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Harvesting the rain: The adoption of environmental technologies in the Sahel*

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Abstract

Many agricultural and environmental technologies require upfront investments. This may deter adoption, particularly in settings characterized by information,

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liquidity and credit constraints. We test for these barriers to the adoption of an agricultural technique that helps address land degradation in Niger. We find little evidence that liquidity or credit constraints deter adoption: instead, providing farmers with training increases the share of adopters by over 90 percentage points. Conditional or unconditional cash transfers have no additional effect. Adoption increases agricultural output and reduces land turnover in the longer-term. In our setting, training provides both specific technical knowledge and addresses behavioral constraints.

JEL Codes: O13, Q16, I15

Keywords: agriculture, technology adoption, climate adaptation, training, Niger

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1. Introduction

Since the 1960s, agricultural yields have more than doubled around the world. An exception to this trend is sub-Saharan Africa, where yield growth has stagnated. To meet the consumption needs of a growing population, the agricultural sector has increased total output by bringing more land into production. This strategy is unsustainable: demand for land has pushed production onto increasingly marginal soils and shortened fallow periods; increasingly frequent climate shocks exacerbating these challenges (Jayne 2014, Warren et al. 2001).

Interrupting the cycle of land degradation and poor yields requires intensive agricultural practices that both increase water storage within the soil and replenish soil nutrients. Rainwater harvesting (RWH) techniques, which capture rainfall and reduce runoff, present a compelling option in settings where irrigation is technically unfeasible and chemical input use is limited. We focus on one type of RWH technique, the demi-lune, because it is particularly well-suited for recuperating degraded soils that are no longer productive.[1] Despite the fact that agronomic trials predict high returns to demi-lunes (Warren et al. 2001, Vohland and Boubacar 2009), adoption levels remain below 10% in Niger, where our study takes place. Like many environmental technologies, demi-lunes require considerable (labor) investment upfront and generate benefits over multiple agricultural seasons.[2] In addition, while awareness of demi-lunes is widespread, technical knowledge about their construction is more limited. Thus, adoption could be low because of a lack of information (e.g., Emerick and Dar 2020), cash-on-hand liquidity constraints at the time of adoption (e.g., Karlan et al. 2014), or high interest or discount rates that make the present value of benefits too small to

[1]Demi-lunes are half-moon shaped berms, constructed on severely degraded fields to collect rainfall and runoff. Farmers plant crops in and around the demi-lunes.

[2]While the costs of demi-lune construction are comparable with other RWH techniques – such as pit planting – they are a non-trivial expense. Agronomists estimate that farmers would need to spend approximately USD 80 to construct demi-lunes on one hectare of degraded land, representing approximately 14% of per capita income in Niger.

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justify the costs (e.g., Berkouwer and Dean 2019).

To test the importance of each of these barriers to adoption, we assigned small-scale farmers in 180 villages to one of four treatment arms or a control. To address information constraints, farmers in the *training* treatment were invited to a training that introduced the technology and taught farmers how to construct demi-lunes, including content on why demi-lunes work, the technical requirements, suggested inputs and optimal timing. The remaining treatment arms offered farmers some type of cash transfer in addition to the training. To relax liquidity constraints for hiring labor at the time of adoption, the "early" unconditional cash transfer arm (*UCT-early*) was assigned to a lump sum payment of USD 20 soon after the training and prior to adoption.To address the time profile of costs and benefits, the conditional cash transfer arm (*CCT*) received a payment of USD 0.40 per demi-lune constructed, approximately three months after the UCT-early payment. Finally, to address the difference in timing between the UCT-early and CCT arms, the *UCT-late* treatment provided an unconditional transfer of USD 20.50 at the same time as the CCT payout. The treatments were administered during the first year of the study, and data collection followed the sample for three subsequent years.

We present four main findings. First, all treatments significantly increased adoption in the short and medium-term, one and three years after treatment. Specifically, treated farmers were 90 percentage points more likely to adopt demi-lunes than those in the control, with no significant differences between the training and cash transfer treatments. The intensity of adoption also increased in response to treatment. In the first year, farmers assigned to any treatment constructed 34 more demi-lunes than those in the control, with higher adoption in the UCT-early and CCT arms as compared with the training arm. Yet by the third year, adoption levels were indistinguishable across treatments. These results have at least two implications for understanding the barriers to demi-lune adoption: (i) they demonstrate the importance of training in alleviating a binding constraint to adoption, and (ii) they imply that both liquidity constraints and upfront investment costs are surmountable.

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Second, adoption occurred through the reallocation of household and hired labor. In the first year, when the bulk of demi-lune construction took place, treated households hired more labor, had fewer household members engage in seasonal migration and did less wage work. They also were more likely to hire labor for other agricultural tasks, such as sowing and weeding. While this latter result persisted over time, the other impacts did not, consistent with the fact that most demi-lune construction happened in the first year.

Third, the interventions had significant impacts on agricultural production and land use, as well as crowded in other productive investments. Across all treatments, the amount and value of agricultural production increased by 0.12 to 0.15 standard deviations relative to the control, with stronger effects over time. By the third year, households in treated villages had restored an additional 0.3 hectares of previously uncultivable land and reported improved soil quality. Households also purchased their own tools and used complementary inputs to build and maintain demi-lunes.

Finally, we observe evidence of adoption spillovers within villages. In a random spillover sample that was not directly exposed to the training or cash transfers, farmers in treatment villages were 18 percentage points more likely to have adopted some demi-lunes by the third year of the study than those in control villages.

We use our results to assess the private costs and benefits of demi-lune adoption. Even in the first year, when most costs were incurred, demi-lune adoption was privately profitable on average: the treatment effect on total agricultural revenue was USD 34, while costs were approximately USD 30 (including foregone income from migration and wage work). The revenue benefits persisted after the first year, while private costs fell to around USD 4.

What makes a one-day training so effective at increasing adoption? Our findings are an outlier in the substantial literature on training and information for agricultural technology adoption, much of which finds comparatively small effects (see Magruder (2018) and Macours (2019) for relevant reviews). Concretely, we observe a 2000% increase in the extensive margin of adoption in the treatment group, as compared to effect sizes of 40-1000% in other studies

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(see Table A.1). Features of both the technology and the training can help to explain our results. First, unlike some agricultural technologies, we show that demi-lunes are privately profitable, at least for a majority of the farmers in our sample. Second, while agricultural investments can be sensitive to the seasonality of income and labor markets (Fink et al. 2020), demi-lunes do not directly compete with other agricultural labor demand. More specifically, demi-lunes must be constructed during the slack agricultural season, when the opportunity cost of labor is relatively low. Third, while the cost of constructing demi-lunes is substantial, our design allows us to rule out that liquidity constraints or risk are persistent barriers to adoption (Jack 2013a, Karlan et al. 2014). Finally, there are few other substitutes for recuperating severely degraded soils in Niger.

Our experiment was not designed to test specific features of the training, so we offer more suggestive evidence on the mechanisms underlying the training impacts. Providing technical advice and alleviating behavioral constraints both appear important for increasing adoption. Baseline data show that demi-lunes were a familiar technology for a majority of farmers, yet their knowledge of specific technical aspects was limited. The training significantly improved this knowledge, providing farmers with the technical know-how necessary for adoption.[3] This mechanism is further supported by data from the spillover sample: while farmers in the spillover sample substantially increased their awareness of demi-lunes, they did not improve their technical knowledge, and they adopted at much lower levels than farmers directly exposed to the training. This suggests that awareness of the technology was insufficient for adoption unless it was also accompanied by technical information. We also provide suggestive evidence that the training helped to overcome behavioral barriers to adoption. Nudges designed to increase the salience of demi-lune profitability and the potential for

[3]The training instructed farmers on how to follow the technical specifications of demi-lune construction using widely accessible methods, such as pacing off the dimensions. This is a departure from other trainings on demi-lunes in Niger, which use more specialized tools and promote adoption on communal (rather than private) land.

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technical support led to modest additional adoption following the endline survey.

Our study contributes to a large literature on the barriers to technology adoption. In low-income settings, liquidity and credit constraints are often blamed for low adoption of agricultural or environmental technologies that carry upfront costs with delayed benefits (Magruder 2018, Fowlie and Meeks 2021, Jack et al. 2016, Berkouwer and Dean 2019). However, recent experimental evidence suggests that they may bind only for a minority of farmers (e.g., Karlan et al. 2014, Beaman et al. 2014, Crépon et al. 2015). Our study design allows us to test the importance of cash-on-hand liquidity constraints and separate them from high discount rates.[4] We find that both of these financial constraints play a relatively minor role in deterring adoption. In doing so, we provide novel evidence on the performance of conditional versus unconditional cash transfers, which have not been directly compared for agricultural technologies (Akresh et al. 2016, Benhassine et al. 2015, Baird et al. 2011). Our design also rules out a problematic confound in most comparisons of UCT and CCT interventions: UCTs come before the desired outcome, whereas CCTs come after, making it difficult to separate the impact of the conditionality from the timing.

Second, as discussed above, our study makes contributions to the literature on the impact of training and informational interventions on technology adoption, particularly in agriculture (Hanna et al. 2014, BenYishay and Mobarak 2019, Barrett et al. 2020, Glennerster and Suri 2018, and Islam and Beg 2021).[5] While our study was not designed to isolate specific

[4]Specifically, the UCT-early treatment will only increase adoption if the technology is privately profitable at current discount rates, but a lack of cash on hand at the time of demi-lune construction deters adoption. The CCT treatment, on the other hand, is unlikely to affect short-run liquidity and therefore will only increase adoption if the benefits are too heavily discounted relative to costs.

[5]Much of the recent literature has focused on who gets trained and who does the training (Kondylis et al. 2017, Beaman et al. 2021), how often (Barrett et al. 2020) and in what format (Emerick and Dar 2020, Cole and Fernando 2021). We study a one-off training for a random sample of farmers, implemented by the Ministry of Environment that consisted of

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mechanisms behind training effectiveness, our results suggest that the technical advice and behavioral cues provided by the training were important channels in driving adoption.

Finally, our study contributes to research on agricultural practices and technologies that either mitigate the impacts of environmental shocks or reduce the environmental externalities from agriculture, including drought-resistant crops (Emerick et al. 2016), conservation agriculture (BenYishay and Mobarak 2019, Beaman et al. 2021, Barrett et al. 2020) and agroforestry (Oliva et al. 2020, Jack 2013b). Despite the importance of these technologies, relatively little is known about their profitability or the dynamics of adoption. Our study offers new evidence on the barriers to adoption of environmental technologies for smallholder farmers, and allows us to study their impacts upon land quality over time.

2. Study Context

2.1 Agriculture, Climate and Land in Niger

With a per capita income of USD 551 and an estimated 85% of the population living on less than USD 2 per day, Niger is consistently one of the lowest-ranked countries on the UN's Human Development Index (UNDP 2020). Agriculture dominates the economy and employs the majority of low income households, 70% of whom live and work in rural areas (Barry et al. 2008).

The primary staple crops cultivated in Niger are millet and sorghum, along with the cash crops of cowpea, peanuts, and sesame. A single annual rainy season occurs between June and September, with the harvest following soon after (Barry et al. 2008). As a result, there is a marked seasonality to income, consumption, prices, and labor (see Figure A.1). The slack agricultural period coincides with a period of seasonal outmigration to neighboring countries, with 50% of households sending at least one seasonal migrant (Aker et al. 2020).

both a classroom and field component.

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The rainy season also overlaps with the "hungry period", the time when credit and liquidity constraints typically bind (Aker et al. 2020).

With limited surface water, agriculture in Niger is primarily rainfed; as a result, inter-annual fluctuations in rainfall are strongly correlated with agricultural output. The region witnessed some of its most serious climate-induced food shortages in the 1970s and 1980s. Since then, Niger has been subject to frequent droughts, the most recent of which occurred in 2018 (OCHA 2018). Though we lack detailed rainfall data, in our surveys, 25% of households report experiencing drought in the previous year. Rainfall fluctuations have also led to shorter fallow periods (Jayne 2014).

Niger has some of the highest rates of soil degradation in the world, with approximately 60% of populated land experiencing soil erosion (Republic of Niger 2017). This is further compounded by population density: approximately 94% of the population lives on 20% of the land, and population growth is estimated at 3.8% per year. In our sample, 64% of farmers cited land quality as a primary constraint to agricultural production.

Customary land tenure practices govern different types of land in Niger, including the privately-owned land in our study area (Hughes 2014). Under customary law, land is formally owned by men. Women are typically allotted a plot – often the most degraded and marginal land – where they can make decisions (alone) about planting, labor and cultivation. On family plots, these decisions are primarily shared by males and females within the household. Formally, men have title to the land and pass it down to their male heirs (Hughes 2014).

2.2 Rainwater Harvesting Techniques

In the semi-arid areas of sub-Saharan Africa, micro-catchments – small structures constructed within a field to collect soil runoff and increase the nutrient content of the soil – are the most appropriate RWH technique for recuperating degraded soils.The most common micro-catchments used in the Sahel are *zaï* (soil pits), demi-lunes (half-moons) and

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banquettes, some of which are indigenous to West Africa (Barry et al. 2008).[6]

Demi-lunes are large, half-circle earthen bunds that are constructed on a plot of land. They are particularly appropriate for sloped land with severely degraded soil, known as *glacis*, which is estimated to cover approximately 40% of degraded land in the agro-pastoral zone of Niger.[7] To maximize organic matter and moisture capture, the technical specifications of demi-lunes are important: size (2 meters by 4 meters), depth (15-30 centimeters) and spacing (2 meters between the bunds, to discharge excess runoff) (Figure A1.1). Following these dimensions, the Ministry of Environment recommends that 250-300 demi-lunes should be constructed per hectare to fully cover the plot and maximize restoration.[8] Technical norms also suggest that the timing of construction is important: demi-lunes need to be constructed after the harvest but before the rainy season in order to collect wind-borne silt and organic matter (before the rains) and rainwater (during the rains). This implies a window of approximately six months for construction. This window coincides with the slack agricultural season in Niger, when local labor demand and wages are low. This also partially overlaps with the start of the hungry season, and the exertion required for construction is

[6]This study focuses on demi-lunes, rather than a broader set of RWH techniques, for several reasons. First, demi-lunes can be used to restore severely degraded land, including land that is no longer productive. Second, the technology is specific and easy to observe (in terms of construction, complementary inputs and maintenance), which facilitates the measurement of adoption and dis-adoption (Figure A1.1). Third, the technology is a strategic priority for Nigerien, regional and international stakeholders, and related projects receive substantial investments each year.

[7]*Glacis* are soils that have developed an impermeable layer across the top of the soil that impedes infiltration of water, primarily due to wind and sun. Sandy soils are a second type of degraded land in Niger, which are not appropriate for demi-lunes.

[8]There is little written about the justification of the technical norms, which appear to be largely mechanical: If each demi-lune is 2 by 4 meters, with 2 meters in between, then this would allow for 16 demi-lunes across 16 rows, so about 256 demi-lunes per hectare.

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substantial. Figure A.1 shows the timing of the agricultural calendar in Niger, along with the appropriate window for demi-lune construction.

Farmers can plant crops in and around the demi-lunes, primarily millet, sorghum, cowpea and sesame. While complementary inputs (such as manure or other fertilizers) can be added, they are not required for reaping soil moisture benefits. Once constructed, the demi-lune lasts for approximately three years without major maintenance, at which point the land in the demi-lune should be recuperated.[9]

Previous agronomic research suggests that the total costs of constructing 250-300 demi-lunes on one hectare are around USD 80, comprised mainly of labor (USD 75) and small tools (e.g., shovel and pickax).[10] Maintenance costs are significantly lower than construction costs (Liniger et al. 2011). Decades of on-farm trials suggest that demi-lunes can significantly reduce soil degradation and the risk of crop failure (Warren et al. 2001, Vohland and Boubacar 2009), as well as increase yields between 63-300%, depending upon whether fertilizers and manure are used (Kabore and Reij 2004, Bouma et al. 2016).[11]

2.3 Barriers to Demi-Lune Adoption

Despite substantial investment in promoting demi-lunes in Niger, it is estimated that only 10% of farmers adopt demi-lunes on any part of their private land (authors' calculations). The majority of farmers in our sample reported knowing about demi-lunes prior to the start

[9]While soil quality in between demi-lunes may also improve, agronomists recommend constructing new demi-lunes in between the old ones in order to fully recuperate the land.

[10]Depending upon the hardness of the soil, studies indicate that an average of three demi-lunes can be constructed per day. Thus, fully covering one hectare with demi-lunes would take between 85-100 person-days, or 500 hours. Labor costs are then estimated by applying the average wage rate. This is slightly less than the costs of pit planting in the same context.

[11]Precise estimates of the returns to adoption of RWH techniques, especially in the Sahel, are limited.

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of the study, yet only 2% had constructed them on their own fields (Table A.4). A number of barriers to adoption are associated with the specific features of the technology.

The first is information: Even if farmers know about demi-lunes, the information they have may be insufficient to know how to construct them or to assess expected costs and benefits. This is consistent with responses to baseline survey questions, which showed that the majority of farmers struggled with the basic technical specifications. While demi-lunes are a familiar technology, farmers may lack important details necessary for adoption.[12]

The second is cash on hand liquidity: Given the nature of the seasonal calendar and low rates of financial inclusion in Niger, farmers may be cash-constrained at the time when demi-lunes are typically constructed (Demirguc-Kunt et al. 2018, Aker et al. 2020). Most households in Niger rely upon informal financial services, such as savings and lending groups, which may be insufficient to cover the costs of demi-lune construction.

A final potential barrier is the time profile of costs and benefits. Labor costs of construction are concentrated in the first year and decrease substantially once the initial construction is complete, while the benefits of additional agricultural production do not arrive until the next harvest (at the earliest). This delay makes demi-lunes less privately profitable at higher discount rates. Our design targets these three primary barriers, although others may of course also be important.[13]

[12]Magruder (2018) classifies agricultural technologies into two types: *familiar* technologies (e.g., fertilizer, seaweed pods, chemical pesticides) and *unfamiliar* technologies (e.g., pit planting in Malawi, new maize seed varieties in Kenya). In contexts where a technology is unfamiliar, awareness is approximately 10% (BenYishay and Mobarak 2019). Information barriers for the adoption of familiar technologies may be the timeliness of the information provided (Cole and Fernando 2021), inattentiveness to some part of the production function (Hanna et al. 2014) or technical advice regarding the profitability of the technology (Duflo et al. 2008).

[13]Because demi-lunes are primarily associated with new production on land that is otherwise unproductive, any income that a farmer earns from demi-lunes is above and beyond

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3. Experimental Design

In 2018, we collaborated with the Ministry of Environment and a data collection firm, Sahel Consulting, to implement four main treatments, summarized in Figure A.2.

3.1 Interventions

Training The first treatment offered an interactive training in February 2018 to all selected farmers in each treatment village. The training lasted half a day and covered the following topics: 1) an explanation of demi-lunes and their purpose; 2) the steps for constructing and maintaining demi-lunes, including how to plant in and around them; and 3) the technical norms for construction, including the appropriate land type (sloped glacis), dimensions and orientation. The training was conducted by one of four Ministry of Environment agents, all of whom were men.[14] Laminated booklets with pictures and text on how to construct demi-lunes were also provided to participants (see Appendix A.1). After the "theory" portion of the training, the group practiced what they had learned by jointly constructing three demi-lunes on a plot of land volunteered by a village resident who was not part of the study.[15]

Our training differed from other demi-lune trainings in several ways. First, as mentioned above, the training provided a booklet in Hausa, which allowed households to follow along, as well as have a reference after the training. Second, the training focused on the fact that

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income earned without demi-lunes. Therefore the variability of production (and risk preferences) is less important than for technologies that displace incumbent technologies, such as drought-resistant varieties, whose benefits depend on whether a drought occurs.

[14]Ministry agents must have a Bachelor's (BA) degree, pass a national entrance exam and complete three months of military service. Agents within our study had at least five years of experience.

[15]The training occurred entirely within the village, with the theory portion in a central location in the village (e.g., under a tree) and the practical portion on a nearby plot, usually no more than 15 minutes' walk from the village.

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demi-lunes could be constructed on farmers' private plots, in addition to communal land. By contrast, prior trainings by the Ministry and NGOs had almost exclusively focused on constructing demi-lunes on communal land. And third, the training emphasized that demi-lunes could be constructed with readily available tools (e.g., shovel, pickax, etc.), rather than specialized tools that were not locally available.

Unconditional Cash Transfer - Early (UCT-early) To address liquidity constraints during the construction window, the second treatment combined the training with an unconditional cash transfer of USD 20, paid in March, approximately one month after the training. The value of the transfer was equivalent to 1/4 of the estimated cost of constructing demi-lunes on one hectare of land, based upon pilot research.[16] A key concern with the UCT-early arm is that farmers could have interpreted the cash transfer as conditional on demi-lune construction (Benhassine et al. 2015). To minimize this effect, we emphasized the lack of conditionality when announcing the cash transfer (Appendix A.2).

Conditional Cash Transfer (CCT) To address the time delay in benefits relative to construction costs, the third treatment combined the training with a CCT worth approximately USD 0.40 for every demi-lune constructed of acceptable quality. Unlike the UCT-early treatment, the transfers were paid in June, at the start of the rainy season and after verifying the number of demi-lunes constructed. All other modalities of the CCT treatment were the same as the UCT-early arm. The amount of the CCT was based upon prior pilot work, as well as the UCT amount; a household that constructed 50 demi-lunes would receive the same payment under the two treatment arms (Appendix A.2).Unlike the other treatment arms, only the CCT arm was told explicitly that they would receive a follow up visit to verify

[16]The cash transfers were announced in all transfer arms after the training took place, and were conditional on training attendance. Transfers were sent via mobile money to beneficiaries in the order of training implementation. A hotline was provided to report issues.

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demi-lune construction.

Unconditional Cash Transfer - Late (UCT-late) The final treatment combined the training with a UCT of USD 20.50, timed to coincide with the CCT payout. The additional USD 0.50 was provided as compensation for the delay in payment relative to the UCT-early arm. The primary goal of this treatment was to distinguish between the UCT-early and CCT arms, which differed both in their modality and timing.[17]

3.2 Sample and Randomization

In December 2017, we identified 184 villages in targeted departments of the Zinder region of Niger. To be eligible, a village needed to: 1) have some households with degraded land appropriate for demi-lunes (e.g., *glacis*); 2) have no chieftancy disputes; and 3) be categorized as an administrative village, meaning that it had its own chief.

Following the initial village identification and prior to the baseline, a census of eligible recipients was conducted. The primary criteria for eligibility was access to degraded land: a household needed to have between 0.5 and 10 hectares of degraded land at their disposal. The same process for listing eligible recipients was used in all villages, yielding a total of 4,944 eligible recipients.During the listing exercise, we also collected information about recipients' age, gender, marital status, mobile phone ownership, household size, land ownership and experience with demi-lunes.

After this listing process, four villages were dropped, either because they were administratively part of another village or because they contained only a few eligible recipients.

[17]The UCT-late arm was introduced at the same time as the UCT-early arm, with an identical script. The only differences between the two treatments were the amount (20.50 USD rather than 20 USD) and the timing (after demi-lune construction rather than prior). The UCT-late arm helps address concerns about reciprocity or experimenter demand effects in the UCT-early arm, since these effects are likely to be similar across the UCT treatments.

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Within each village, we stratified by gender and randomly chose 16 individuals, 8 men and 8 women, from the list of eligible recipients.[18] This yielded a final sample of 180 villages and 2,861 participants. We also randomly drew a spillover sample from among the 2,083 eligible households who were not chosen to participate in the study. The spillover sample was comprised of two men and two women per village, yielding a sample of 670 participants.

The 180 study villages were stratified by three geographic sub-regions before being randomly assigned to one of the four treatment arms (150 villages) or a control (30 villages). Treatment villages were assigned to either the training (40 villages), training plus UCT-early (40 villages), training plus CCT (40 villages) or training plus UCT-late (30 villages) arms. To ensure balance, we used the min-max t-statistic method with village and household-level characteristics, balancing on variables collected during the listing exercise and choosing the assignment allocation that minimized the maximum t-statistic (Bruhn and McKenzie 2009).

4. Data and Empirical Strategy

4.1 Data

The data we use in this paper come from three primary sources over a four-year period. First, we collected household-level survey data in February 2018, 2019 and 2021. Second, we collected observational data on demi-lune construction in June of each year from 2018 to 2021. And finally, we collected household survey data from a spillover sample in February

[18]In this context, "male" or "female" refers to the targeted respondent *within* the household, rather than a female-headed (versus male-headed) household. We first identified all eligible households in the village, regardless of marital status. If the household included a married couple, then both the primary male and female were listed. Among all eligible households, we then randomly chose whether the male or the female would be the primary recipient. In a small number of villages, there were not enough eligible females, and so all eligible females were enrolled. Over 94% of female recipients were married.

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2021. A summary of each dataset, the timing and the sample size is provided in Table A.2.

Household Surveys The first data source includes information on household characteristics before the interventions took place (baseline), as well as after (midline and endline). The baseline survey was conducted in all 180 villages in February 2018, approximately one month after the listing exercise, with follow-up surveys in February 2019 and 2021. Due to funding and time constraints, we were unable to interview all households within each village at baseline, and instead randomly sampled 12 (out of the 16) participants. We attempted to interview the full sample for the midline and endline surveys. Each survey collected detailed information on household demographics, assets, agricultural production, land and labor outcomes and demi-lune construction. Baseline data are primarily used to test for imbalance across the different treatments, while midline and endline data are used to estimate impacts of the program one and three years after the intervention, respectively.

Demi-lune Construction The second data source contains annual field observations of demi-lune construction in June of each year, from 2018 to 2021. For each data collection round, an enumerator and a Ministry of Environment field agent counted the number of demi-lunes on farmers' fields and noted which demi-lunes followed technical norms, including depth, dimension and spacing. In 2018, the verification data were also used to determine the payout in the CCT treatment arm. As mentioned above, only farmers in the CCT treatment arm were explicitly informed that monitoring would take place; any reference to future data collection details was left vague in the other treatment arms. The enumerator also asked questions about demi-lune construction and took the GPS coordinates of the plot where demi-lunes were constructed. The visit protocol was the same for treatment and control farmers, and the field team was unaware of farmers' treatment status.

In 2018 and 2019, only fields where farmers reported constructing some demi-lunes were visited for verification. In the 2020 and 2021 data collection rounds, the protocol was adjusted slightly. In 2020, the enumerators visited all fields and took their coordinates. This ensured a

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consistent sample of field geo-coordinates and observations, regardless of adoption outcomes. In addition, enumerators were asked to observe the presence of any demi-lunes on adjacent fields. In 2021, enumerators only verified *new* demi-lune construction, i.e., construction that had taken place between February and June 2021. Since the 2021 round verified only new construction, we do not include it in our main analysis.

Spillover Sample Survey The final data source is a household survey conducted with the spillover sample in February 2021. Similar to the household survey with the full sample, we collected information on asset ownership, agricultural production, land and labor outcomes, demi-lune knowledge and self-reported demi-lune construction. These data enable us to assess adoption and learning spillovers within villages. Field verification of adoption outcomes was not conducted for the spillover sample.

4.2 Balance and Attrition

Baseline Balance Table A.3 shows the balance of pre-program characteristics using the listing data, whereas Table A.4 uses the baseline sample. In each table, Column 1 shows the mean and standard deviation for farmers in the control group, and Columns 2-5 show the difference in means between each of the treatments and the control. The pairwise comparisons by treatment arm are shown in Tables A.5 and A.6.

Overall, differences in pre-program household characteristics are small (Tables A.3 and A.4). The average household size is 8.5 people, with 4.4 adults. Households own approximately 4 hectares of land, almost half of which is degraded, although not necessarily *glacis*. Almost half of all households belong to a savings group and are active in lending and borrowing money from family members, friends and money lenders. Households have access to three plots of land (owned or rented), and grow millet, sorghum, cowpea and peanuts. Rates of food insecurity are high: 93 of households reported experiencing food insecurity over the course of the past agricultural season.

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Across the characteristics tested for balance in a total of 198 separate tests (each pairwise comparison), a total of 15 (or 7.6%) show imbalance at the 10% level. Of these, the potentially problematic variables pertain to households' previous experience with demi-lunes: households in treatment villages were more likely to have had prior experience with demi-lunes and are about 4 percentage points more likely to have constructed demi-lunes in the past year.[19] The magnitude of the difference is small: baseline adoption along the extensive and intensive margins was low in all treatment arms. Nevertheless, we control for outcomes that are imbalanced at baseline as a robustness check during our analysis.

Attrition Table A.7 tests for differential attrition by treatment group across the different survey rounds. Attrition in the control group ranged from 1% in the demi-lune verification survey (Column 5) to 16% in the endline survey (Column 6). Differential attrition is most pronounced at midline (Panel A): households in treatment villages were 3 percentage points less likely to attrit than those in the control, with a statistically significant difference at the 10% level. This is potentially driven by labor reallocation as a result of treatment, as we discuss below. Analyzing differential attrition by treatment arm (Panel B), the UCT-late treatment is less likely to attrit than the control group at midline and endline, and the CCT treatment is less likely to attrit than the control group at endline. To correct for potential bias due to differential attrition, we bound our main treatment effects using Lee bounds for the midline and endline outcomes. Attrition rates are low and not correlated with treatment in all of our verification rounds, which we use for measuring adoption.[20]

[19]We cannot distinguish between demi-lune experience on private or communal land; both the government and NGOs hired farmers to construct demi-lunes on communal land during the dry season, in order to provide off-season jobs and regenerate pastureland.

[20]According to our pre-analysis plan, if we find evidence of differential attrition by treatment status, we will estimate Lee bounds. Thus, we focus our attrition corrections on the midline and endline data, rather than on the adoption outcomes.

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Compliance To interpret the results, it is important to check that the experimental design was implemented as planned. Table A.8 shows the statistics on training attendance and cash transfer receipt across all groups. Overall, participation in the program was high: 94% of households assigned to treatment had at least one household member attend the training, 73% of households sent the targeted beneficiary, and an average of 15 participants attended per village (Panel A). In general, there are no statistically significant differences in training attendance across treatment arms, with the exception of the "any household member attending" variable, though the magnitudes of differences between the treatments is small (3-4 percentage points, Column 1).[21] For the cash transfer arms, 94% of households (and nearly 100% of those eligible for a transfer) received a cash transfer (Column 5). There were also similar payouts between the UCT-early and CCT arms (Column 6).

4.3 Empirical Strategy

The random assignment of treatments across villages means that, in expectation, households in the control and the treatment groups have comparable background characteristics and agricultural constraints. We estimate the effect of being assigned to each of the treatment arms using the following specification:

$$Y_{iv} = \alpha + \sum_{j=1}^{4} \beta_j T_v^j + \gamma X_{i0}^{'} + \theta_v + \epsilon_{iv},$$

where Y_{iv} it the outcome of interest for individual i in village v. Treatment T^j is defined by village-level assignment to the training, UCT-early, CCT, or UCT-late treatments; θ_v is a vector of indicators for the three geographic strata, and $X_{i0}^{'}$ are the controls used to test balance during the randomization. In some cases, we also include the baseline measure of Y_{iv}, which lowers the number of observations given that the baseline survey covered a partial

[21]Women were one percentage point less likely to have a family member attend the training, and four percentage points more likely to have another household member attend.

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sample. We cluster our standard errors at the village level, the level of randomization. To correct our standard errors for multiple hypothesis testing, we also show adjusted p-values that control for the false discovery rate (FDR) (Benjamini et al. 2006).

Each of the β_j coefficients represent the effect of treatment assignment relative to the control group. For our main adoption results, we estimate results by treatment arm and show the pairwise tests between treatment arms. For other outcomes, we pool the treatments and estimate a single treatment coefficient.

5. Results: Adoption

We first analyze the impact of the treatments on the extensive and intensive margins of adoption, measured as the probability that a household adopted any demi-lunes and the unconditional number of demi-lunes adopted.We start by analyzing short-run effects, followed by adoption over time, heterogeneity in treatment effects and within-village spillovers.

5.1 Short-Run Adoption

Figure 1 shows demi-lune adoption in the first year, approximately three months after the initial training and UCT-early interventions. The impacts are substantial: while only 4% of households in control villages adopted demi-lunes on any part of their land, farmers in treated villages were 91 percentage points more likely to adopt (Figure 1, top panel). There are no statistically significant differences between the treatments in the probability of adoption. The treatments also significantly increased the intensity of adoption: households in treated villages adopted an additional 34 demi-lunes relative to the control (Figure 1, bottom panel).

Table 1 presents the results from estimating equation (1) for a variety of adoption outcomes. Consistent with the figures, all treatments significantly increased the extensive and intensive margins of adoption, with treated farmers adopting 28-40 additional demi-lunes relative to the control (Panel A, Columns 2 and 3). Much of the average effect across the

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treatment arms can be attributed to the training only, which increased the level of adoption by 28 demi-lunes relative to a mean of 1.3 demi-lunes in the control, or over 2000%. Relative to training, the UCT-early and CCT treatment arms adopted 27 to 43% more demi-lunes, respectively (Column 2). Other pairwise comparisons are not significantly different from zero.[22] We interpret the lack of impact of the UCT-late arm relative to the training as evidence that adoption in the UCT-early arm was not driven by reciprocity or experimenter demand effects. While we cannot rule out that the larger effects in the CCT arm were due to beliefs about future monitoring, this could not have contributed to treatment effects in the other arms, since only the CCT group was informed that they would receive field visits.

Farmers may have adopted demi-lunes without regard for quality (thereby reducing their effectiveness) or constructed demi-lunes without using them. Columns 4-6 show that this was not the case. First, the quality ratio (i.e., the ratio of demi-lunes that conform to technical norms relative to the total number of demi-lunes) is similar across groups: in the control group, 88% of demi-lunes met technical norms, with similar quality ratios across all treatment groups (Column 4). Second, 80% of treated households planted crops in and around the demi-lunes, and approximately 20% of treated households applied manure to their demi-lunes, with few statistically significant differences between treatments. This suggests that demi-lunes were being used and maintained in the first year.[23]

In addition to the treatment, several other characteristics were correlated with short-term

[22]The 20 farmers in the control group who adopted any demi-lunes adopted a mean of 31 demi-lunes in the first year. Conditional on adoption, households in treated villages adopted an additional 13.2 demi-lunes relative to adopters in the control.

[23]Planting and manure usage were only recorded the first year, as demi-lune verification was conducted immediately after the start of the rainy season, in order to give farmers sufficient time to adopt. In following years, the field visits were conducted immediately before the rainy season, and so planting and manure application had not yet occurred for a majority of farmers.

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adoption (Table A.9). For example, households living in one commune (Kantche) adopted significantly fewer demi-lunes than those in Takieta. In addition, households where women were targeted adopted 3.5 fewer demi-lunes than those where men were targeted. We assess heterogeneous treatment effects below.

5.2 Adoption Over Time

The short-term adoption of agricultural and environmental technologies may not persist in the medium- to long-term (Barrett et al. 2020). Our research design allows us to study disadoption – in other words, demi-lunes that are abandoned after the first year – as well as persistent and new adoption. However, unlike seeds and fertilizers, the decision to adopt demi-lunes is not made each agricultural season, since they can be used for three years with little maintenance. At the same time, if farmers completely neglect their demi-lunes after the first year, their quality is likely to deteriorate.[24]

To assess the dynamics of adoption over time, we use data from three rounds of demi-lune verification (2018, 2019 and 2020). Three main patterns emerge. First, the probability of demi-lune adoption increased in the control group over time, from 4% of farmers in 2018 to 17% in 2020 (Figure 2, top panel). By 2020, a total of 80 farmers in control villages (out of 470) had constructed at least one demi-lune on their plot of land. The pattern is similar for the intensive margin (Figure 2, bottom panel): farmers in control villages had adopted an average of 10 demi-lunes by the third year.[25]

Second, while the probability of adoption remained stable across all treatment arms over

[24]We observe some farmers whose demi-lunes disappeared over time. This could be explained by a failure to respect technical norms. For example, if demi-lunes are constructed on heavily sloped land or sandy soils, they can be destroyed during the rainy season, which – anecotally – occurred in our context.

[25]Conditional upon adoption, control households adopted a total of 61 demi-lunes by the third year, with similar levels in the treatment group.

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time, the level of adoption increased slightly in the pooled treatment group, by 3-5 additional demi-lunes per year (Figure 2, bottom panel). Most notably, adoption levels converged across treatments: by the third year, the training arm had caught up with the UCT-early and CCT arms (Table A.10).[26] This suggests that training had a persistent effect on adoption, but that the cash transfers did not have additional longer-term effects relative to the training alone.

Third, by the third year (2020), farmers were still actively using their demi-lunes. While 16% of farmers in control villages had operational demi-lunes – defined as demi-lunes where crops were planted – farmers in treated villages were 74 percentage points more likely to use demi-lunes, for a total of 90% of farmers in treated villages (Column 5, Table A.10). This is only slightly less than the percentage of farmers who had adopted.

5.3 Heterogeneous Adoption

We would expect higher levels of adoption for sub-populations for which the treatments alleviated key barriers. We therefore test for heterogeneous treatment effects by a number of pre-specified characteristics, namely gender, household labor, land size, previous demi-lune experience and geographic location.[27] For this analysis, we pool across the treatment

[26]By the third year, the UCT-early arm had fewer demi-lunes than both the training and CCT arms. While the difference between the UCT-early and CCT arms is statistically significant at the 10% level, this is primarily driven by an outlier in the CCT arm. When outcomes are winsorized, the difference between the UCT-early and CCT arms is no longer different from zero.

[27]Our pre-analysis plan also included heterogeneity by mobile phone ownership as a proxy for wealth. Mobile phone ownership significantly increases the magnitude of the treatment effect in the first year but not the third year. Though not pre-specified, we also test for differential effects by baseline migration status and whether the household borrowed money in the past year. Neither of these interaction terms is statistically different from zero.

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arms and estimate the interaction between each heterogeneity variable and an indicator for treatment, focusing on the intensive margin of adoption.

Table A.11 presents the results. First, while the treatment had differential impacts along a number of dimensions in the short-term (Panel A), most of these differences did not persist in the longer-term (Panel B), with the exception of geographic area.[28] Second, with the exception of geography and previous experience, many of these heterogeneous effects are relatively small in magnitude, representing 5-13% of the main treatment effect. Perhaps most notable is the lack of persistent differential effects by gender: in the first year, women in treated villages adopted 5 fewer demi-lunes than men in treated villages (Panel A, Column 1). By the third year (Panel B, Column 1), the magnitude of this effect had decreased slightly and lost statistical significance. In a context where women cannot own private land and have limited access to financial services, the training still led to a large increase in adoption among households that targeted female farmers.[29]

5.4 Adoption Spillovers

The previous results show that the treatment induced adoption in the short- and medium-term among eligible farmers. However, with village sizes ranging from 250 to 1000 people, only a small fraction of the village was selected for treatment. We therefore test for adoption spillovers using two separate measures. The first is an observational measure of neighbors'

[28]We interpret these effects by sub-region with caution, as only 34 of the 180 villages were in the Takieta sub-region. Nevertheless, one potential explanation for this geographic difference could be differences in land size. On average, households in Kantche owned 1.2 hectares less land than those in Takieta, and 0.3 hectare less degraded land.

[29]Since demi-lunes can help to minimize the likelihood of crop failure, we also test whether demi-lune adoption varied by exposure to self-reported climatic shocks in the prior season. We find that exposure to a climatic shock increased the effect of treatment on the propensity to adopt, although it did not have an effect on the level of adoption.

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adoption, whereby enumerators noted whether a farmer's neighbor's plot also had demi-lunes. The second is self-reported demi-lune adoption from the spillover sample.

Table 2 shows the impact of the training on spillovers. Using observational measures, farmers in treated villages were 50 percentage points more likely to have neighbors who adopted demi-lunes than those in control villages, with adoption on an additional 0.7 neighboring fields (Columns 1 and 2).[30] Using the spillover sample, we find that eligible individuals living in treated villages were 18 percentage points more likely to construct demi-lunes than the same sample in control villages, and constructed approximately 6 additional demi-lunes (Columns 3 and 4). While the impact on the intensive margin is not statistically significant, the magnitude is substantial, representing 53% of adoption in control villages.[31] However, relative to the direct effects main sample (see Table A.10 and Figure 2), these effects are modest: by endline, the direct treatment effect on any demi-lune adoption is 79 percentage points and the effect on the number of demi-lunes is 32.5. Thus, the effects of direct exposure to training on adoption are significantly larger than the indirect effects.

5.5 Interpreting Adoption Magnitudes

Despite the high rate of adoption in treatment villages, the number of demi-lunes constructed remained below the Ministry of Environment's recommended levels of 250-300 per hectare. Using a baseline measure of total degraded land (although not necessarily *glacis*), farmers in treated villages adopted between 32-41 demi-lunes per hectare of degraded land by the third year, representing 11-16% of the Ministry's technical norms.[32] Do these adoption magnitudes

[30]We cannot distinguish between neighboring fields that belong to main sample farmers who participated in the training or other farmers who did not.

[31]In addition, the spillover sample in treated villages cultivated an additional 0.15 ha of previously degraded land, and acquired new assets for demi-lune construction.

[32]The lower number is based on the unconditional mean of 32 demi-lunes per hectare for treated farmers and a norm of 300 demi-lunes per hectare; the upper number is based on

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signify underadoption? And if so, why?

The first answer is that the recommended norms are based on calculations that maximize coverage, rather than profits. Given the size of demi-lunes and the distance between them, this implies that 256 demi-lunes should be constructed on one square hectare of sloped and degraded land. Yet this ignores the economic costs and benefits from the farmer's perspective. If the cost of demi-lune construction is increasing in the number of demi-lunes or benefits are decreasing, then the recommendation to cover all degraded land may lead to negative profits on the margin, even if average profits are positive. Thus, adoption levels may maximize profits at a number that is less than "full" adoption.[33] Yet to be consistent with the modest levels of new adoption after the first year, increasing marginal costs would have to be persistent (such as land quality), rather than variable (such as labor).[34]

Second, our measures of land quality may suffer from measurement error, resulting in an underestimate of adoption per hectare (Abay et al. 2019). As outlined above, demi-lunes are appropriate for a common type of degraded land, *glacis*. While we have baseline self-reported measures of land quality, these do not distinguish between *glacis* and other types of degraded soils, nor do they account for the slope. If we are overestimating the size of *glacis* or the amount of land with the appropriate slope, then our measures may underestimate the rates of adoption per degraded hectare. There is some evidence that this is the case:

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the conditional mean of 41 demi-lunes per hectare and a norm of 250 demi-lunes.

[33]See also Duflo et al. (2008) in Kenya, who find that one reason why farmers may not use fertilizer and hybrid seeds is that the official recommendations are not locally adapted.

[34]The modest additional adoption over time, particularly given the positive average profit in the first year, is consistent with a time-invariant component to those costs that determine adoption levels. Adoption at a particularly steep part of the labor cost curve in one year could be deferred to the next year (and to a flatter part of the curve), while marginal costs that increase due to the difficulty in working degraded soils are unaffected by spreading adoption over time.

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during the field observations in 2020, Ministry agents calculated the amount of *glacis* land. According to these data, farmers owned approximately 1.3 hectares of *glacis*, representing approximately 36% of the degraded land. Using this measure of *glacis* suggests that farmers were adopting at approximately 30-47% of the technical norms.

Third, market failures in complementary markets, such as labor, seeds or insurance, may persist despite our interventions, resulting in a constrained optimal level of adoption that is lower than the unconstrained optimum. Our data suggest that this is not the case. For labor, demi-lunes are constructed during the slack agricultural period, when labor availability is high, and we observe no general equilibrium effects on wages (Table A.12). Seed availability also does not appear to constrain adoption: while 25% of households cited seeds as an important constraint at baseline, 90% of households were still using their demi-lunes in the third year (Table A.10). In addition, while risk aversion combined with missing insurance markets could lead to under-adoption, we observe no heterogeneous treatment effects with respect to baseline risk preferences. The relatively modest additional impacts of the CCT treatment, which guarantees a minimum payout in the first year, further suggest a minimal role for risk aversion as a barrier to adoption.

Taken together, the above results suggest that while adoption levels are below full adoption, they appear at or near the point where private returns are maximized.

6. Results: Inputs and Outputs

Given large effects on adoption, we next assess the impact of the interventions on households' input usage and agricultural outcomes. Since differences across treatments dissipated by the third year, we focus on a pooled specification that compares farmers assigned to any treatment with those in the control.[35] We interpret these impacts as driven by the training (which was common across all treatment arms), particularly by the third year.

[35]Results by treatment arm are described in the text or provided in the appendix.

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6.1 Inputs to Demi-Lune Construction

Since demi-lune construction is labor intensive, labor costs are often cited as a potential barrier to adoption (Barry et al. 2008). Table 3 shows the impact of the treatments on households' allocation of labor over time. Most of the demi-lune construction took place in the first year, so we test for treatment effects on demi-lune specific labor investments in year 1 (Panel A, Columns 1 and 2). In the short-term, additional family labor was allocated to demi-lune construction: while households in the control group used two person-days of family labor to construct demi-lunes, households in the treatment group used an additional 15 person-days, a statistically significant effect at the 1% level. Treated households also hired more non-family labor to construct demi-lunes, for a total of 6 additional person-days (Panel A, Column 2). On average, households in the treatment group used approximately 24 person-days of labor for demi-lune construction, implying a mean productivity of approximately two demi-lunes per person per day.

This allocation of family labor to demi-lune construction was accompanied by a corresponding reduction in family labor supply off-farm, both in the number of household members involved in seasonal migration (Panel A, Column 3) and in local labor sales (Panel A, Column 4). These effects were substantial, representing 17-35% of the mean of the control group. In the medium-term, effects on off-farm labor supply had dissipated (Panel B, Column 3). Households in treated villages were also more likely to hire labor for other agricultural work, an effect that persisted over time (Panels A and B, Column 5).[36]

Overall, households in treatment villages spent approximately USD 15 on labor for demi-lune construction in the first year, with similar expenditures across treatment arms (Table A.13, Column 1). This was almost equally divided between non-family and family labor,

[36]Estimating the impacts by treatment arm yields few statistically significant results between treatments, with the exception of the UCT-late treatment in the first year. Households in the UCT-late treatment did not significantly modify their household's migration patterns or sale of family labor.

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with slightly higher expenditures on family labor (Columns 2 and 3).[37] While the treatment increased labor expenditures for demi-lunes, it did not crowd out expenditures on labor hired for non-demi-lune purposes (Column 4). Given that the training led to nearly universal adoption, with labor as the primary input, these findings suggest that labor and credit were not binding constraints to adoption in this context.

In addition to labor, demi-lunes also require small tools, such as shovels and pickaxes. Figure A.4 shows that the treatments crowded in investment in these productive assets. Households in treated villages owned 17-26% more assets than those in control villages, primarily pickaxes and shovels, with no statistically significant difference by treatment arm. Higher asset ownership also persisted in the medium-term, suggesting that households initially purchased these tools to construct demi-lunes, and did not sell them after construction.

6.2 Agricultural Output

The agronomic literature suggests that demi-lunes can improve soil quality, reduce the risk of crop failure and increase agricultural productivity, especially with the use of complementary inputs. However, results from actual adoption decisions may differ from agronomic trials. Table 4 shows the estimation results for equation (1) for agricultural outcomes, again pooling across treatment arms.

The treatment did not affect households' crop allocation in the short- or medium-term (Column 1). While households in the treated villages had a 40% lower likelihood of crop failure than those in the control in the first year (Column 2, Panel A), this did not persist (Panel B). Yet the treatments led to a 0.12-0.15 standard deviation increase in both the

[37]Expenditures are similar for family and non-family labor because average daily wages for demi-lune family labor were USD 0.40, while average wages paid for non-family labor was USD 1.20. These are both significantly less than wages paid for non-demi-lune labor, which are USD 1.60-2.00 (Table A.12), and do not necessarily reflect the opportunity cost of family labor.

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quantity and value of total agricultural production (across all plots), with larger and more precise effects over time (Columns 3 and 5, respectively). Concretely, these effects translated into an 80 to 90-kg increase in the amount produced and an additional USD 34-37 in revenues per year, implying that the treatment group earned 10-13% more than the control.[38]

Figure A.3 shows the impacts by crop, pooling across treatment arms. The impacts on agricultural production were primarily driven by increased sorghum and sesame production: on average, households in treated villages produced 50% more sesame than those in control villages during the first year, with persistent effects in the medium-term.[39] There were also sizable increases in millet and sorghum production, the two staple crops, although these impacts were only statistically significant at the endline.

It is possible that the short-term impacts on agricultural production could have been affected by channels other than demi-lune adoption, such as the cash transfers. Yet it seems unlikely that these transfers could have affected agricultural outcomes in the third year, for two reasons. First, the cash transfers were relatively small in magnitude and unlikely to lead to persistent shifts in household incomes. Second, there was not a statistically significant difference in adoption between treatment arms by the third year.

6.3 Land Quality and Usage

Beyond the impacts on agricultural output, one of the touted benefits of demi-lunes is their effect on soil moisture and quality, and hence their contribution to reversing the process

[38]Table A.14 shows effects by treatment arm. Agricultural production was slightly higher in the UCT-early group relative to both the training and UCT-late groups in the first year, but differences did not persist over time. This is largely consistent with the patterns of demi-lune adoption.

[39]While millet, sorghum, cowpea and sesame can be planted in and around demi-lunes, planting peanuts is not recommended. As expected, we find no effects of the treatments on peanut production (see Figure A.3).

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of land degradation. Table 5 shows the results of regressions of equation (1) for a number of self-reported measures of land usage and soil quality. In the first year (Panel A), there is little evidence of impacts on land use or quality (Columns 1-3), with the exception of self-reported soil quality (Column 4), a scale measure ranging from 1 (poor quality) to 5 (extremely fertile).[40] While households in control villages rated their average soil quality across all fields at 2.76, corresponding to "average" soil quality, those in treated villages rated it marginally higher.

By the third year (Panel B), self-reported land usage significantly improved: households in treated villages were 33 percentage points more likely to cultivate previously uncultivable land (Column 2), cultivating an additional 0.30 hectares relative to the control. In addition, they were 7 percentage points less likely to retire land from planting due to degradation (Column 3). Self-reported soil quality also improved (Column 4): farmers were 45 percentage points more likely to report an improvement in soil quality over the past three years. Effects on additional self-reported soil quality measures are shown in Figure A.5.

Using an observed measure of soil quality, we find no treatment effects on the average hectares of degraded land.[41] Nevertheless, there were some distributional effects: the treatment shifted more of the mass to very small amounts of degraded land, with a statistically significant difference between the treatment and control groups (Figure A.6, with a p-value of 0.07 from a Kolmogorov-Smirnov test).

Taken together, these results are consistent with the fact that demi-lune adoption slowed

[40]While the impact of the treatment on the number of degraded hectares cultivated in the first year is not statistically significant, the magnitude is important: households in treated villages reported cultivating an additional 0.08 ha of previously degraded land, which roughly coincides with the land area covered by the average number of demi-lunes constructed.

[41]These data were collected by trained enumerators and Ministry of Environment field agents during the third demi-lune field verification round. For each plot of land, the agents estimated the total plot size, as well as the portion of land that was glacis.

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the land retirement process and improved self-reported soil quality in the medium-term, allowing farmers to cultivate previously degraded land. This shift did not impact the land market: our data suggest that farmers did not change their ownership or rental patterns.[42]

6.4 Are Demi-Lunes Privately Profitable?

While we do not have detailed measures of all revenue and cost streams, we conduct back of the envelope calculations of the impact of demi-lunes on farmers' profits. On the revenue side, treated households increased their agricultural revenue by USD 34 and USD 37 in the first and third years, respectively, using an exchange rate of 500 CFA per USD (Table 4). On the cost side, households spent approximately USD 15 on labor for demi-lune construction and received USD 4.30 less in income from local wage work (Table A.13).[43] Treated households also sent fewer family members for seasonal migration, implying a cost of USD 11.40 and USD 2.85 in foregone remittances in the first and third years, respectively.[44] Finally, households purchased approximately USD 5 worth of assets in the first year (Figure A.4).

We combine these estimates to calculate the present value of private benefits and costs in Table A.16 (Panel A). Even in the first year, when most costs were incurred, the private benefits outweighed the private costs by a little over USD 3. At a 5% discount rate, the present value of benefits over three years was nearly three times the private costs, ignoring

[42]Table A.15 estimates equation (1) for a variety of proxies of well-being, including income, expenditures, livestock and food security. Households in treated villages had higher food security in the short-term and owned more assets.

[43]Since we lack detailed labor expenditure and earnings data from subsequent years, we use the cost data from the first year to extrapolate to later years. Treated farmers constructed 4 and 2 new demi-lunes in the second and third years; we use per-demi-lune labor treatment effects from the first year to calculate associated labor costs.

[44]These costs are calculated by taking the estimates of reduced migration in Table 3 and an estimate of USD 57 in remittances per season (Aker et al. 2020).

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the cash transfers. This is further supported by farmers' revealed preferences: three years after the initial intervention and adoption, farmers were still actively using their demi-lunes.

7. Mechanisms

7.1 Why Was the Training so Successful?

The impact of the training over time suggests that it was successful in relaxing a binding constraint to demi-lune adoption. Above, we discussed features of the technology that facilitated high rates of adoption: the timing of labor inputs, the private profitability and the limited number of substitutes. In this section, we provide evidence that the training alleviated both informational and behavioral barriers to adoption. As a first step, we focus on farmers in our spillover sample, who were indirectly exposed to the training content. This allows us to test whether direct participation in the training was necessary for adoption, or whether indirect exposure was sufficient.

The Training Addressed Barriers to Technical Knowledge. As shown above, spillover farmers in treated villages constructed an average of six additional demi-lunes as compared to those in control. While significant, this effect was much smaller than the direct effect of training on adoption. Why was direct exposure to the training key? Demi-lunes were a relatively familiar technology in our context: a majority of farmers had heard about demi-lunes at baseline, and over 1/3 had prior experience, despite low baseline adoption levels. By the endline, awareness was widespread (over 95%), both in control villages and in the spillover sample. Yet adoption rates in these groups remained low – approximately 20-30% – relative to trained farmers. Taken together, this suggests that increased awareness was not the key mechanism through which the training spurred adoption.

Technical details about the technology may have diffused from trained to untrained farmers less readily than awareness. Using tests of farmers' demi-lune knowledge over time, we

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find that the training increased farmers' test scores by 14% as compared with the control.[45] While these impacts are modest, farmers in treated villages were 8-21 percentage points more likely to know specific technical details – such as the correct dimensions, depth and number of demi-lunes – as compared with the control (Figure 3).[46] Yet this technical knowledge did not diffuse to the spillover sample: on average, spillover farmers did not have higher test scores compared to the control, except on one out of seven technical items.[47] The fact that technical information improved substantially in treated villages but did not diffuse is consistent with technical information acting as a barrier to widespread adoption (Cole and Fernando (2021) and Hanna et al. (2014)).[48]

The Training Addressed Behavioral Barriers. In February 2021, we embedded a nudge intervention in the endline survey in an effort to better understand the mechanisms underlying adoption. The interventions included five treatments and one control, with each

[45]We tested all respondents on their demi-lune knowledge at baseline, midline and endline. While the test covered the same topics in the midline and endline, the endline test was open-ended, to more accurately gauge respondents' knowledge. Thus, we cannot directly compare the endline results with the baseline and midline results.

[46]A related question is why awareness was high but technical information was modest. As outlined above, other projects hired farmers to construct demi-lunes on communal land. Our training specifically trained the farmers to adopt the technology on their own land. In focus groups, farmers reported that the accessibility of the information (and implementation) was important for their adoption decisions.

[47]In the spillover sample, we observe a correlation between adoption and knowledge, but this is not related to the farmer's treatment status. This is consistent with the interpretation that knowledge is important for adoption, but that the technical details provided to main sample farmers did not diffuse to spillover farmers.

[48]These spillover findings also suggest that social learning is insufficient to generate widespread adoption when specific technical details must also diffuse in the population.

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treatment designed to address a behavioral barrier to adoption. Within each village, we stratified by gender and assigned recipients to either one of the nudges or none. The nudges addressed five topics: permission-seeking, procrastination, feedback, the salience of cost and benefits, and access to inputs.These nudge scripts were delivered three years after the initial training, when adoption levels for treated farmers were already high. We measure new adoption associated with the nudges during the 2021 verification round, which we exclude from the main analysis since it measured only new adoption. We interpret any new adoption resulting from these nudges as suggestive of the behavioral barriers and cues that may influence adoption decisions, but cannot directly test whether these same barriers or cues were impacted by the training content.

Overall, being assigned to any nudge led to statistically imprecise increase in the number of new demi-lunes as compared with no nudges. When looking at the impact of different scripts, two of the nudges had the largest effect, as shown in Appendix Figure A.7: providing information about the costs and benefits of demi-lunes, and reminding farmers that Ministry agents were available for questions each led to adoption of 5-7 additional demi-lunes. While difficult to interpret quantitatively, these findings suggest that support from outside organizations, and increased salience of costs and benefits, may have been important for increasing adoption in our context.

Taken together, these results suggest that participation in the training was important for adoption, both because the training provided the technical knowledge that farmers needed to adopt and – more speculatively – because it addressed behavioral barriers. Given the technical complexity of the construction and the fact that construction is labor and energy intensive, this combination of channels seems relevant for the technology we study.

7.2 Why did the Cash Transfers not have more of an Impact?

While the UCT-early and CCT treatments led to initially higher levels of adoption as compared to the training alone, these impacts dissipated by the third year. These treatments

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were designed to relax cash-on-hand liquidity constraints and increase the short run benefits of adoption, respectively. The fact that we see little lasting effect on adoption levels suggests that while they may lower adoption in the short run, they represent relatively minor barriers to adoption. This interpretation is supported by other results. For example, female farmers in Niger are more likely to face liquidity and credit constraints, yet we do not find strong or persistent differences in adoption by gender. Family labor dominated non-family labor in constructing the demi-lunes (Table 3), resulting in lower construction costs. In addition, baseline measures of access to borrowing show that over 85% of households reported borrowing money or food during the previous agricultural cycle, and the majority had access to savings opportunities outside of the home. While farmers lack access to formal credit to finance agricultural investments, access to diversified borrowing and saving opportunities will tend to both ease liquidity constraints and increase the profitability of investments with delayed benefits. Our study therefore joins a growing number of RCTs that show modest overall effects of liquidity and credit constraints on agricultural technology adoption (Magruder 2018). Like Karlan et al. (2014), we find that farmers can – when the necessary barriers are relaxed – come up with the financial resources to cover agricultural investments.

7.3 Threats to Identification

There are several potential confounds to interpreting our main results. First, given imbalance in some of our baseline characteristics, our results may be driven by these pre-existing differences. Table A.17 shows the ANCOVA specification for key outcome variables, where baseline data are available. Overall, most of our results are robust to controlling for baseline outcomes (and some are stronger), despite the lower number of observations.

A second potential confounding factor is differential attrition. The results on attrition in Table A.7 show that attrition is higher in the control villages in the midline and endline surveys, but not in other data collection exercises, which implies that our main treatment effects on adoption are not affected. For the survey results, if attrition is correlated with

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outcomes, then this could bias our estimates of treatment effects measured in the surveys. We therefore use tightened Lee bounds to correct for potential bias due to differential attrition in the midline and endline surveys for agriculture, land and labor outcomes for the main sample (Table A.18). Unsurprisingly, almost all of the upper bounds are statistically significant (Columns 3 and 6, respectively). While the lower bounds are all the same sign as the original coefficients, some lose statistical significance (Columns 2 and 4). Several key impacts on labor, agriculture and land use show significant lower bounds. This implies that differential attrition is not driving the results measured at midline and endline.

A third potential threat is spillovers across villages. As mentioned previously, demi-lune adoption in the control group increased from 4 to 17% between 2018 and 2020. If adoption in the control group was driven by exposure to treatment, this would violate the stable unit treatment value assumption (SUTVA). We therefore test whether distance to the nearest treated village drives control group adoption and find no significant correlation. In addition, the intra-cluster correlation of adoption in the control group was high (0.4), and adoption was primarily concentrated in six villages. This suggests that new adoption in control villages may have been driven by other NGO programs, rather than spillovers across villages.

A fourth potential threat is the (differential) effect of monitoring on our outcomes. All study farmers received annual field visits to verify adoption outcomes, although only the CCT arm was aware that these would occur sometime in the first year. We therefore cannot rule out that monitoring contributed to differences between the CCT arm and other treatments in the first year. Yet monitoring is unlikely to contribute to initial adoption outcomes in the other treatments, given that farmers were unaware that detailed adoption data would be collected. Even if it did contribute to adoption in later years, we posit that these effects would not fully explain the adoption magnitudes.

Finally, we have estimated the impact of the treatments on a number of different (primary) outcomes. To address concerns about multiple hypothesis testing, we report sharpened q-values based on corrections for the false discovery rate (using Benjamini et al. (2006)) in Ta-

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ble A.19, focusing on our main outcomes (those reported in the tables in the main text).Using these sharpened q-values, significance levels are mostly unchanged from our main analyses.

8. Conclusion

Technologies that can address soil degradation are key for ensuring sustained yield improvements in the semi-arid areas of sub-Saharan Africa, especially the Sahel. Climate change exerts additional pressure on farmers and has the potential to accelerate land degradation and desertification. Despite decades of investment in promoting such technologies, their sustained adoption has been mixed.

This paper assesses the impact of training and cash transfer interventions on the adoption of one type of environmental technology – demi-lunes – in Niger. The treatment effects are striking: a one-day training increased the probability of adoption by over 90 percentage points relative to the control, with no statistically significant differences between the treatments. Treatment also led to improvements in downstream outcomes, namely, agricultural production and land use, with persistent effects up to three years later. The training was more cost effective in increasing medium-run adoption than the cash transfer treatments, given that the latter had no additional impact on adoption intensity. As shown in Table A.16, all treatment arms delivered benefits in the form of higher agricultural revenues far in excess of the cost, even in the first year of implementation. Over the three-year time horizon of the study, the present value of these benefits was eight times the implementation costs in the training-only arm. This compares favorably with BenYishay and Mobarak (2019), who conduct a one-year cost benefit analysis of their project and find benefits per dollar spent of 0.83 for pit planting and 15 for composting, including research costs. If we focus on agricultural revenue impacts in the first year alone, the benefits per dollar are equal to 1.6, excluding research costs. Yet as noted above, these impacts persist over time.

Our results are primarily driven by training alone, rather than the cash transfers, and

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further research is needed to identify the specific features of the training underlying its effectiveness. For example, scaling up may depend on hitting on the right bundle of technical information and behavioral barriers. The effectiveness of training in other contexts will also upon the suitability of the technology – in our case, the private profitability presumably contributed to the impacts – the availability of labor, and the capacity of key partners to implement effective trainings. Nevertheless, given the widespread issue of land degradation, and the mandate of many Ministries to provide trainings, there are reasons to think that simple trainings could be effective in increasing adoption of rainwater harvesting to address land degradation and increase resilience to climate shocks in other contexts.

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Tables and Figures

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Table 1: Demi-lune Adoption, Year 1

	(1) Constructed any demi-lune	(2) No. of verified demi-lunes constructed	(3) No. of verified demi-lunes constructed per degraded ha	(4) Ratio of verified to total no. of demi-lunes constructed	(5) Sowed in demi-lunes	(6) Used manure in demi-lunes
Panel A						
Any treatment	0.91***	34.45***	25.94***	0.04	0.77***	0.20***
	(0.02)	(2.83)	(2.66)	(0.08)	(0.02)	(0.02)
Panel B						
Training	0.90***	28.24***	20.93***	0.06	0.74***	0.16***
	(0.02)	(2.88)	(2.76)	(0.08)	(0.04)	(0.03)
UCT early	0.93***	35.46***	27.54***	0.04	0.79***	0.22***
	(0.02)	(3.94)	(3.60)	(0.08)	(0.04)	(0.03)
CCT	0.89***	39.91***	30.44***	0.06	0.75***	0.20***
	(0.02)	(4.38)	(5.39)	(0.08)	(0.04)	(0.03)
UCT late	0.92***	34.22***	24.57***	0.02	0.82***	0.21***
	(0.02)	(4.92)	(3.85)	(0.08)	(0.04)	(0.03)
Mean in control	0.04	1.30	1.10	0.88	0.04	0.00
No. of observations	2850	2850	2850	2279	2850	2850

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Table 2: Adoption Spillovers, Year 3

	(1) Any demi-lunes adopted on neighbors' plots	(2) No. of fields where neighbors' adopted	(3) Adopted any demi-lunes	(4) Total no. of demi-lunes
Any treatment	0.50***	0.69***	0.18***	5.89
	(0.05)	(0.06)	(0.05)	(5.34)
Mean in control	0.17	0.20	0.12	11.07
No. of observations	2,834	2,834	639	639
R squared	0.19	0.15	0.04	0.03

Notes: Each column presents the results from a regression of the dependent variable on a binary variable for *any treatment*, as well as stratification fixed effects and variables used to check balance in the min-max t-statistic method. Columns 1 and 2 are from enumerators' field observations of neighboring plots during the 2020 field verification round. Columns 3 and 4 are collected at endline from the sample of spillover households. Robust standard errors clustered at the village level are provided in parentheses. P-values from pairwise F-tests of the coefficients are provided below the regression results. Asterisks denote a statistically significant difference at the 1% ***, 5% **, or 10% * levels.

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Table 3: Labor Outcomes

	(1) Person-days of DL family labor used	(2) Person-days of DL non-family labor used	(3) No. of migrants	(4) No. of family members selling labor	(5) Hired any non-family non-DL labor
Panel A: Year 1					
Any treatment	15.05***	6.03***	-0.21**	-0.12	0.06*
	(1.62)	(0.83)	(0.09)	(0.08)	(0.03)
Mean in control	2.35	0.65	1.12	1.08	0.36
No. of observations	2,535	2,535	2,536	2,535	2,535
R squared	0.12	0.05	0.05	0.03	0.04
Panel B: Year 3					
Any treatment			-0.05	-0.12	0.10***
			(0.07)	(0.11)	(0.03)
Mean in control			1.02	1.76	0.38
No. of observations			2,486	2,486	2,486
R squared			0.05	0.04	0.02

Notes: Each column presents the results from a regression of the dependent variable on a binary variable for *any treatment* for year 1 (Panel A) and year 3 (Panel B), as well as stratification fixed effects and variables used to check balance in the min-max t-statistic method. Robust standard errors clustered at the village level are provided in parentheses. P-values from pairwise F-tests of the coefficients are provided below the regression results. Asterisks denote a statistically significant difference at the 1% ***, 5% **, or 10% * levels.

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Table 4: Agricultural Outcomes

	(1) No. of crops planted	(2) Percentage crops failed of crops attempted	(3) Z-score of production (kg) of crops	(4) Z-score of value (CFA) of crop production
Panel A: Year 1				
Any treatment	0.06	-0.02*	0.12	0.12
	(0.07)	(0.01)	(0.08)	(0.08)
Mean in control	3.88	0.05	797.27	164,702.12
SD in control	0.81	0.12	674.91	146,702.32
No. of observations	2,535	2,535	2,535	2,535
R squared	0.05	0.05	0.11	0.11
Panel B: Year 3				
Any treatment	0.00	-0.01	0.15**	0.12*
	(0.06)	(0.01)	(0.07)	(0.07)
Mean in control	4.01	0.10	642.79	139,315.76
SD in control	0.84	0.17	594.71	149,714.87
No. of observations	2,486	2,485	2,486	2,486
R squared	0.03	0.01	0.11	0.08

Notes: Each column presents the results from a regression of the dependent variables on a binary variable for *any treatment* for year 1 (Panel A) and year 3 (Panel B), as well as stratification fixed effects and variables used to check balance in the min-max t-statistic method. Robust standard errors clustered at the village level are provided in parentheses. P-values from pairwise F-tests of the coefficients are provided below the regression results. Asterisks denote a statistically significant difference at the 1% ***, 5% **, or 10% * levels.

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Table 5: Land Usage and Soil Quality

	(1) No. of fields owned or rented	(2) Ha. of land cultivated	(3) Ha. of degraded land cultivated	(4) Self-reported soil quality
Panel A: Year 1				
Any treatment	0.01	0.04	0.08	0.04*
	(0.12)	(0.22)	(0.17)	(0.02)
Mean in control	2.60	4.81	3.16	2.76
No. of observations	2,535	2,535	2,535	2,535
R squared	0.07	0.08	0.06	0.01

	(1) No. of fields owned or rented	(2) Renewed cultivation on any land	(3) Stopped cultivating any land	(4) Soil quality improved
Panel B: Year 3				
Any treatment	-0.08	0.33***	-0.07***	0.45***
	(0.12)	(0.04)	(0.03)	(0.04)
Mean in control	2.86	0.39	0.21	0.44
No. of observations	2,486	2,486	2,486	2,486
R squared	0.06	0.08	0.01	0.20

Notes: Each column presents the results from a regression of the dependent variables on a binary variable for *any treatment* for year 1 (Panel A) and year 3 (Panel B), as well as stratification fixed effects and variables used to check balance in the min-max t-statistic method. Robust standard errors clustered at the village level are provided in parentheses. Asterisks denote a statistically significant difference at the 1% ***, 5% **, or 10% * levels.

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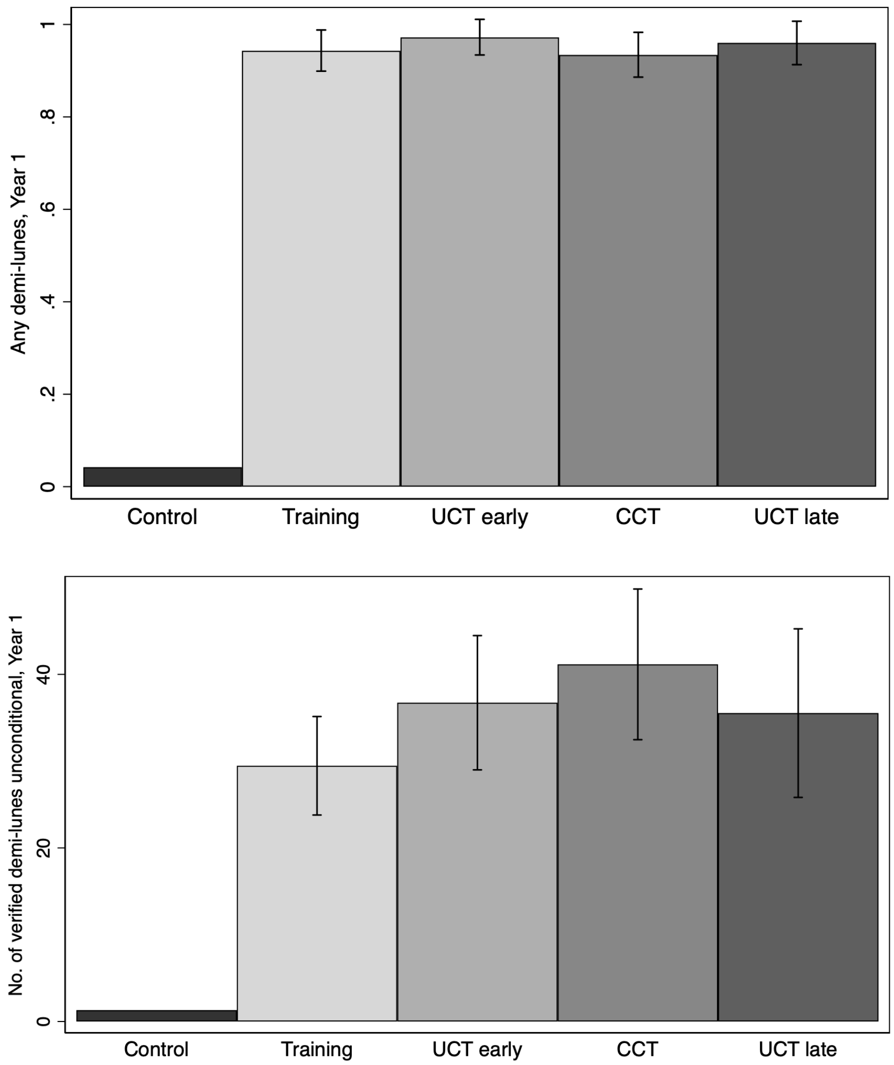

Figure 1: Demi-lune Adoption, Year 1

Notes: Results from a regression of measures of the extensive and intensive margin of demi-lune adoption on binary variables for each treatment variable and strata fixed effects, using data from the June 2018 field observations of demi-lune construction. Standard errors are clustered at the village level.

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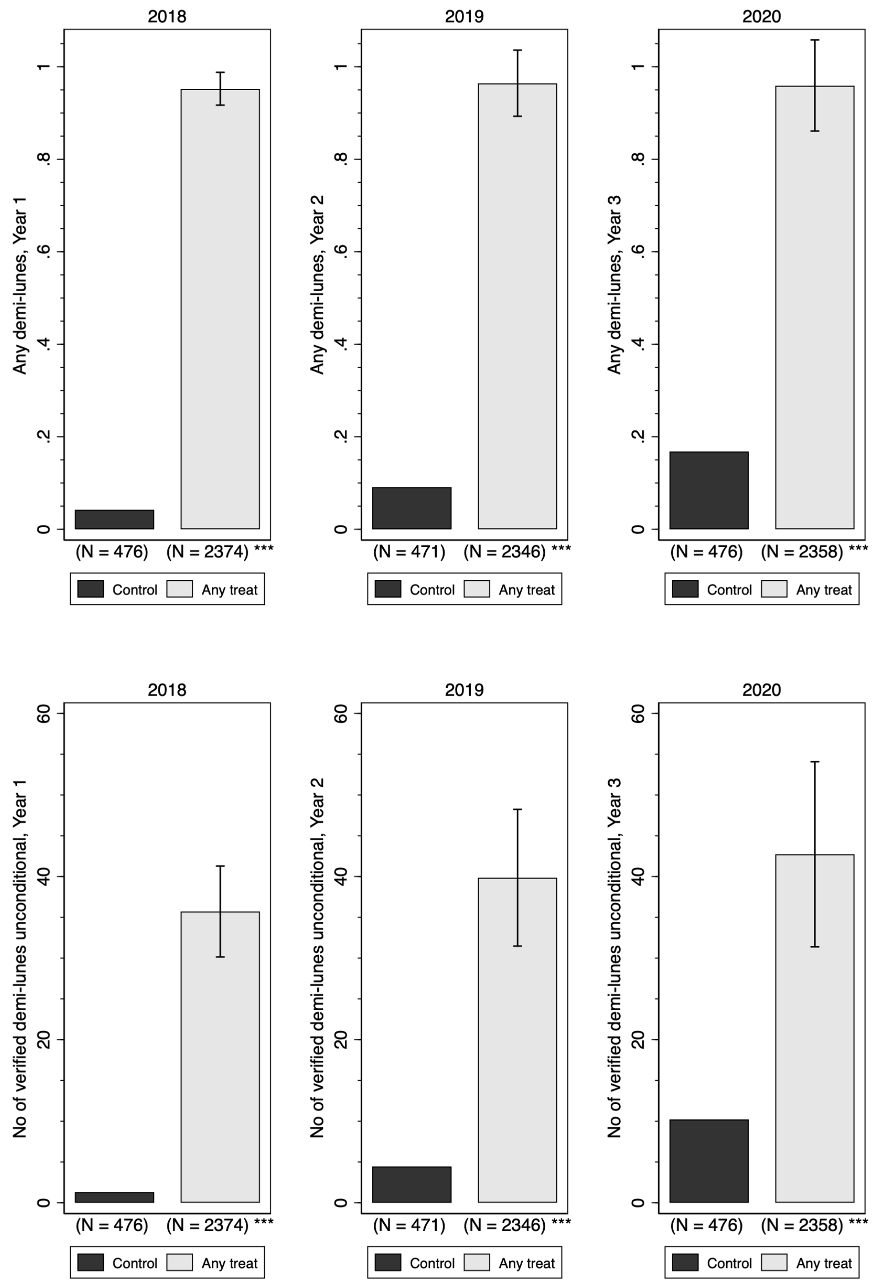

Figure 2: Demi-Lune Adoption over Time

Notes: Results from a regression of adoption outcomes on a binary variable for *any treatment* and stratification fixed effects. Data are from the field verification rounds in 2018, 2019 and 2020 (years 1, 2 and 3). Standard errors are clustered at the village level.

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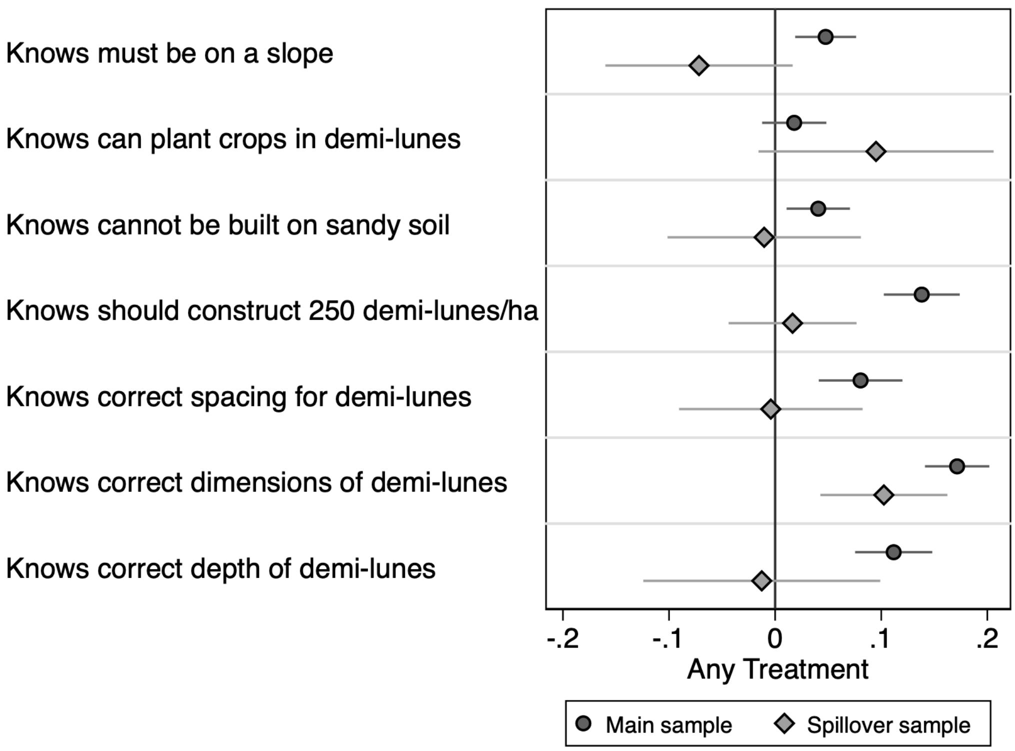

Figure 3: Test Scores, Main Sample and Spillover Sample, Year 3

Notes: Results from a regression of each variable on a binary variable for *any treatment* and stratification fixed effects, using data from the endline survey. Standard errors are clustered at the village level.