Impacts & Sustainability of Irrigation in Rwanda

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Motivation

Irrigation investments have enormous potential to improve the lives of smallholder farmers who otherwise depend on rain-fed agriculture, through increasing yields, adding additional cultivating seasons, and reducing risk (Burgess et al., 2014). However, these benefits come at substantial construction costs. Even where cost-recovery is not an objective, smallholders are ultimately responsible for recurring costs coming from operations and maintenance (O&M) of the irrigation schemes. Governments must weigh the costs against the benefits of the second-best product that may be delivered as commons problems affect water delivery.

We partner with the Ministry of Agriculture and Animal Resources (MINAGRI) in Rwanda on a research program around 5 recently constructed irrigation schemes under the Land Husbandry, Water Harvesting and Hillside Irrigation (LWH) Project. These hillside irrigation schemes share a similar structure. In each case, hillside terraces were recently rehabilitated; a main canal runs along a contour of the hillside, with a slope prescribed by engineering calculations. Secondary pipes tie into the main canal and bring water down the hillside, where tertiary outlets allow irrigation along individual terraces. Most of the farmland in each of these schemes is currently planted with staple crops (primarily, maize and beans). For the full benefits of these schemes to be realized, farmers will have to adopt higher value horticultural crops. Moreover, maintaining and managing the schemes will require a mix of monetary and effort-based fees which will be pose substantial challenges.

The Government of Rwanda (GoR) considers agriculture an engine for the economy (cf. Rwanda Vision 2020; Rwanda's Economic Development and Poverty Reduction Strategy) and aims to reduce poverty and achieve food security through commercialized and professional agriculture. This calls for improved and sustainable productivity. LWH is a flagship project of MINAGRI designed to meet this objective through a modified watershed approach. It introduces sustainable land husbandry measures for hillside agriculture on selected sites and develops hillside irrigation for subsections of each site. Our study context consists of 4 such hillside irrigation schemes and their surrounding terraced land across four districts of Rwanda.

Irrigation investments have enormous potential to improve the lives of smallholder farmers in the Rwandan context. There are three agricultural seasons in Rwanda. In season A, rainfall is sufficient for production in most years. In season B, rainfall is sufficient in an average year but insufficient in dry years. In season C, rainfall is insufficient for agricultural production. Thus, we expect irrigation to have large effects by increasing yields across all seasons, eliminating risk in Season B, and adding cultivation in Season C. This is reflected in MINAGRI's ambitious expansion and scale-up plans for hillside irrigation: between 2017/20, MINAGRI plans 15,300 ha of planned hillside irrigation development. Hence, the lessons learned from the LWH experience have the potential to not only affect ongoing investment, but to massively affect returns to irrigation investment in the coming 5 years.

Research Questions

We evaluate four questions that are core to irrigation in developing countries:

1. What is the impact of irrigation on farmers' welfare, as captured by yields, profits, labor markets,

rental and land markets, migration, and education? This evaluation will be quasi-experimental and use a Spatial Regression Discontinuity approach, comparing farmers who own land just below the main canal with those who own land just above it. Given that this land was presumably quite similar before the construction of the main canal, there is strong reason to believe these estimates will be valid.

2. What is the impact of escalating irrigations fees on farmers' adoption of high-value cropping system and land sales? Sustainable management and maintenance of the irrigation schemes will ultimately require farmers to pay fees that are high enough to render staple crops unprofitable and force them to choose between selling their land or cultivating high value crops. Here we hypothesize that one or two seasons of low fees before the eventual roll-out of system-wide higher fees may encourage experimentation rather than sales. We further hypothesize that if farmers are sufficiently impatient, then a non-zero fee in earlier seasons may nonetheless be necessary for experimentation. This evaluation will be completed by randomized controlled trial (RCT), where all farmers are informed of the fees, but some (at random) receive a subsidy for the first season or two.

3. What is the impact of experiential learning on adoption behavior and fee repayment? Here, we will examine whether the provision of a mini-kit package of inputs increases adoption of high value crops; whether this effect interacts with the current level of usage fees in the area; and whether there are important spillovers between neighboring farmers (including farmers who share parts of the irrigation infrastructure) in adoption. This evaluation will also be completed by RCT.

4. Effective usage of the irrigation system additionally requires farmers to maintain and enforce an operation schedule, as well as perform some routine maintenance. Solving this classic common pool resources problem has been a challenge for irrigation systems historically. Users typically do not invest in operations and maintenance (O&M) due to low returns in the absence of complementary investments, and because of collective action problems where individuals fail to internalize the externalities of their own O&M decisions. The poor O&M results in disappointing returns, as users are stuck in a low-output equilibrium. We experiment with solutions to the collective action problem while simultaneously estimating the value of complementary investments. Through a RCT, we will test whether water user groups (WUGs) are better able to achieve high quality operations and maintenance outcomes through one of two different structures: either a decentralized structure, where farmers develop, monitor, and control their own schedule and maintenance, or an agency-assisted structure, where irrigation employees take on these tasks. This component will be randomly assigned at the WUG level, the relevant level of collective action for these tasks.

The proposed evaluation design will feature 2-4 rounds of survey data collection on approximately 2300 farmers living in 4 of these sites. Construction of three of the irrigation sites was completed in 2015; for these sites, a baseline survey was conducted in 2015, a first follow-up survey in 2016, a second follow-up survey in 2017, and a third follow-up survey is currently in the field. Construction of the fourth site was finished in late 2017; the baseline was conducted in early 2017, and a first follow-up is scheduled for early 2018.

Literature Review

Irrigation investments have enormous potential to improve the lives of smallholder farmers who otherwise depend on rainfed agriculture, both through increasing yields, adding additional cultivating seasons, and reducing risk. However, rigorous evidence of the economic benefits of irrigation is scarce. While there is some evidence of these returns in the literature (Hussain and Hanjra 2004; Dayton-Johnson 2000), our identification strategy relies on weaker assumptions to identify the effects of irrigation than have typically been available. The credibility of our research design stems from both the technical characteristics of irrigation in Rwanda (hillside terraces) and from our early identification, allowing a true baseline.

There is suggestive evidence from observational studies that irrigation increases the value of production. The FAO estimates that in Asia, yields from most crops increased 100–400% after irrigation [FAO (1996)]. Dregne and Chou (1992) estimate that irrigation increases the value of cropland more than 6-fold (estimated value of irrigated land is $625/ha/year, compared to $95/ha/year for rainfed cropland). A 1997 study in Kenya and Zimbabwe showed that the average net increase in income from irrigation was $150–$1000 per family farm [FAO (1999)]. Tsur et al. (2004) show that non-irrigated grazing land in the area of a major irrigation scheme in South Africa is worth between R1000/ha and R1500/ha, while land with irrigation pivots is worth R10,000/ha.

Our study is unique in combining an estimate of the overall benefit of irrigation with randomized evaluation of complementary interventions. Smallholders are ultimately responsible for the recurring costs coming from the operation and maintenance (O&M) of the irrigation schemes. Many schemes fail for lack of collective action over basic maintenance issues, absence of a coordination mechanism to allocate water across users in the system, or for lack of adoption of a higher-value crop. Yet there is little to no rigorous evidence as to what fee structure and O&M arrangements can lead to higher sustainability of irrigation investments. We build on a literature that studies the role of different governance structures in achieving public good provision (Alesina, Baqir, and Easterly 2000; Galliani, Gertler, and Schargrodsky 2005; Glennerster, Miguel, and Rothenberg 2013). Our contribution includes the randomized design, and the fact that we are able to carefully measure an important, homogeneous public good with nearby natural variations in the underlying governance structure across contiguous plots.

The recent literature on technology adoption suggests moving away from traditional extension models and taking advantage of peer-to-peer learning and learning-by-doing (e.g. Kondylis, Mueller, and Zhu 2014; BenYishay and Mobarak 2015; Jones, Kondylis, Mobarak & Stein 2016). We will provide further policy insights by rigorously testing self-demonstration in lieu of traditional demonstration plots. In addition, by distributing mini-kits for high-value horticulture, we will contribute to the literature on technology diffusion and learning. Recent experimental evidence indicates that traditional demonstration plots are not sufficient in getting farmers to adopt new yield-enhancing practices or inputs (Duflo et al

2011; Kondylis et al 2017). However, there is also growing evidence that leveraging social networks (Beaman et al 2018; BenYishay and Mobarak, 2018) and encouraging experiential learning (Jones et al ongoing) can affect the pace of technology diffusion. Indeed, in a recent study in Bangladesh, two of the participating PIs found that allowing farmers to demonstrate new seeds on their own plot lead to higher adoption in the subsequent years than encouraging traditional or shared demonstration plots in the community, holding the cost of the intervention constant across arms (Jones et al ongoing). They also document strong social learning effects in the self-demonstration treatment, suggesting that learning from experience and learning from others may be complements rather than substitutes. The proposed study design takes these results into account and proposes self-demonstration to optimize the allocation of demonstration resources. By building the evidence base on what works in getting farmers to adopt new technologies, the proposed study will help design policies that allocate demonstration resources in a way that pushes farmers closer to the efficient frontier.

These knowledge gaps impose different sets of constraints across levels of policy-making. At the local level, the LWH project team has a pressing need to test what fee structure, O&M arrangements, and self-demonstration can lead to higher technology adoption and repayment rate. At the international level, donors and multilateral agencies are anxious for evidence on not only the returns, but also the sustainability of irrigation investments. Our proposed research will shed light on these central issues, from local to international policy dialogues.

Intervention

The LWH Project uses a modified watershed approach to introduce sustainable land husbandry measures for hillside agriculture on selected sites and develops hillside irrigation for subsections of each site. The irrigation schemes share similar design features: a main canal is directed from the water source along contours of the hillside. The first, smaller stretch of the main canal is an existing but recently rehabilitated canal. In most of the irrigation scheme, the main canal is newly constructed and there was no existing canal system. Secondary pipes then run perpendicular to the main canal, spaced at approximately 200m intervals.

Groups of approximately 20 households (range of 5- 50 at baseline; median of 19) will rely on a secondary canal to irrigate their terraces. These groups are referred to as Water User Groups (WUGs). Along the secondary canal, there is a tertiary inlet with a flexible pipe on every third terrace. Working on the terraces, farmers dig (temporary) tertiary canals in the soil to draw the water from the flexible pipe and irrigate each terrace bench. In general, farming households own plots on multiple terraces and multiple households own plots on a terrace bench being irrigated by a given tertiary canal. Hence, operating the irrigation system demands terrace-level cooperation.

Construction of the irrigation schemes began in 2012. All four sites are now completed: all farmers in the irrigated area have access to irrigation water and are charged water usage fees this year. To afford the water usage fees, farmers will need to transition away from the current staple crops of maize and beans, and on to high-value crops, such as horticulture. While it may be the case that a few farmers choose to forego using irrigation water, high adoption rates will still be guaranteed.

There is considerable heterogeneity among the smallholder farmers who have access to the irrigation infrastructure, with certain dimensions of heterogeneity are particularly salient (the poorest, renters). As a result, we expect access to irrigation to have differential effects on technology adoption across farmers (Suri 2011), as well as on O&M outcomes across WUGs (Dayton-Johnson 2000).

The primary outcomes of interest to be studied are at the plot level: crop choice, agricultural yields (at the crop and plot level), commercialization, and gross and net revenues. At the household level, we will study expenditures, labor allocation, migration decisions, and land sales and rentals. We are also interested in intermediate outcomes such as adoption of high value crops, payment of water usage fees, and maintenance of the irrigation scheme.

Theory of Change

Figure 1 presents a simplified theory of change behind the interventions to be evaluated, including its main components/inputs, activities, outputs, and the hypothesized causal chain to select outcomes of interest.

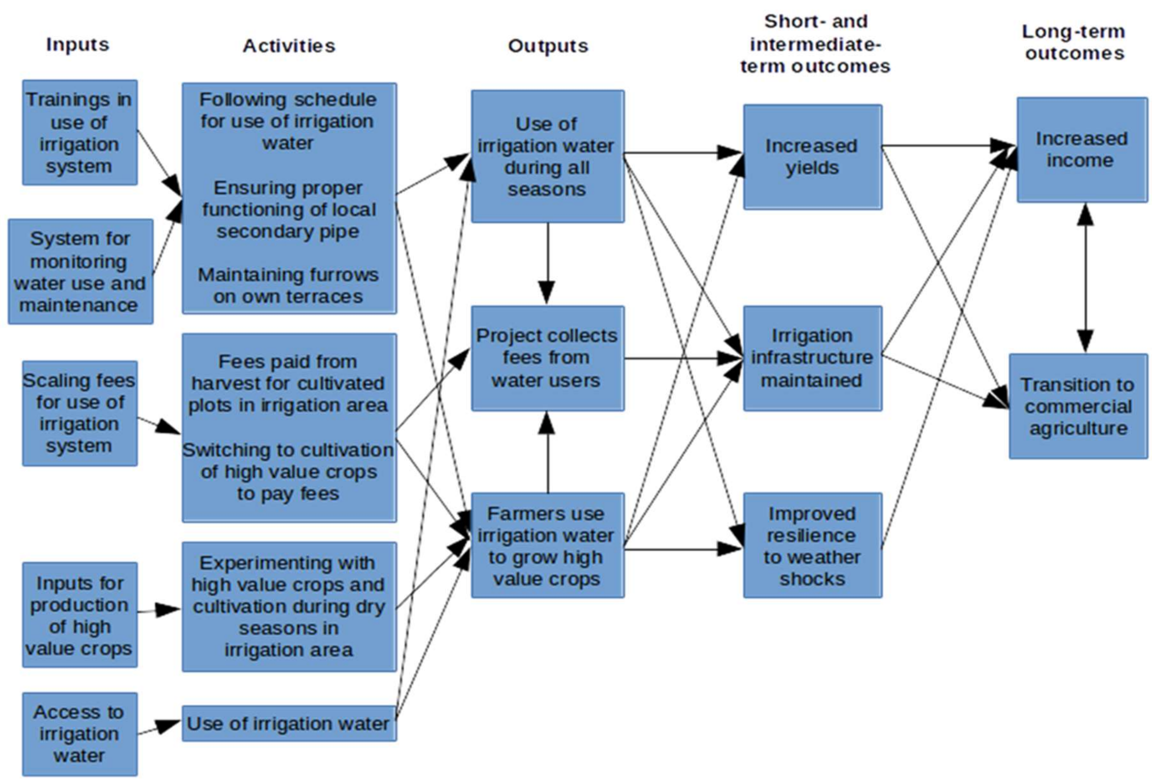

Figure 1: Theory of Change

There are two main assumptions behind the theory of change.

First, we postulate that farmers cannot afford the usage fees (which cover the costs of maintaining the infrastructure) while cultivating traditional crops, but can while cultivating high value crops. This is confirmed both by numbers from a crop model used by our partner organization, LWH, and in data from our baseline, in which observed horticultural revenue per hectare is double or more revenue from traditional crops. However, adoption of high value crops requires learning, and experimentation is costly and risky since households have small landholdings. Farmers may not experiment with adoption of high-value crops if the gains from adoption are not clear. Access to irrigation infrastructure enables off-season cultivation of high value crops and reduces the yield risk associated with cultivating high value crops the rest of the year. At baseline, very few of the sampled farmers used any type of irrigation on any of their plots, and as a result few commercially cultivate high value crops.

Second, we assume that the irrigation infrastructure cannot add value unless farmers coordinate both their usage of the irrigation water (operations) and contribute to maintaining the public good, while adopting high-value crops. WUGs have been organized to monitor and coordinate O&M. O&M will not occur in the absence of a switch to high-value crops, as irrigation does not add value in cultivation of traditional crops in the irrigation sites we study. Moreover, even under adoption of high-value crops, incentives to coordinate vary within the water user group. Farmers with tertiary valves near the bottom of their secondary pipe can use water even when other farmers are using their tertiary valves, while the reverse is not true, and as a result, farmers near the bottom have no private incentive to coordinate operations. For instance, farmers with plots furthest from the secondary pipe need the furrows which carry water from the tertiary valves to their plot to be properly maintained, or else they cannot use the water.

The remainder of the theory of change follows from these two assumptions. A virtuous cycle occurs when farmers begin to experiment with high value crops – productivities improve as farmers learn how to cultivate high value crops, they use the irrigation system because it is necessary for their cultivation, and they properly use and maintain the irrigation system because their production becomes dependent on it. Additionally, this constant use of the irrigation system allows LWH to collect enough fees to make the irrigation scheme sustainable.

Within the irrigation schemes, we will run three experiments that target these causal pathways at the inputs stage. First, we will vary the season in which farmers begin to pay water usage fees, delaying the first season of payments one or two seasons for some farmers. Second, we will give some farmers agricultural minikits to experiment with high-value horticultural crops. These minikits include small quantities of inputs for cultivation of high-value crops on a small plot of land. Additionally, we will provide them to farmers before the off season, enabling low-cost experimentation with cultivating high-value crops using the irrigation infrastructure in the newly added season. Third, we will randomize how monitors are chosen within water user group and whether these monitors have incentives to ensure optimal operations and maintenance activities. The monitor will either be an employee of LWH, appointed by the water user group, or appointed by the water user group with the spot reserved for a farmer with plots near the top of their secondary pipe (the farmers who are most negatively impacting by collective action failures). Across treatment arms, a subset of monitors will be paid based on how often water flows from the tertiary valves on their secondary pipes at the scheduled times.

We can now fit these interventions into the theory of change. Delaying implementation of fees reduces the riskiness of experimentation, but also weakens the push for farmers to adopt high value crops. Agricultural minikits reduce the cost of experimentation with high value crops. Experimentation and eventually cultivation at scale of high-value crops is only possible while the irrigation system is properly maintained and used, since the high-value crops are more dependent on access to water than traditional crops. By targeting all these barriers to adoption simultaneously, we can move households in the irrigation schemes into a new equilibrium where the irrigation infrastructure is actively used to cultivate high value crops year-round, significantly increasing profits for these households.

Analytic Design

There are four primary research questions, each with a separate identification strategy. We address each research component separately below.

Overall Impact of Irrigation

Research Question

What are the impacts of irrigation on smallholder welfare? Specifically, we will examine impacts of large-scale irrigation on yields, cropping and input choices, expenditures, labor supply and employment, land sales and rentals, migration, and whether those impacts differ by gender.

Identification Strategy

The primary canals were built along hillside contours following the water source and occasionally a smaller, older existing canal. For the newly constructed portions of the main canal, the location of the canal on the hillside was determined by slope gradient and altitude relative to a distant and unusable water source. This suggests that before construction, terraces just above the new canal should not have been different from the terraces just below the new canal. Following construction, however, the terraces just below the new canal are irrigated while the terraces just above are not. This allows for a spatial regression-discontinuity analysis (Conley and Udry (2010) Goldstein and Udry (2009), Magruder (2012, 2013)) with key outcome indicators of yields, crop choices, land sales and rentals, labor supply, and migration. We oversampled households living just above and below the canal. As many households rent land along these terraces, we sampled both current operators and landowners for these samples. There are potential spillovers if farmers just above the canal can access the water, making the identification strategy a fuzzy spatial regression discontinuity design. While engineers assure us this is unlikely, we will test whether irrigation access changes relative to the baseline.

Water-User Fees

Research Question

What is the impact of escalating irrigation fees on farmer behavior? In the long-run, farmers will have to pay substantial fees. Fees will outweigh benefits if farmers continue to produce low-value crops; therefore, for sustainability, farmers will have to either adopt high-value crops or reallocate land (through sales or rental). We hypothesize that a short window of subsidized fees will induce farmers to experiment with high-value crops.

Identification Strategy

Cost-recovery via usage fees is a necessary feature for sustainable irrigation systems.
The SPIU plans to offer farmers two choices: to cultivate, and pay usage fees, or to not cultivate. Profitable cultivation with these fees requires adoption of high value crops, and the SPIU recognizes that the sudden imposition of these fees could pose a challenge to farmers who may instead stop cultivating altogether. As a result, they are interested in finding the best way to phase in these fees to achieve high adoption.

Our experiment will randomly allocate subsidies to different farmers. Since learning may take more than one season for full results, we will randomize a path of subsidies over two seasons. Fees will be around 40,000 RWF/hectare-season (about $52 per hectare; the average farmer cultivates about 0.3 hectare within the scheme) when all costs are included; this level of fees will be collected from all cultivating plots. After discussing the eventual fee with farmers, they will take a lottery to pay according to one of four schedules:

Option	2016 Season C Fee (RWF/hectare)	2017 Season A Fee (RWF/hectare)	2017 Season B/C Fee (RWF/hectare)	Approximate Number Farmers
1	0	0	40000	300
2	0	20000	40000	300
3	0	40000	40000	300
4	40000	40000	40000	800

By comparing farmers who receive different subsidies this season and next, we will test whether higher water usage fees discourage cultivation and/or encourage experimentation with higher value crops. Comparing across treatment groups yields tests of whether short term subsidies can induce experimentation, and whether there is an optimal schedule of subsidies.

If farmers choose not to cultivate in response to the fees, it may have implications for the maintenance and usability of the system. We will also measure and test whether farmers are maintaining the furrows necessary to draw irrigation water along the hillside benches, and whether they are completing local maintenance such as removing sediment from secondary and tertiary inlets.

Self-demonstration

Research Question

Do self-demonstration kits encourage experimentation and long-run adoption? If so, how does this interact with water usage fees? We hypothesize that farmers who receive minikits will be more likely to experiment with high-value crops, and that effects will be larger when water usage fees are higher. Moreover, we hypothesize that farmers who experiment will be more likely to continue using the irrigated land when charged full water usage fees in the future.

Identification Strategy

We will randomly distribute mini-kits for self-demonstration of high value crops at the farmer level. We will test whether receiving a mini-kit leads to contemporaneous adoption. Additionally, since farmers are selected at random to receive the mini-kits in season C only, differential re-adoption in later seasons will indicate that farmers learned through experimentation about the benefits of high value crops. Moreover, we will test whether experimentation with minikits interacts with subsidies to reveal whether fees affect the demand for experimentation. Finally, we will test whether any experimentation leads to changes in productive practice by examining whether farmers continue producing on their irrigated plots and are differentially less likely to sell or rent out their land after usage fees have risen to their maximum.

Operations and Maintenance

Research Question

Does the placement of a monitor within the irrigation scheme affect resource sharing? A key dimension of heterogeneity in irrigation schemes relates to plot location: people living near the main canal will have different incentives to maintain the secondary and tertiary canals than those who live far from it. They will also have different incentives to (over)use water. We will measure the impact of empowering a monitor within a WUG, and of imposing that the monitor cultivates a plot in the area most likely to be harmed by overuse of the resource.

Identification Strategy

In her seminal work on governing the commons, Ostrom lists empowering a monitor as a key intervention to induce collective action over the O&M of an irrigation system (Ostrom 1990). Further, theory (Bardhan 1984, Ostrom 1994) suggests that the farmers most exposed to pitfalls of collective action have the greatest incentive to maintain, and monitor the most closely. We design an RCT to test the optimal monitoring structure.

Working with irrigation engineers, we develop a monitoring worksheet and incentivize a WUG member to complete the worksheet on a weekly basis. The randomization will determine which member is empowered as a monitor. In 76 randomly-selected WUGs, the WUG will elect a monitor from its members. In another 76 random WUGs, the WUG will elect a monitor, but the position will be reserved for a farmer who cultivates land close to the main canal. Counterintuitively, these are the farmers most exposed to collective action problems in our context, since they cannot draw water while farmers below them are using the water. The remaining 100 groups will continue to have an employee of LWH monitoring their water use.

Our primary indicators for this intervention are measures of irrigation performance: both objective measures of water flow taken from enumerator observations of field conditions and data from the worksheets themselves. If access to water improves in response to these interventions, we also expect impacts on the broader set of yield, production, and welfare indices described in the main evaluation.

Model Specification for Quantitative Data Analysis

There are two different statistical models which will be used for analysis.

For the usage fee subsidies and saturation intensity, the intervention is randomized at the block level. We can therefore regress for block *b*

$$Y_b = \beta T_b + \delta X_b + \epsilon_b$$

Where T_b is an indicator for treatment status and X_b are covariates and be guaranteed an unbiased estimate ofβ. For observations which vary at the individual level, we will cluster at the level of the block. We also will test robustness of errors to potential spatial correlations between nearby blocks using Conley (1999) clusters. We will additionally test for heterogeneity in treatment effects depending on characteristics of the block, including inequality and number of farmers.

For the effects of receiving the mini-kits themselves, they are randomized at the individual level. For individual *i* in block *b,* we can therefore regress

$$Y_{ib} = \beta T_{ib} + \delta X_{ib} + \alpha_b + \epsilon_b$$

Since the saturation varies at the block level, errors will be clustered at the block level. We will test for productive and learning spillovers by examining the effects of treatment on others in the same block, and on plot neighbors and connected individuals.

For overall impacts, we will complete a spatial regression discontinuity design following Conley and Udry (2010), Goldstein and Udry (2009), and Magruder (2012). This approach suggests that for plots sufficiently close together, placement on one side of the boundary or the other is close to random. More specifically, for each individual *i* with plot *p*, we define *R(p)* to be the set of plots within radius *R* of plot p. Suppose there are $n_{R(p)}$ plots in set *R(p).* The spatial fixed effects used in this approach are specific to the plot and thus cannot be represented by a block diagonal set of binary variables as conventional fixed effects can; however the within estimator is still achievable.

$$(Y_{ip} - \frac{1}{n_{R(p)}} \sum_{p' \in R(p)} Y_{ip'}) = \beta(T_{ip} - \frac{1}{n_{R(p)}} \sum_{p' \in R(p)} T_{ip'}) + (X_{ip} - \frac{1}{n_{R(p)}} \sum_{p' \in R(p)} X_{ip'}) + u_{ip}$$

For time-varying variables, we will complement this analysis by including plot-level fixed effects to use the difference in spatial differences estimator suggested in Magruder (2013). In all cases, errors will be spatially clustered following Conley (1999).

We will complement this analysis with a more traditional distance to the border estimation which ignores the two-dimensional nature of space but does allow a more conventional graphical representation. In our context, where control group areas are not evenly dispersed along the boundary, this approach has some severe limitations which motivates the preference for the spatial fixed effects approach.

Both approaches estimate LATE. We are collecting extremely rich baseline data on farm production and profits, income, and demographic variables which will be used to test balance and evaluate the performance of the spatial RD approach. In addition, we will use multi-season, plot-level data to explore inter-temporal and spatial reallocations of risk and production inputs.

The primary source of bias that could affect our estimation would happen if farmers endogenously sort in or out of particular contract or irrigation regimes. To test for this, we are following a panel of plots, and collecting retrospective data. We will know whether there was immediate sorting prior to the completion of irrigation, or subsequent sorting that takes place after the water starts flowing through land sales or rentals. In all cases, we will follow the plot's owners who may sort into other local areas. We will take steps to guarantee low attrition, including collecting multiple contact numbers and are well-enough integrated into the community to be encouraged of a high success rate in finding individuals who move.

We registered this IE in the AEA trial registry.

Data

Household Sample

The population of interest is the households cultivating within the irrigation schemes. To identify these households, we implemented a geographic sampling scheme. Each site was divided into 3 areas – Command Area buffer (BCA), Command Area Catchment buffer (BCAC), and Command Area terraces (TCA). BCA is the area inside of the Command Area (CA, below main canal) within 50m of the boundary of the CA. BCAC is the area in the Command Area Catchment (CAC, above main canal) within 50m of the boundary of the CA. TCA is the terraced farmland that is in the CA, but more than 50m from the boundary of the CA.

We constructed the household sample by dropping a uniform grid of points across the full site at 2-meter resolution, and then sampling particular points within the grid. After each point was sampled, we excluded any points within 10m of that that point (to keep from selecting multiple points too close together). Enumerators were then given GPS devices with the locations of the points, and sent to each point, with a key informant (often the village leader). For each point, they were asked to identify whether the point was on cultivable land (this was to discard forest, swamps, thick bushes, bodies of water, or other terrain which would make cultivation impossible). For all points in cultivable land, they recorded:

1. The name of the point visited (which was displayed on the GPS)
2. The name of the cultivator, the location of their residence, and their phone number
3. A description of the plot, detailed enough that the cultivator would be able to identify the exact plot described

We used the data from this listing to construct a roster of all the unique names of cultivators, clustering points together when the names seemed identical. This roster was then used to contact village leaders and verify that the listed individuals in fact existed. Multiple follow-ups were sometimes needed when village leaders suggested that one individual lived in a different village, or multiple village leaders said an individual lived in their village.

Finally, a sample plot was selected for each verified 1,879 household. To select this sample plot, one point was randomly selected for each household. The probability of selecting a particular point was weighted – a weight of 1 was assigned to points in the BCA and BCAC, and a different weight was assigned for points in the TCA, to balance the number of sample plots in these areas.

Key Indicators

Table 1 lists the primary and secondary outcome indicators for the study.

Table 1: Key Indicators

Outcome Type	Outcome Name	Definition	Level
Primary	Gross Agricultural Yield	Total value of output per hectare	Agricultural plot
Primary	Net Agricultural Yield	Total value of output per hectare minus total value of inputs (including labor) per hectare	Agricultural plot
Primary	Expenditures	Household expenditures in the past month (frequent) and year (infrequent)	Household
Secondary	Adoption of high-value crops	Choice of crop(s) cultivated, per season	Agricultural plot
Secondary	Payment of water-usage fee	Amount paid as a proportion of the amount owed (given subsidy)	Agricultural plot
Primary	Primary employment	Primary source of employment, self-reported	Household member
Primary	Land sales and rentals	Land sales over the past 5 years; ownership status and decision to rent out or in by plot	Agricultural plot
Primary	Migration	Dummy for whether or not the HH member migrated for work during the reference period	Household member
Primary	Maintenance of irrigation scheme	Score based on a number of objective measures of level / quality of maintenance performed, directly observed through monitoring	Tertiary Valve

summarizes the modules included in the household survey.

Module	Content	Level
Identification	Identification of enumerator and respondent; informed consent	Household

Household Roster	Sex, age, education, employment, migration	Household member
Plot Roster	Plot identification, ownership status, cultivation by season, past land transactions	Plot
Crop Production	Crops produced, amount of seed, amount harvested, amount consume, amount sold, amount lost to spoilage	Crop, by plot and by season
Irrigation Use	Use of irrigation, source, method, frequency	Sample plot
Farm Labor	Use of household and hired labor for agriculture	By plot and by season
Agricultural Inputs	Quantity, source, and amount spent on all organic and chemical inputs	By plot and by season
Irrigation (general)	Experience with irrigation, knowledge of maintenance, participation in maintenance activities, participation in trainings	Household
Extension	Interaction with public, private, and not-for-profit sources of agricultural extension	Household, by season
Housing	Construction material of walls and floors, source of drinking water, sanitation	Household
Farmer Group	Participation in farmer group, cooperative, water user group, and water user association	Household
Social Networks	Interactions, transfers to/from, and loans to/from, community work with neighbors and members of water user groups	Household
Income & Expenditures	Disaggregated income over the past 1 year; disaggregated expenditures over the past 1 month (frequent categories like communications and transportation); disaggregated expenditures over the past 1 year (infrequent categories like school fees and health insurance)	Household
Animals & Assets	Total owned; sales and purchases over the past one year for: cows, goats, pigs, poultry, radios, mobile phones, furniture, bicycles, hoes and shovels, and other agricultural equipment	Household
Rural Finance	Bank accounts; formal savings; contributions to ROSCAs	Household
Credit	Number of loans requested; amount and purpose of loans received	Household
Shocks	Crop failure in the past year associated with drought; amount of loss and means of coping	Household, by season
Future Expectations	Future expectations and perceptions of agricultural production, household wellbeing, impacts of irrigation, asset purchases, participation in contract farming	Household
Food Security	Food Consumption Score (developed by World Food Program)	Household
Plot mapping	Plots are mapped, soil judged for evidence of effective irrigation use	Plot

Table 2: Summary of Household Survey Modules

Power Calculations

We perform four sets of power calculations, one for each research question. For all power calculations, we assume 80% power, alpha of 5%, and two follow-up surveys. Please refer to the spreadsheet for details on the calculations, including software package used and all assumptions.

Overall Impact of Irrigation

We conduct power calculations for an individual level randomization, using data from a baseline survey conducted in two sites in 2015. We use the assumption that within a narrow range of the cutoff, a discontinuity design behaves like a randomized control trial. Given the fixed location of the canal, there cannot be mis-assignment of plots to treatment or control. We calculate power based on the number of households within a 25m band of the primary canal (359 below; 331 above). The outcome of interest is agricultural production in RWF/hectare, which in our baseline has a mean of RWF12,761 and standard deviation of RWF24,233. Taking into account two rounds of planned follow-up surveys, we find a minimum detectable effect size (MDE)S between 0.13 and 0.18 (depending on the assumed level of autocorrelation). Extrapolating based on our estimate of the full sample size across all six sites, we estimate the final MDES to be between 0.08 and 0.11 standard deviations.

Water-User Fees

The water usage fee subsidy will be randomized at the farmer level. The 1700 farmers will be divided among 3 treatment arms and a control: each treatment group will have 300 farmers, and the control group 800. The outcome of interest is again agricultural production; the mean and standard deviation are the same as reported above. We conduct two types of power calculations: first, comparing one treatment arm to another (e.g. T1 v T2) and second, comparing one treatment arm to the control (e.g. T1 v C). We find a MDES between 0.12 and 0.17 standard deviations for the test of one treatment arm against the control group. We find a MDES between 0.14 and 0.20 for the test of one treatment arm against another treatment arm.

Self-demonstration

The mini-kits will be randomized at the farmer level. The 1700 farmers will be divided into 2 treatment arms: 850 will receive a mini-kit and 850 will not. The outcome of interest is again agricultural production; the mean and standard deviation are the same as reported above. We find a MDES between 0.08 and 0.12 standard deviations.

Operations and Maintenance

The randomization for the monitoring intervention will be at the Water User Group (WUG) level. There are 252 WUGs. Those are divided into two treatment arms and one control arm. Each treatment arm has 76 groups, the control has 100 groups. For these power calculations, we use group-level data from a study of rural savings groups among the same population in 2013. From that survey, intracluster correlation (ICC) for our outcome of interest (agricultural yields) was 0.05. To be conservative, we also estimate with a higher ICC of 0.15. We find a MDES of between 0.09 and 0.18 standard deviations, depending on the level of ICC (0.05 - 0.15).

Policy Impact

The research team has strong reasons to expect results from this impact evaluation program to have deep policy impacts. As the irrigation schemes were very costly to construct, the government is extremely concerned with both the cost-effectiveness and the sustainability of these investments. Given the planned scale up of irrigation, these issues are particularly salient to high-level policymakers in MINAGRI.

The irrigation research builds on an ongoing program of impact evaluation with the Government of Rwanda. The first generation of trials focused on the rural finance and agricultural extension components of the LWH project; they were designed over the course of a DIME workshop during which training was provided to the World Bank operational team and government counterparts on rigorous evaluation methods. Each trial was conducted over the course of 1-2 years, with results informing the project design as it scaled up to new watersheds. For instance, based on these results a hotline to register farmers' feedback on extension visits was scaled up to the entire service area, country-wide, boosting attendance and demand for the service. Now that the irrigation infrastructure construction is completed in four of the watersheds, the LWH team is interested in testing operational strategies to secure higher sustainability of their investment.

The influence of the proposed IE on policy will be secured through three main channels:

1. Building ownership within the implementation team and line ministry, from permanent secretary down to lead farmer level. Policy influence is secured by building ownership of the program at all levels of government implementation and decision making, from farmers to minister level. As described above, this is done by including all levels in the conception of the IE design. As the results come out, all levels, from farmers to minister, have ownership of the findings and appropriate them to take decisions. Engagement at all levels are done through day-to-day engagement with the teams on the ground, as well as periodical missions during which dissemination events are organized and briefs are delivered to high-level ministry staff, up to Permanent Secretary and Minister.
2. Ensuring that findings are incorporated in joint donors-GoR strategies, working with a coalition of actors in Rwanda and beyond. The research team is working closely with the WB Country Management Unit in Rwanda to build ownership of the activity and ensure its impact in the policy dialogue both at the country and sector levels. Brown-bag seminars are regularly held by the team at the CMU to ensure that the country office staff is aware of the work and learning coming out of this program, and that the IE work is aligned and informs to the Bank's agricultural strategy in Rwanda. Similar efforts are made to communicate research findings to other donors in Rwanda, including DFID, the Netherlands, and the EU.
3. Building international awareness of the findings. High-quality research papers based on this research will be disseminated in international policy and academic circles (e.g. UC Berkeley, WB, international conferences, etc), in the form of events, trainings, as well as international development conferences. Finally, the findings will be published in working paper series and submitted to peer-reviewed economics and field journals, thus reaching a wide audience of

researchers and graduate students worldwide. All data will be made available online on the databank for IE, following the Bank's open data policy, influencing empirical work beyond this specific research effort.

MINAGRI is an informed consumer of IE and has a demonstrated commitment to using impact evaluation results to inform policy design and scale-up. The government team receives day-to-day technical support of DIME staff and STCs based in Kigali, as well as periodical visits from the research team. This ensures full communication between researchers and policy actors and a high level of buy in and commitment from the government team to use research insights to shape their policies. Through this process, policymakers become informed consumers of IE and learn how to use it as a management tool. The research program is designed to yield actionable, just-in-time recommendations, with tangible impact on policy decisions. Surveys are collected using computer assisted personal interviewing technology which significantly shortens the field-to-analysis period. Missions are organized around main dissemination dates and ahead of season planning to ensure the absorption of the analytical findings into the operational schedule.

Irrigation is a policy priority for the region more broadly. As of 2010, only 6% of total cultivated area in Africa was irrigated; all other production was rainfed (IFPRI 2010). This impact evaluation will contribute data on the returns to hillside irrigation and lessons for scheme management, critical to informing the discussion on how to smartly invest in irrigation infrastructure to boost agricultural productivity and manage increasing climate variability.

In addition, this research contributes to a large, global research agenda on aid effectiveness in agriculture (DIME-aadapt), which counts over 30 participating projects in over 20 countries. The Rwanda IE team has taken part in three global aadapt meetings so far (Dakar, 2011; Naivasha, 2012; Kigali, 2014), and will share the results and experience from the ongoing IE work in future events, thus reaching a wide audience of policymakers worldwide.

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Acronyms

Aadapt:	DIME program of agricultural impact evaluations
CA:	Command Area
CAC:	Command Area Catchment
DfID:	Department for International Development
EU:	European Union
GoR:	Government of Rwanda
ICC:	intracluster correlation
IE:	Impact Evaluation
LWH:	Land Husbandry, Water Harvesting and Hillside Irrigation Project
MDES:	Minimum Detectable Effect Size
MINAGRI:	Rwandan Ministry of Agriculture
O&M:	Operations and Maintenance
RCT:	randomized controlled trial
SPIU:	MINAGRI's Special Project Implementation Unit
SPRD:	Spatial Regression Discontinuity
SWAP:	Sector Wide APproach
WUG:	water user group