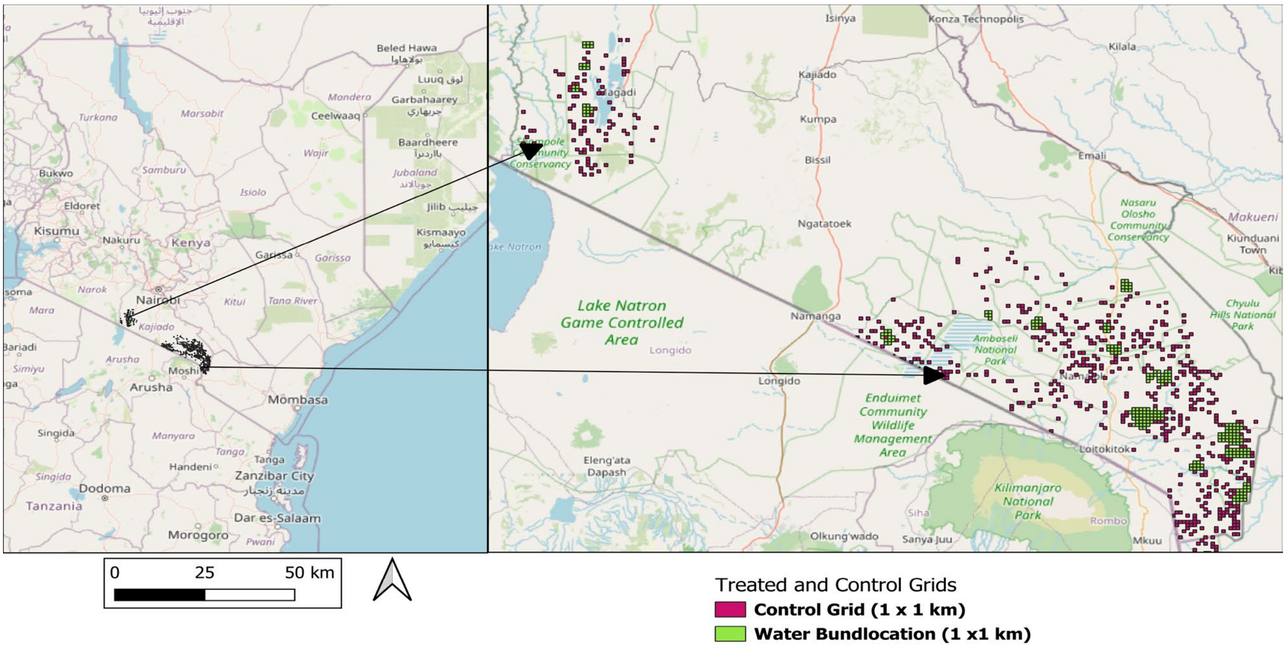

Figure 2. Spatial Distribution of Treated and Control Grids in the Study Area.
Source: Created by Authors
Note: The figure shows the spatial distribution of grid cells classified as treated (exposed to water bund interventions) and control (comparable grid cells without water bund interventions) within Kajaido, Samburu and Taita Taveta. The balanced grid sample provides the spatial units used to compare changes in hydrological, ecological, and socio-economic outcomes between treated and control areas. The analysis includes 239 treated grids and 613 control grids, selected to provide a balanced comparison.

6. Results

6.1 Summary Statistics

Table 1 presents the summary statistics for the matched sample of grid cells, comparing areas with water bunds (treated) and without water bunds (controls). The sample is constructed as a balanced panel of grid-year observations pooled over the period 2014–2025. The results indicate that the propensity score matching procedure has successfully generated a highly comparable control group. Treated and control grid cells exhibit identical mean NDVI values, indicating similar vegetation conditions over the study period. Annual rainfall is also very similar between the two groups (59.42 mm for treated versus 59.07 mm for controls), with a small and statistically insignificant difference. Night-time light intensity is identical across groups (0.23), suggesting comparable levels of human activity. Land surface temperature is nearly the same for treated and control grids (32.39°C versus 32.36°C), with a negligible and statistically insignificant difference. Soil moisture variables, including both topsoil (0–7 cm) and subsurface (7–28 cm) layers, likewise show no meaningful differences between groups. However, we observe statistically significant difference in Sentinel-1 backscatter between treated and control grid cells. Both VV and VH polarization signals are lower in treated areas compared to control areas. It is important to note that the matching procedure was not explicitly conducted using Sentinel-1 backscatter variables, as these measures were not included in the propensity score estimation. Therefore, these differences are not mechanically balanced by construction and instead reflect underlying variation in radar-based surface and vegetation characteristics across treated and control grid cells.

Table 1. Summary Statistics of the Balanced Sample of 1km x 1km Grid Cells in the Study Area, Kenya.

	(1)		(2)		(3)	
	Grids with Water Bunds		**Grids with No Water Bunds**			
	Mean	**S.D.**	**Mean**	**S.D.**	**Mean Difference**	**S.E.**
NDVI	0.30	0.08	0.30	0.08	0.00	0.00
Annual Rainfall (mm)	59.42	18.45	59.07	19.08	-0.35	0.44
Night-time Light Intensity	0.23	0.12	0.23	0.13	0.00	0.00
Land Surface Temperature (Celsius)	32.39	2.26	32.36	2.29	-0.04	0.05
Topsoil Moisture (0-7 cm) (m^3/m^3)	0.20	0.05	0.19	0.05	-0.00	0.00
Subsurface Soil Moisture (7-28 cm) (m^3/m^3)	0.21	0.05	0.22	0.05	0.00	0.00
VV Backscatter (dB)	-12.57	1.82	-13.08	2.06	-0.52***	0.05
VH Backscatter (dB)	-20.09	2.94	-19.09	2.43	-0.99***	0.06
Observations	2,856		7,368		10,224	

Note: Refer Figure 2. We have 852 grids in our sample of which 239 are treated grids and 613 control grids. For each grid data was collected from 2014 to 2025. Abbreviations: S.D. = Standard Deviation. S.E: Standard Error.

6.2 Adoption Timing of Water Bunds

Water bunds were implemented by Justdiggit over the period 2016 to 2025, with the timing of construction varying across 1 km × 1 km grid cells. Figure 3 illustrates the staggered adoption pattern of water bunds across time within the study area. The figure highlights substantial variation in the timing of treatment, which is a key feature of the empirical design and is essential for identifying causal effects using a staggered difference-in-differences estimation. In particular, the rollout was not uniform across years, with implementation intensity varying over time. The years 2022 and 2024 stand out as the peak adoption periods, during which the largest number of grid cells received water bund interventions. This difference in the timing when different grid-cells received water bunds provides important identifying variation for the analysis and allows for the comparison of early-treated, late-treated, and control grid cells (those that were never treated) within the same empirical framework.

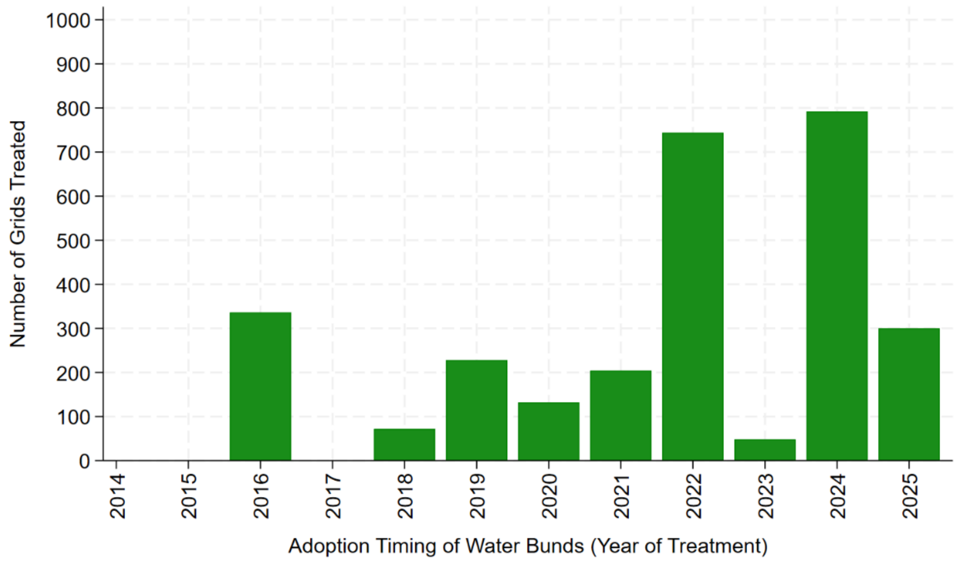

Figure 3. Adoption Timing of Water Bunds Across 1 km x 1 km grids
Source: Created by Authors

6.3 Parallel Trends

Balancing is crucial for the credibility of the identification strategy, as it ensures that treated and control grid cells exhibit similar observable characteristics prior to treatment. By reducing systematic differences in vegetation, climate, soil moisture, and nighttime economic activity, the matching procedure strengthens the assumption that, in the absence of water bund construction, both groups would have followed comparable trends over time. As a result, any post-treatment differences observed in the staggered difference-in-differences analysis can be more confidently attributed to the effect of water bunds rather than pre-existing differences between treated and control locations.

To further assess the validity of the identifying parallel trends assumption, we plot the trends of the outcome variables for treated and control grid cells over the full study period (2014–2025). The trend graphs (Figure 4) show that treated and control grids follow closely aligned paths prior to and during the study period, with no systematic divergence in vegetation (NDVI) and soil moisture. In particular, the absence of noticeable pre-treatment divergence provides visual support for the assumption that, in the absence of water bund construction, both groups would have experienced similar trajectories over time. The observed co-movement of treated and control groups across the study period reinforces the credibility of the parallel trends assumption and supports the validity of the staggered difference-in-differences framework used in the analysis.

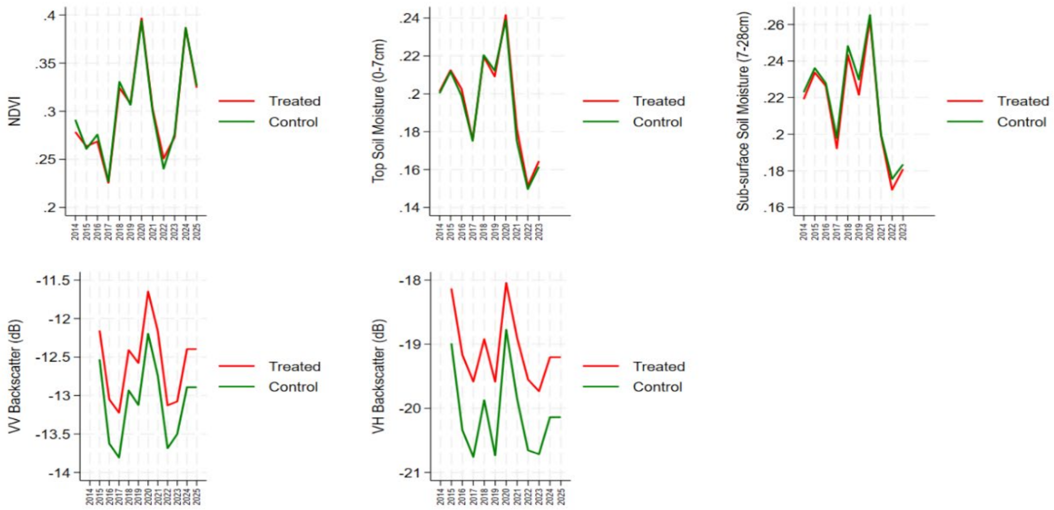

Figure 4. Trend in NDVI, Soil Moisture (topsoil and sub-surface), Mean VV (Vertical-Vertical Co-polarization) and VH (Vertical-Horizontal Cross-Polarization) Backscatter for treated and untreated (control) grids.
Source: Sentinel-1 Synthetic Aperture Radar (SAR)

6.4 Average Treatment Effects on the Treated

In this section we answer the question: How much did water bund construction change environmental outcomes for the grids that received bunds, compared to what those same grids would have experienced if they had not been treated? Table 2 reports the estimated Average Treatment Effects on the Treated (ATT) obtained using the staggered difference-in-differences estimator proposed by Callaway and Sant'Anna (2021). The treatment is defined as the first year in which a 1 km × 1 km grid cell received a water bund, after which the grid remains treated for all subsequent periods. The specification exploits the staggered rollout of water bund construction across grid cells and accounts for both grid fixed effects, which control for time-invariant differences across locations, and year fixed effects, which capture common shocks affecting all grid cells over time. In addition, the model includes annual rainfall, land surface temperature, and night-time light intensity as time-varying covariates to account for changes in climatic and anthropogenic conditions that may influence the outcomes of interest. Standard errors are clustered at the grid level to account for serial correlation within grid cells over time.

The results indicate that water bunds have a positive and statistically significant impact across all outcome variables. On average, the construction of water bunds increases NDVI by 0.009, corresponding to a 3.01% rise relative to the baseline mean. This suggests an improvement in vegetation greenness and health in treated grid cells relative to comparable untreated grids. Water bunds also improve soil moisture conditions. Topsoil moisture (0–7 cm) increases by 0.002 m^3/m^3(1.03% increase), while subsurface soil moisture (7–28 cm) increases by 0.003 m^3/m^3 (1.38% increase). The larger and more statistically significant effect in the deeper soil layer suggests that water bunds enhance water infiltration and storage below the surface, thereby increasing water availability beyond the immediate surface layer. These findings are consistent with the intended hydrological function of water bunds in reducing surface runoff and promoting groundwater recharge. It is important to note that, since one 1x1 grid could have multiple 3-5meter water bunds, the effect size at the grid level hence likely understates the effect at the bund level.

The Sentinel-1 SAR indicators further support these findings. Water bund construction increases VV backscatter by 0.261 dB (approximately 2% relative change from the baseline mean) and VH backscatter by 0.290 dB (approximately 1.46% relative change from the baseline mean). An increase in VV backscatters is consistent with higher surface soil moisture, while the increase in VH backscatters suggest improvements in vegetation structure and above-ground biomass. Together, these radar-based measures corroborate the positive effects observed in the optical vegetation and soil moisture datasets, providing independent evidence that water bunds contribute to improved environmental conditions in treated areas.

Table 2. Average Treatment Effects on the Treated (ATT)

Outcome	ATT	Std. Error	Baseline Mean	Percentage Increase from Baseline
NDVI	0.009**	0.004	0.299	3.01%
Top-soil (0-7 cm) moisture	0.002**	0.001	0.195	1.03%
Sub-surface (7-28 cm) moisture	0.003***	0.001	0.218	1.38%
VV Backscatter	0.261***	0.059	-12.984	2.00%
VH Backscatter	0.290***	0.082	-19.868	1.46%

Note: ATT obtained using the staggered difference-in-differences estimator proposed by Callaway and Sant'Anna (2021). Each row presents a different model. The models includes annual rainfall, land surface temperature, and night-time light intensity as time-varying covariates Standard errors are clustered at the grid level, allowing for arbitrary within-grid correlation of the error terms across years and thereby accounting for serial correlation in the panel. Percentage changes are calculated relative to the average pre-treatment (baseline) value for all pretreatment years of each outcome. The baseline mean is computed using all observations prior to the treatment year for treated grid cells. Thus, the baseline represents the average outcome before the construction of water bunds for each treated grid cell.
*** Significant at 1%, ** Significant at 5% level, *Significant at 10% level.

6.5 Dynamic Treatment Effects

Figure 4 presents the dynamic treatment effects of water bund construction on vegetation greenness and soil/radar-based moisture indicators, estimated using the Callaway and Sant'Anna (2021) estimator. For NDVI, pre-treatment estimates in years −3 to −1 are small and statistically insignificant, supporting the parallel trends assumption. The results highlight that in the year of water bund construction NDVI turns negative and the effects are significant. This pattern likely reflects land disturbance during construction which could reduce NDVI. Following the year of construction, NDVI turns positive and rises steadily over the subsequent years. Relative to the baseline means, NDVI increases by approximately 3% in the first year after construction, and this gain grows to roughly 12% by the fifth year Although the estimated effect in the second year after construction is not statistically significant, this likely reflects the non-linear nature of ecological recovery. While water bunds begin to improve soil moisture conditions soon after construction, vegetation establishment and biomass accumulation require time, and the benefits may not emerge uniformly across growing seasons. From the third year onward, the treatment effects strengthen and remain statistically significant, indicating that the ecological benefits of water bunds accumulate progressively over time.

The results for top-soil (0-7 cm) moisture also show a similar pattern. We observe insignificant pre-trends followed by an immediate and statistically significant increase in the construction year (approximately by 3.4% compared to baseline mean) that persists through year 1 (about 3.5% compared to baseline mean), though the effect attenuates and loses significance by year 3.

Sub-soil moisture exhibits a significant negative pre-trend at year −1, which violates the parallel trends assumption for this outcome; nonetheless, a sharp and statistically significant positive shift occurs at year 0 (about 3.6% from baseline mean) and is sustained through year 2, before narrowing toward insignificance by year 3. The radar backscatter outcomes (VV and VH) show noisier pre-trends, including a significant dip in VV backscatter at year −2, but both measures display a marked and statistically significant increase in soil/vegetation-related backscatter emerging around year 1–2 post-construction, peaking at year 2 before partially receding by year 3. Taken together, the results are consistent with water bunds generating a lagged but meaningful improvement in soil moisture retention and vegetation greenness, with effects that build over the first two to three years following construction rather than materializing immediately.

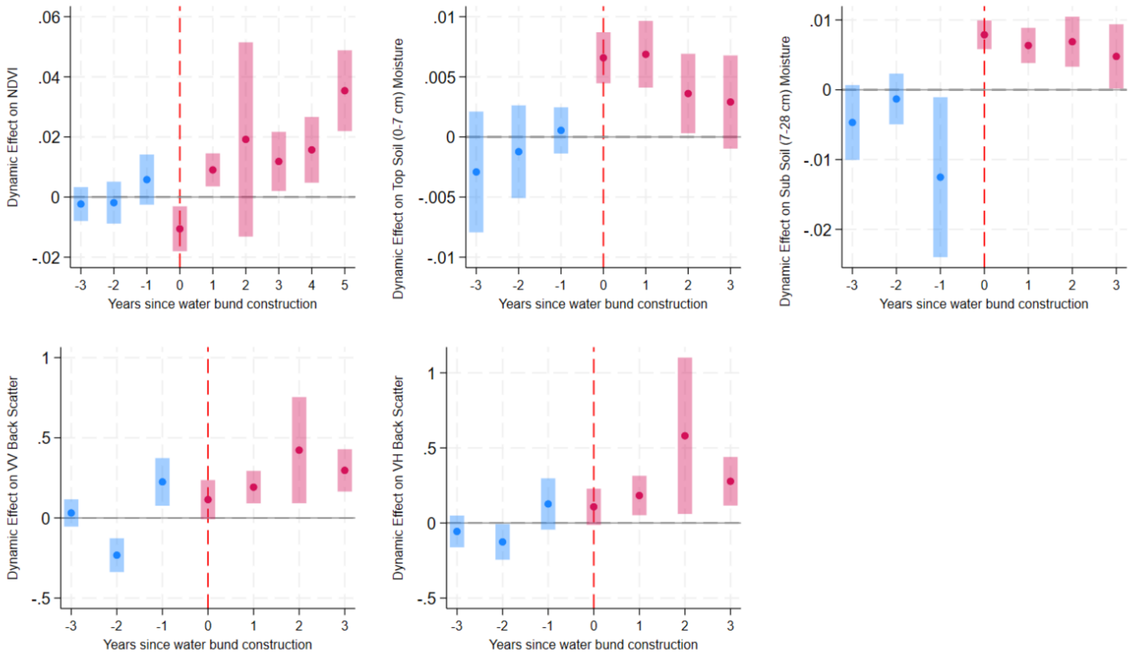

Figure 4. Dynamic treatment effects of water bund construction on environmental outcomes.
Source: Computed by Authors using data described in Section 4.
*Note:*The figure presents event-study estimates of the effects of water bund construction on (a) NDVI, (b) topsoil moisture (0–7 cm), (c) subsurface soil moisture (7–28 cm), (d) Sentinel-1 VV backscatter, and (e) Sentinel-1 VH backscatter. Estimates are expressed relative to the pre-treatment period, with year 0 representing the year of water bund construction and negative and positive values representing years before and after construction, respectively. The dots represent the estimated treatment effects for each event year, while the vertical bars represent 95% confidence intervals based on standard errors clustered at the grid-cell level. The estimates compare treated 1 km × 1 km grid cells with their counterfactual outcomes in the absence of water bund construction, using the staggered difference-in-differences framework of Callaway and Sant'Anna (2021).

6.6 Limitations of the Study

Several limitations of the study should be acknowledged. First, although the matching procedure substantially improves the comparability of treated and control grid cells, unobserved time-varying factors may still influence treatment placement and environmental outcomes. Consequently, the estimates should be interpreted as the effects associated with water bund implementation conditional on the observed covariates and matching procedure. Second, the timing of treatment is defined by the year of water bund construction, whereas restoration activities such as community engagement, site preparation, or voluntary grazing restrictions may begin earlier. If these pre-construction activities affect vegetation or soil moisture, part of the estimated treatment effect may reflect the broader restoration process rather than the physical construction of the water bunds alone. Although the event-study analysis provides limited evidence of statistically significant pre-treatment effects for most outcomes, suggesting that such anticipation effects are limited, they cannot be ruled out entirely. Third, water bunds are implemented alongside Grass Seed Bank (GSB) Program, which may independently contribute to vegetation recovery and improvements in environmental conditions. Because the analysis does not explicitly account for the timing, intensity, or spatial coverage of GSB activities, the estimated effects may capture the combined influence of water bunds and other concurrent restoration interventions. Thus, the results should be interpreted as the environmental effects associated with the broader intervention package in areas where water bunds were implemented, rather than as effects attributable exclusively to the physical presence of water bunds. Fourth, the relatively coarse spatial resolution of the ERA5-Land soil moisture data may not fully capture localized hydrological changes associated with water bunds. The Sentinel-1 radar results provide complementary evidence at finer spatial resolution, but these measures also capture multiple dimensions of surface conditions and therefore cannot be interpreted as direct measures of changes in water storage or groundwater recharge. Finally, the analysis focuses on biophysical outcomes and does not examine whether improved environmental conditions translate into agricultural productivity, groundwater recharge, or livelihood benefits. Establishing these downstream effects would require additional socioeconomic, agricultural, and hydrological data and represent an important area for future research.

7. Conclusion

This study evaluates the environmental impacts of water bund construction on vegetation and soil moisture dynamics in semi-arid landscapes using a staggered difference-in-differences framework and high-resolution remote sensing data. By combining propensity score matching with the Callaway and Sant'Anna (2021) estimator, the analysis exploits the staggered rollout of water bunds between 2016 and 2025 while accounting for time-invariant spatial heterogeneity, common temporal shocks, and time-varying climatic conditions. The use of multiple Earth observation datasets, including MODIS, ERA5-Land, CHIRPS, and Sentinel-1 SAR, provides a comprehensive assessment of the ecological impacts of water bunds.

The results consistently demonstrate that water bund construction improves vegetation greenness, soil moisture, and radar-based indicators of environmental conditions. On average, treated grid cells experienced a 3.0% increase in NDVI relative to pre-treatment conditions, accompanied by significant improvements in both topsoil and subsurface soil moisture. Sentinel-1 VV and VH backscatter also increased following treatment, providing independent evidence of enhanced surface moisture and vegetation structure. The dynamic analysis further reveals that these benefits accumulate over time. While vegetation greenness initially declines during the year of construction, likely reflecting temporary land disturbance, positive effects emerge thereafter and continue to strengthen over subsequent years. This pattern suggests that the environmental benefits of restoration may accumulate gradually rather than materializing immediately following construction.

The study contributes to the growing evidence on the effectiveness of nature-based solutions for dryland restoration by providing quasi-experimental estimates based on satellite observations. Unlike many previous studies that rely on localized field measurements or before-and-after comparisons, the present analysis evaluates impacts over a large spatial extent and across multiple years using quasi-experimental methods. The consistency of the findings across different EO datasets strengthens confidence in the estimated impacts and demonstrates the value of integrating different remote sensing products for monitoring landscape restoration interventions. However, the findings should be interpreted within the broader context of the restoration program in which water bunds were implemented. Ecological recovery may have begun before the period captured by the treatment definition, and water bunds were implemented alongside other management and restoration activities, including grazing exclusion, and GSB Program. Consequently, the estimated effects should not be interpreted as attributable exclusively to the physical construction of water bunds. Rather, they provide evidence that areas receiving water-bund interventions experienced improvements in vegetation and soil-moisture conditions relative to comparable areas, consistent with water bunds contributing to the broader restoration process. Future research combining more detailed information on the timing and intensity of complementary restoration activities with field-based hydrological and socioeconomic data would help isolate the contribution of individual interventions and assess whether the observed environmental improvements translate into agricultural and livelihood benefits.

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