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The joint effects of information and financing constraints on technology adoption: Evidence from a field experiment in rural Tanzania

Aurélie P. Harou [a,*], Malgosia Madajewicz [b], Hope Michelson [c], Cheryl A. Palm [d], Nyambilila Amuri [e], Christopher Magomba [f], Johnson M. Semoka [e], Kevin Tschirhart [g], Ray Weil [h]

[a] McGill University, Department of Natural Resource Sciences, Agricultural Economics, Canada
[b] Columbia University, Center for Climate Systems Research, United States of America
[c] University of Illinois at Urbana–Champaign, Department of Agricultural and Consumer Economics, United States of America
[d] University of Florida, Department of Agricultural and Biological Engineering, United States of America
[e] Sokoine University of Agriculture, Department of Soil and Geological Sciences, Tanzania
[f] Sokoine University of Agriculture, Department of Agricultural Economics and Agribusiness, Tanzania
[g] Columbia University, Center for International Earth Science Information Network, United States of America
[h] University of Maryland, Department of Environmental Science and Technology, United States of America

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ABSTRACT

Low investment in profitable technologies contributes to persistent poverty. Many farmers in developing countries invest too little in fertilizer despite evidence that fertilizer is profitable. This field experiment investigates a two-part explanation: (1) farmers are reluctant to invest without farm-specific evidence of profitability, possibly because of heterogeneous returns, and (2) information is not sufficient to increase investment because of financing constraints. Farmers in one arm of the experiment receive fertilizer recommendations based on tests of their soils, others receive recommendations paired with an input subsidy, and others receive only the input subsidy. Only farmers who receive recommendations and the subsidy increase fertilizer application and yields relative to the control group. The financing constraint may explain limited response to heterogeneous fertilizer recommendations. The approximate net benefit of increased yields, accounting for the full cost of inputs and soil tests, is equivalent to average wages for seven days of work.

1. Introduction

Low agricultural productivity is a major contributor to poverty (Sanchez, 2002; Minten and Barrett, 2008; Sanchez and Swaminathan, 2005), and a threat to food security as the climate changes and the population grows. Slow adoption of technologies that have been shown to improve crop yields, in particular fertilizer, is only partly understood. Lack of awareness about fertilizer and/or its profitability as well as farmer inability to finance fertilizer are contributing factors (Emerick et al., 2016; Duflo et al., 2008; Karlan et al., 2014; Kihara et al., 2016; Suri, 2011; Xu et al., 2009). The evidence regarding effectiveness of information in increasing adoption of fertilizer is mixed (Duflo et al., 2008). Subsidies are unpopular due to fears that they will result in excessive investment and an unwillingness to pay the market price even after the benefits of fertilizer have been established (Schultz, 1964; Suri, 2011; World Bank, 2007).

Chemical fertilizers have been around for a long time and have been shown to be profitable across a range of contexts (McArthur and McCord, 2017; Evenson and Gollin, 2003; Harou et al., 2017). Yet low fertilizer use continues to constrain yields and to contribute to poverty in many parts of the world (Tittonell and Giller, 2013; Dzanku et al., 2015). Differences in fertilizer use at least partly explain the enormous difference between average maize yields in the United States, 11.5 metric tons per hectare in 2019, and in sub-Saharan Africa, about 2 metric tons per hectare, where yields are well below the world average of 5.5 metric tons per hectare (USDA, 2020; FAOStat, 2020).

This study uses a randomized controlled trial to investigate the impact of an intervention that combines farm-specific information and financing on fertilizer adoption. The two reasons for low investment that we explore may apply to adoption of new technologies or behaviors in other contexts, such as adoption of weather index insurance or improved seeds, and health behaviors. First, we investigate whether information about fertilizer that is tailored to the farmer's own soil increases use of fertilizer more effectively than does generic information from extension services. Returns to new technology can depend on unobserved and heterogeneous characteristics of the adopters (Strauss

* Corresponding author.
E-mail address: aurelie.harou@mcgill.ca (A.P. Harou).

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and Thomas, 1995; Deaton, 1995). The profitability of applying fertilizer has been shown to depend on deficiencies of soils on farmers' plots (Duflo et al., 2008; Kihara et al., 2016; Nziguheba et al., 2010; Suri, 2011). If the advice as to types and amounts of fertilizer that they should apply is not well-suited to farmers' soils, as is the case for information provided by government extension services for all farmers in our study area, farmers may "learn" that fertilizer is not profitable.

Second, this study fills a gap in the literature by examining the interaction between information and farmers' ability to invest in fertilizer. Studies have addressed each of these constraints separately (Carter et al., 2013; Duflo et al., 2011; Murphy, 2018; Corral et al., 2020). However, a farmer's liquidity may affect his/her willingness to learn about profitability of fertilizer given available information by applying the fertilizer and observing realized profits.

We conduct a field experiment among small farmers cultivating maize in the Morogoro Rural district of Tanzania, where fertilizer use is rare and maize productivity is low. Our intervention has three treatment arms. Farmers in the first treatment group receive recommendations for the type and amount of fertilizer based on results from a test of their own soils. Farmers in the second arm receive vouchers that fund the cost of enough fertilizer to cover a 0.5-acre plot, but can be redeemed for any agricultural input or for cash. In the third arm, we offer farmers both plot-specific recommendations and a voucher for inputs in order to determine if and how the impact of information depends on farmers' ability to finance the investment in fertilizer.

We find that addressing both information and financing constraints increases the amount of fertilizer applied and maize yields substantially more than does addressing either constraint alone or neither constraint. Farmers who receive both fertilizer recommendations and a voucher for agricultural inputs increase the application of mineral fertilizer on maize on the plot of land on which the project tests the soil by 23 kg per acre more than do farmers in the control group. Average fertilizer application at baseline is 0.46 kg and fewer than one percent of farmers in our sample used any fertilizer at baseline. Farmers who receive the voucher apply only 10 kg per acre more than farmers in the control group and the difference with the recommendation plus voucher group is statistically significant. Fertilizer use remains at baseline levels among farmers who receive only recommendations and also among farmers in the control group.

The effect on maize yields is much larger in the group that receives both fertilizer recommendations and input voucher than in all other groups. The treatment group that receives both recommendations and vouchers avoids a 30% decline in yields that both of the remaining treatment groups and the control group experience as a result of a drought that occurred during the study. Yields in the treatment group that receives only vouchers and the group that receives only recommendations are not distinguishable from each other or from yields in the control group.

The substantial impact of the combination of recommendations and vouchers on maize yields may be due to an increase in fertilizer amounts and/or the application of fertilizer types that address prevalent soil deficiencies. In the recommendations plus voucher group, 92% of farmers purchased fertilizer compared with 31% of farmers who received vouchers only, and they purchased different fertilizers. The soil tests showed that soils of about 92% of farmers were deficient in sulfur. In the recommendation plus voucher group, 50% of farmers applied Ammonium Sulfate (SA) fertilizer, which replenishes sulfur, while 43% of those who increased fertilizer application applied only urea. In the voucher only group, only 4% of farmers applied SA. Farmers who only received vouchers were only made aware of the government recommendations, and the 27% who applied more fertilizer but did not apply SA followed government recommendations partially, applying urea but not DAP. The lack of a treatment effect on yields in the voucher group suggests that urea alone does not raise yields among these farmers.

An important role of the plot-specific recommendations in this study has been to show that government recommendations neglect a major soil deficiency in the study area. The extension service recommends the application of urea and DAP, neither of which addresses the deficiency in sulfur found on 92% of the plots. However, the finding does not imply that augmenting extension service recommendations with the advice to apply SA would necessarily reproduce the results in this study. First, the farmers in the recommendation plus voucher group who did not apply SA had the recommendation to apply other types of fertilizers that address a combination of sulfur and other nutrient deficiencies, which they did not follow. Whether or not these farmers would have benefited from applying SA to address the sulfur component of the deficiencies remains for further study. Second, the fact that no farmer used the voucher to fully follow the extension service recommendations suggests that farmers may not trust fertilizer recommendations from the government extension service. Since urea alone does not seem to raise yields, farmers who relied on government recommendations in the past may have learned that fertilizer is not profitable, potentially explaining the low baseline fertilizer use in the area, though we do not know for sure that applying urea and DAP would be equally ineffective. How farmers may regain trust in recommendations from extension services requires further research.

The plot-specific recommendations show that soil deficiencies are heterogeneous in the study area. Farmers tested the benefit of only a small part of that heterogeneity; therefore, the full benefit of plot-specific recommendations requires additional research. If farmers are aware of the heterogeneity, then they may not be willing to increase investment in fertilizer without information that is specific to their soil. In particular, they may not consider their neighbors' experience to be relevant.[1,2] In fact, the intervention did not have any spill-over effects in the treatment villages; except for the seven farmers in the voucher group who applied SA.

An approximate cost–benefit analysis shows that the fertilizers applied by farmers in the recommendation and voucher group are profitable even without any subsidy for fertilizer or soil tests. Farmers who pay the full cost of fertilizer would increase their profits by about 47,000 Tanzanian shillings (TzSh) on a one-acre farm if they do not pay for the soil tests, or nine days of work at the median daily wage. The profits would be equivalent to about seven days of work if farmers paid for soil tests.

The net benefit of the recommendation plus voucher approach could be larger with a redesigned voucher component. As Duflo et al. (2011) shows, a much smaller subsidy could be sufficient if offered immediately after harvest, when farmers have cash, rather than at the beginning of the planting season, when cash is often scarce. The difference in behavior at the two time periods arises if farmers face small fixed costs of purchasing fertilizer, such as transportation and/or decision costs, and the rate at which they discount the future changes stochastically over time.

Our results have two implications for improving the productivity of smallholder farms. First, small farmers with limited cash flow and access to credit like the farmers represented in our study are willing to test whether application of fertilizer is profitable when they receive information specific to their farm plots but only if they also receive support with financing the fertilizer. Farmers had not used the SA fertilizer before; therefore, they did not know its profitability. Second, national extension services should use soil tests to verify the relevance

[1] Learning about the profitability of fertilizer from others is difficult when variation in soil quality induces heterogeneity in economic returns (Suri, 2011; Marenya and Barrett, 2009; Munshi, 2004).

[2] Some evidence suggests that information that is specific to an individual is more likely to change behavior than is general information in other contexts, in which the value of information varies across individuals (Madajewicz et al., 2007).

of their recommendations. Inappropriate recommendations can lead to farmers learning that fertilizer is not profitable and that they should not apply it. Determining the appropriate spatial scale for such tests remains for further research since the farmers' response to treatment was not sufficiently differentiated to determine the full potential of information provided at the plot level.

2. Context

The site of the study is Morogoro Rural, a district in Tanzania's Morogoro Region. Maize is the primary cereal produced and consumed in the region. According to the 2007 Tanzania Agricultural Census, 98 percent of households in Morogoro grew maize on at least one plot. Few farmers use agricultural inputs such as fertilizer and improved seed; less than one percent reported using any fertilizer. Maize yields in Morogoro are low, averaging 1.4 tons per hectare between 1994 and 2001 (Paavola, 2008), well below the 4.7 tons per hectare achieved with experimental applications of 80 kilograms of nitrogen per hectare in the region (Mourice et al., 2014).

In many parts of sub-Saharan Africa (SSA), including Morogoro, governments make national or regional recommendations for fertilizer application at relatively high levels of geographic aggregation based on regional soil surveys (Tittonell et al., 2008). Governments promote one recommendation for an entire region or country despite evidence suggesting that important spatial heterogeneity exists in soil quality within regions (Vanlauwe et al., 2010; Wopereis et al., 1988; Zingore et al., 2007) and that such heterogeneity can have important effects on response of yields to fertilizer. For example, Duflo et al. (2008) finds that many farmers in Kenya receive recommendations for fertilizer application rates that are not profitable.

Only a small number of farmers throughout SSA, and very few small-scale farmers, know which nutrients are deficient in their soils, despite national and regional efforts to convince farmers that application of mineral fertilizer is profitable.[3] Few soil testing services are available to farmers in SSA and those that do exist are either prohibitively expensive for small farmers or respond with long delays.[4] Farmers operate with some sense of their soil quality and how it varies within the farm (Zingore et al., 2007), relying on observed crop yields as an indication of soil quality. However, research by Berazneva et al. (2018) finds a low correlation among farmer-reported subjective assessments of soil quality, actual yields, and laboratory measures of soil quality. In our study, the correlation between farmers' assessments of soil quality and the SoilDoc test results is 0.154.[5]

The Tanzanian government has established recommendations for fertilizer application on maize in four regions: Eastern and Central Highlands, Northern, Southern, and the Southern Highlands. Morogoro is located in the Eastern Highlands region, where soils from four research sites were tested in the late 1980s for pH, organic carbon, nitrogen, and available phosphorus. The resulting recommendations are problematic for three reasons. First, the recommendations are likely to be outdated since continuous cultivation without nutrient replenishment changes deficiencies over time. Second, the scale of soil testing may be too aggregated to produce results that accurately reflect deficiencies within villages in Morogoro Rural. Third, existing government recommendations are based primarily on soil parameters (C, total N, pH) that are not useful in making soil test recommendations and do not include important macronutrients such as sulfur and potassium.

3. The experiment

3.1. Selection of study sites and assignment to treatment

Selection of participants in the experiment proceeded in two stages: at the village level and at the individual level. We randomly selected 50 villages in Morogoro Rural out of all villages that were accessible by vehicle and known to grow maize. We assigned 20 randomly chosen villages to the treatment group and 30 to the control group.[6] We later discovered that two treatment villages and three control villages did not in fact grow maize during the long rains season. We replaced the two treatment villages with two other, randomly selected villages that did grow maize. These villages were chosen from the remaining villages on the original list that were not yet selected as treatment or control. We did not replace the three control villages due to time and budgetary constraints. Fig. 1 presents the locations of the 47 villages assigned to treatment and control.

In each of the final 47 villages, we obtained lists of all households who grew maize from the village leaders. We randomly selected farmers[7] for the study from among those maize farmers who a) had not participated in Tanzania's National Agricultural Input Voucher Scheme (NAIVS) in the last three years; and b) planned to cultivate a plot of maize in the 2016 growing season on which they also had cultivated maize in the 2014 season. In each of the 20 treatment villages, we randomly selected 40 farmers to participate in the study, and we assigned 10 farmers randomly selected from these 40 to each of the three treatment arms and to the control group.[8] In each of the 27 control villages, we randomly selected 10 farmers. The treatment group includes 600 farmers in 20 treatment villages. The control group includes 470 farmers: 200 control farmers in treatment villages and 270 farmers in control villages. The total selected sample is 1070 farmers. Fig. 2 presents the study design.

Our design includes a sample of control farmers in treatment villages for two reasons. First, in the absence of spillovers, control farmers in treatment villages enable a more precise estimation of treatment effects. Second, comparing outcomes between control farmers in treatment villages and farmers in the control villages allows us to estimate spillover effects that the treatments could plausibly generate within villages.

[3] For example, recent research shows that as much as 20% of land under cultivation in SSA does not respond to applications of standard fertilizers (containing nitrogen, phosphorus, and potassium), suggesting that underlying soil constraints to production may be related to pH, sulfur or other macronutrients, or other biological factors (Vanlauwe et al., 2010; Zingore et al., 2007).

[4] Soil samples must be mailed to laboratories for testing. A comprehensive test of soil macronutrients plus pH, electrical conductivity (EC), and a measure of soil organic matter in the commercial laboratory located in Dar es Salaam costs $60 per test if 100 tests are ordered (SGS Labs, personal correspondence, 2020). Tests are less expensive in national laboratories, but they are much slower, with delays of more than a year.

[5] More specifically, the correlation between measured Electrical Conductivity (EC) (measured in dS/cm), a proxy for soil fertility, and soil quality (where 1 = very poor and 5 = very good) is 0.154.

[6] We acquired lists of every village in Morogoro Rural known to grow maize and accessible by vehicle from the regional extension office. Each village was assigned a number using a random number generator. This number was then ranked in ascending order and the top 50 villages were selected to participate in the study. The first 20 villages of the randomized list were assigned to the treatment group and the last 30 villages were assigned to the control group.

[7] Each farmer was assigned a number using a random number generator. This number was then ranked in ascending order and the top 40 (10) farmers were invited to participate in the study in the treatment (control) villages. In treatment villages, the first 10 farmers in the list were assigned to the control group, the following 10 farmers were assigned to the voucher group, the following 10 farmers were assigned to the recommendations group, and the final 10 farmers were assigned to the recommendations + voucher group.

[8] Assignment to treatments and control was done simultaneously.

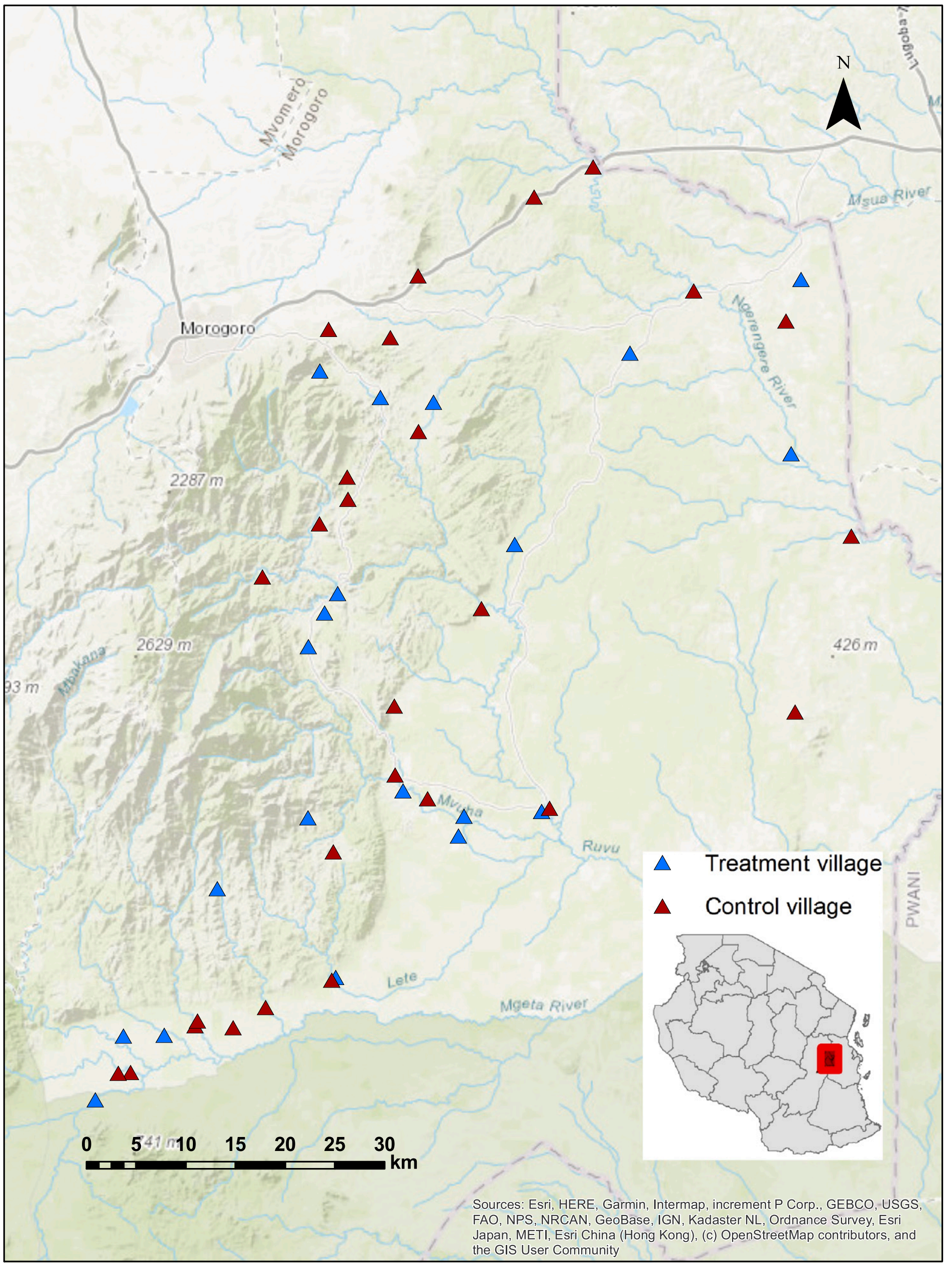

Fig. 1. Spatial distribution of the control and treatment villages in Morogoro Rural district.

3.2. The intervention

The project team included soil scientists and economists from Columbia University, McGill University, the University of Illinois, and Sokoine University of Agriculture (SUA), Tanzania's leading agricultural university. The **first phase** of the intervention took place in December 2015, after the team conducted the baseline survey discussed in Section 4. A team of agronomists explained the project to all farmers in treatment and control villages. The team discussed the importance of fertilizer and informed the farmers about the standard, regional-level recommendations for fertilizer application on maize provided by the government — 60 kg urea and 40 kg DAP per acre.[9] Communicating the government recommendations to all farmers in the sample ensured that we would compare effectiveness of plot-specific information to effectiveness of standard government recommendations, rather than to no knowledge at all. Only 3.7% of farmers reported knowing the regional recommendations in the baseline survey, before this information was provided to the participants.

Farmers in the control group in treatment villages and farmers in control villages received only the general information about fertilizer described above. However, agronomists informed these farmers, as well as farmers in the voucher only treatment arm described below, that they would receive plot-specific recommendations in time for the 2017 growing season, after the completion of the study.

In treatment villages, the SUA agronomists met separately with farmers assigned to each of the four arms of the experiment. Farmers in the three treatment arms received the following interventions:

Arm 1: Plot-specific recommendations (Group R) This group of farmers received recommendations for the types and amounts of fertilizer that each farmer should use on her/his main maize plot during

[9] We modified the government recommendations to one 50 kg bag of urea and one 50 kg bag of DAP per acre to facilitate the purchase of fertilizers, which are most commonly found in 50 kg bags.

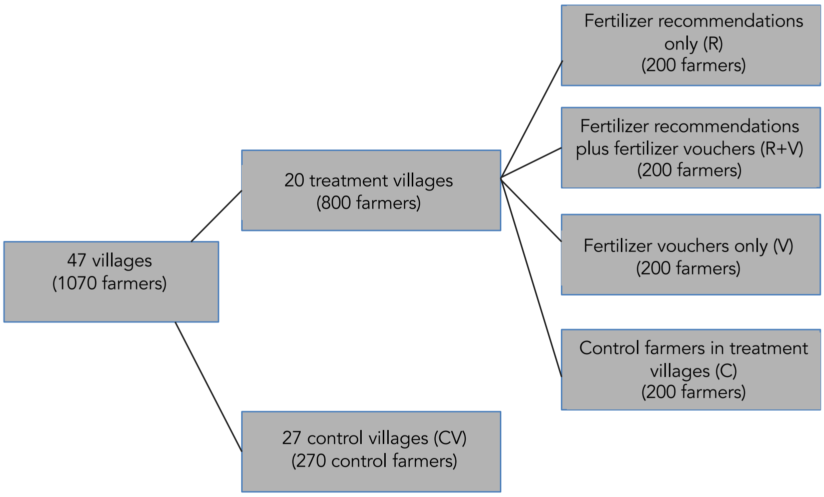

Fig. 2. Study design.

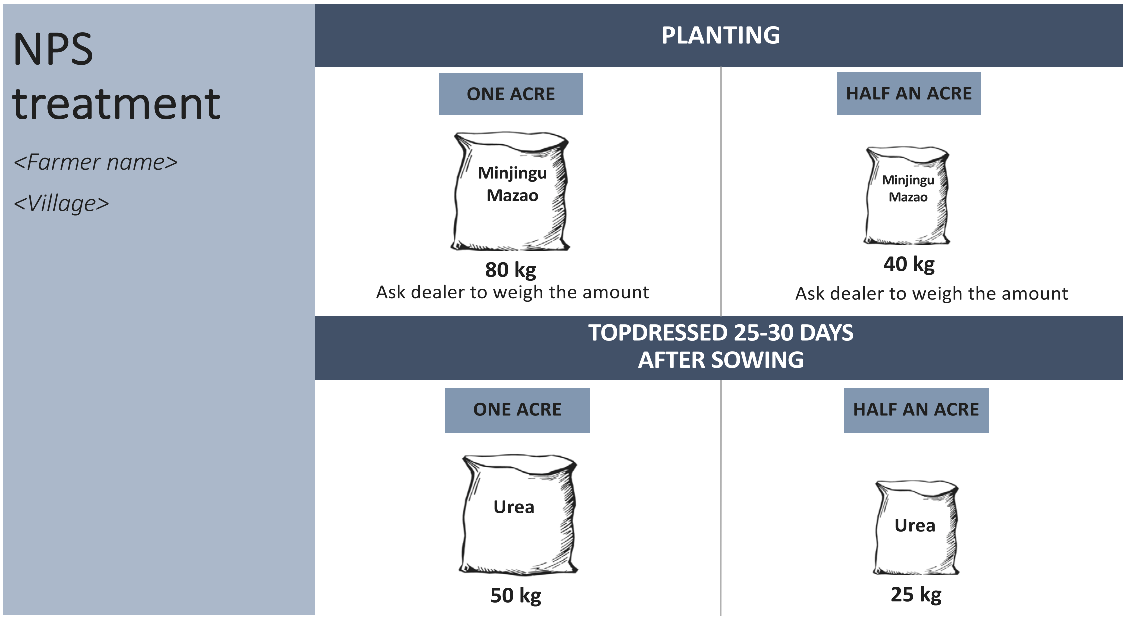

Fig. 3. Recommendation for a farmer deficient in nitrogen (N), phosphorus (P), and sulfur (S) (English version). NOTE: The figure shows an example recommendation card that farmers in recommendation and voucher (R+V) and recommendation (R) groups received. Every card included recommendation for fertilizer that should be applied at time of planting and fertilizer that should be applied at time of sowing as topdressing (25–30 days after sowing). Recommendations are provided for one acre (left column) and one half acre (right column) for maize cultivation.

the 2016 growing season, based on the results of a test of the soil from that plot, which we describe in Section 4.1. Agronomists distilled information from soil tests into specific, clear recommendations for the type of fertilizer and amount of each type.[10] In each village, agronomists met separately with groups of farmers organized so that all farmers in a group were receiving the same recommendations, and explained the recommendations in detail. The direct communication enabled farmers to ask questions. Fig. 3 presents an example card for a farmer whose soils were found to be deficient in nitrogen, phosphorus, and sulfur. We provided recommendations for both one acre and half of an acre so that farmers could more easily understand which fertilizers and what quantities to purchase and apply for plots of different sizes.[11]

Arm 2: Plot-specific recommendations and agricultural input voucher (Group R+V) This group of farmers received fertilizer recommendations for the main maize plot for the 2016 growing season and a voucher worth approximately 40 USD or 80,000 TZ Shillings. The voucher entitled a farmer to purchase any input available from a selected agro-input dealer. The value of the voucher was sufficient to purchase the standard, regional government recommendation of fertilizer for 0.5 acres of maize. Farmers had the option to redeem the voucher for cash instead of inputs, but they would receive 85% of the value of the voucher. In addition, if farmers purchased inputs that were less than the value of the voucher, they could redeem 85% of the remainder of the value of the voucher for cash. The agronomists

[10] Soil test results are often cumbersomely provided to farmers by communicating raw values of numerous measured soil parameters at the same time. India's soil health cards, for example, are extremely detailed. Cole and Sharma (2019) finds that the typical farmer does not understand soil health cards well, but that understanding improves when farmers meet with an agronomist who can explain the information.

[11] The mean baseline main maize plot size in the sample was 2.55 acres.

explained these rules to farmers at the village meeting, and they gave farmers the voucher coupons, which also listed the rules.

Arm 3: Agricultural input voucher (Group V) This group received only the vouchers described in Arm 2.

Arm 4: Control (Group C) This group of farmers did not receive information or vouchers.

In the **second phase** of the intervention, conducted in January 2016, we provided an opportunity for farmers in both treatment and control villages to purchase fertilizer and other inputs in their villages for two reasons. First, differences in transaction costs of accessing inputs between farmers would increase the variance of the impacts of our interventions. Second, eliminating these differences would facilitate the interpretation of the results by separating the effects of information and ability to finance the purchase of the inputs from the effect of variations in accessibility and costs of transportation.

We informed farmers in both treatment and control villages that an agricultural input dealer would visit their village on a given day, which would be announced one week in advance of the visit. Farmers who had received vouchers could redeem those vouchers for inputs or for cash, according to the voucher rules, from this dealer. Farmers who did not receive a voucher received an information card, which provided information about the availability of inputs from the dealer.[12] A dealer agreed to travel to each village and to spend six hours in each one to give farmers the opportunity to purchase any input. The dealer stocked all inputs recommended based on the soil analysis as well as hybrid seeds and other agricultural chemicals. The dealers offered the same prices to all farmers in all villages.[13]

4. Description of data

4.1. Soil data

Between September and November 2014, a team of soil scientists and agronomists from SUA collected soil samples from all farmers in the study. The team sampled the soil from the plot that each farmer identified as his or her main maize plot, on which the farmer cultivated maize during the baseline 2014 long rains season as well as intended to grow maize during the endline 2016 long rains season. A farmer's main plot was defined as the plot that the farmer considered to be most important to their household's livelihood in terms of food security and income generation.

Soil scientists performed the soil tests at SUA laboratories using SoilDoc, a diagnostic kit that combines the capacity to conduct measurements of essential soil physical and chemical parameters rapidly and in the field with information communications technology (ICT) to provide plot-specific management recommendation.[14] Soil scientists developed SoilDoc to facilitate access to soil tests in rural areas. The technology is new and not yet widely available. SoilDoc results have been demonstrated to be as accurate as those produced by commercial laboratories (Dimkpa et al., 2017; Weil and Gatere, 2015). The test analyzes the following soil fertility parameters: soil pH, biologically active soil carbon, electrical conductivity (indicative of general fertility as well as salinity issues) and extractable macronutrients (nitrate-N, sulfate-S, phosphate-P, and potassium-K). These nutrients are critical for plant growth. Two of these macronutrients are the primary components in the most widely used fertilizers in the world: urea (46% nitrogen) and di-ammonium phosphate (DAP, typically 18% nitrogen, 46% phosphate).

The team classified the continuously measured values for the nutrients N, K, P, and S into low, optimum, and high categories, which are specific to each nutrient and are based on protocols and thresholds developed by the SoilDoc team. The fertilizer recommendations included application of the fertilizer that contained the deficient nutrient when the level of the nutrient was below the optimum. They did not recommend additional fertilizer application when the level of a nutrient was at or above the optimum.

4.2. Household surveys

The team conducted a baseline survey of all treatment and control farmers in August 2014, before the intervention began. Survey modules included demographic characteristics, household and dwelling characteristics, credit, savings and assets, risk preferences, plot locations, and amounts of all agricultural inputs used. We conducted a second baseline survey in August 2015, during which we asked farmers about their 2014 harvest on their main maize plots, total quantities of maize sold, stored and consumed, as well as their expectations about the effect of fertilizers on yields. We conducted the endline survey in August 2016. All surveys took place at the same time of the year, in August, after farmers harvested the long rains maize crop.

Out of the 1070 farmers selected for the study in 47 villages, a total of 806 farmers participated in all three survey rounds plus the soil analysis, representing an overall attrition rate of 23%. A total of 1050 farmers completed the baseline survey: 190 control farmers residing in treatment villages, 198 farmers in the voucher only group, 191 farmers in the information only group, 203 farmers in the information plus vouchers group, and 268 farmers in control villages. The second baseline survey had an attrition rate of 20% from the first baseline, with 841 farmers completing the survey. A total of 984 farmers completed the endline survey, which represents an attrition rate of 6% from the first baseline survey. The soil sampling and analysis covered 1007 households, which represents an attrition rate of 4% from the first baseline. We present attrition statistics and analysis in Table 1 Panel B. We test whether attrition rates for each survey differ by treatment. Farmers in the recommendation group are less likely to have had their soils analyzed, though this finding is only statistically significant at the 10% level. Given that attrition is mostly balanced among treatments, we do not correct for it in the analysis that follows.[15]

5. Verifying random assignment to treatment

We define treatment throughout the paper as a farmer being assigned to one of the treatment groups: R, R+V, or V. We test whether differences between means of selected baseline variables for households assigned to treatment and those assigned to control are statistically significant by regressing baseline variables on binary treatment assignment indicators. The baseline variables include the main outcomes, fertilizer use and yields, and household characteristics that may influence the use of agricultural inputs and yields, including amount of land and other assets owned by the households and household characteristics. We estimate the following Ordinary Least Squares (OLS) regression:

$$b_i = \alpha_0 + \sum_{i=1}^{3} \beta_i T_i + \epsilon_i \tag{1}$$

[12] All farmers in the community could purchase inputs from the dealer, but only study participants (treatment and control) received the information cards providing information about what inputs the dealer would have in stock.

[13] The project subsidized the dealers' transportation costs.

[14] The SoilDoc kit was developed by Dr. Ray Weil based on many years of working with farmers in sub-Saharan Africa. It was a collaboration between Columbia University and the University of Maryland, and more recently the University of Florida.

[15] The difference between attrition rates in treatment villages (24%) and in control villages (9%) is statistically significant at the 1% level in the second baseline in August 2015. This difference is mostly driven by the inaccessibility of two treatment villages in August 2015 (Kiwege and Pulambili).

Table 1
Verification of random assignment to treatment: Control group includes only control households in treatment villages.

	(1) *n*	(2) Control	(3) Vouchers only	(4) Recommendations only	(5) Recommendations +Vouchers	(6) *F-test p-value*
Panel A: Baseline variables						
Total land held by household (acres)	782	5.676	−0.410	−0.222	−0.745	0.699
		(0.465)	(0.652)	(0.657)	(0.648)	
Total land cultivated by household (acres)	782	3.765	−0.157	0.105	−0.541	0.352
		(0.277)	(0.387)	(0.391)	(0.385)	
HH marketed maize (1=Y)	597	0.354	−0.031	−0.035	−0.035	0.902
		(0.039)	(0.054)	(0.056)	(0.054)	
Share of land in maize	782	0.542	0.025	0.009	0.025	0.734
		(0.193)	(0.027)	(0.027)	(0.027)	
Size of baseline main maize plot (acres)	782	2.712	−0.342	0.253	−0.282	0.191
		(0.220)	(0.309)	(0.311)	(0.307)	
Female headed household (1=Y)	782	0.168	0.029	0.010	−0.055	0.128
		(0.027)	(0.036)	(0.038)	(0.037)	
Head completed at least elementary school	782	0.679	0.018	0.028	−0.014	0.814
		(0.034)	(0.047)	(0.048)	(0.047)	
Applied mineral fertilizer to maize (1=Y)	782	0.005	0.005	0.005	−0.001	0.875
		(0.006)	(0.009)	(0.009)	(0.009)	
Used improved maize seeds (1=Y)	782	0.189	0.002	0.004	0.022	0.942
		(0.029)	(0.040)	(0.041)	(0.040)	
Quantity of mineral fertilizer applied to maize on the baseline main maize plot (kg/acre)	777	0.013	0.444	0.253	0.006	0.368
		(0.213)	(0.297)	(0.300)	(0.295)	
Maize yields on entire farm (kg/acre)	782	442.66	42.32	−1.933	43.42	0.565
		(31.151)	(43.61)	(44.00)	(43.34)	
Maize yields on baseline main maize plot (kg/acre)	688	379.65	−16.33	37.70	−17.04	0.281
		(22.703)	(31.52)	(32.41)	(31.35)	
Hotelling F-statistic			0.895	0.633	0.856	
Panel B: Attrition						
Soil Analysis baseline (2014)	782	0.953	−0.003	0.032*	0.023	0.1663
		(0.013)	(0.019)	(0.019)	(0.018)	
2nd Baseline in August 2015	782	0.774	0.009	−0.051	−0.0002	0.4939
		(0.031)	(0.043)	(0.044)	(0.043)	
Endline in August 2016	782	0.942	0.002	−0.015	−0.006	0.8928
		(0.017)	(0.025)	(0.025)	(0.025)	

NOTES: Columns 3-5 report the coefficients of respective treatment indicators from an OLS regression of each baseline variable or attrition on all three treatment indicators. Standard errors are clustered by village and are in parentheses. Column 6 reports the *p*-value for the F-test that coefficients for all treatment indicators are jointly equal to 0 for each baseline variable. Hotelling's F-statistic is for a test of equality of the means of all baseline variables jointly between each treatment group and the control group.

where b_i are the baseline variables and T_i are the assignments to treatments groups R, R+V and V. We find one important difference that informs our empirical strategy going forward, presented in Table A.1. Comparison of the differences between baseline mean maize yields on the farmer's main maize plot between control and the R+V group and control and the V group are statistically significant at 1% level of confidence when we include the control village farmers. Maize yields on the main maize plot is one of the two main outcome variables and so out of an abundance of caution we have chosen to exclude the control villages and rely exclusively on the control farmers in treatment villages in our analysis. Note that our final results are very similar if we include the control villages in the control group, as we show in Table A.2.

Table 1 presents the results of Eq. (1) with a control group consisting of only the control farmers within treatment villages. We find no statistically significant differences between households assigned to each treatment group and households assigned to the control group in the treatment villages. Columns 3–5 show the coefficients of the respective treatment indicators. Column 6 shows the p value for the joint hypothesis test that all coefficients on the treatment indicators are jointly equal to 0. Since the variables are not independent, we confirm that a Hotelling's T-square test, which accounts for correlation between the variables, fails to reject the null hypothesis that the mean differences of all variables are jointly equal to 0 for the comparison between each treatment group and the control group.

6. Methodology

We estimate the average treatment effect of the three treatments – plot-specific recommendations, recommendations combined with input vouchers, and vouchers – on two main outcomes: the amount of fertilizer that the farmer applied to maize and maize yields. Both the amount of applied fertilizer and yields are reported by the farmer.

As noted in Section 5, we define treatment as being assigned to one of the three treatments. Not everyone who was assigned to treatment came to a meeting to pick up their recommendations or voucher and not everyone used the information or voucher that they received.

Our main specification is the following first-difference regression estimated on a sample that includes all treated households and control households in treatment villages but excludes the control villages:

$$\Delta y_{iv} = \alpha_0 + \sum_{j=1}^{3} \beta_j T_{iv} + \upsilon_v + \epsilon_{iv} \tag{2}$$

Δy_{iv} are differences between the amount of fertilizer applied by farmer i in village v at endline (2016) and baseline (2014) or between the farmer's maize yields at endline and baseline, T_{iv} are the three treatment groups, υ_v are the village fixed effects, and ϵ_{iv} is the error term. The intercept is the mean change in the outcome variable among control farmers in treatment villages. Parameters β_j are the main parameters of interest. We cluster standard errors at the village level to account for the effect of potential within-village correlation given that we stratify random assignment by village.

We investigate impacts on outcomes reported at two levels of spatial aggregation: the entire farm and the farmers' main maize plots (the plots on which the survey team tested soil nutrients and for which we provided recommendations). Approximately 5% of farmers identified a different plot as their main maize plot at endline in 2016 than at baseline in 2014. We report the impacts on plots identified as the main maize plots at baseline. Our results are similar when we estimate the treatment effects on main maize plots that the farmer designates in either year, baseline or endline,[16] as we show in Table A.2, panel B.

7. Results

We find that plot-specific recommendations increase fertilizer application, but only when farmers also receive input vouchers. Farmers who received recommendations and vouchers increased their application of fertilizer on maize relative to the control group twice as much on average as did the group that received only vouchers. The recommendation plus voucher group increased the amount of fertilizer applied on average by 23 kg/acre more than did the control group, while the average increase in the voucher only group relative to control was 10 kg/acre, as we report in Table 2, panel A.[17] The increases are substantial relative to the miniscule average amount of fertilizer applied at baseline of 0.46 kg/acre. The difference between the impacts of the two treatments is statistically significant at the 1% level.[18]

Maize yields increased in the R+V group relative to baseline but not in the V group. Yields declined by an average of 121 kg/acre on the main maize plot in the control group from baseline to endline, as we show in Table 2 Panel C, Column 4. The most likely reason for the decline is that the growing season at baseline was better than at endline, when the area experienced a drought. Farmers in the R+V group maintained similar average yields between baseline and endline despite the drought, experiencing only a small decline on average. Farmers in the V group experienced the same change in yields as did the control group. The difference between the impacts of the R+V and the V treatments on maize yields is statistically significant at the 5% level.[19] The lack of a statistically significant impact of additional fertilizer use on yields in the V group suggests that applying urea alone has a limited effect on maize yields compared to applying urea with SA among these farmers.

Farmers in the R group experienced the same outcomes as farmers in the control group. The increase in amount of fertilizer applied by these two groups is not statistically significant and maize yields declined for both groups. Available resources appear to be a binding constraint on investment in testing the profitability of fertilizer.

Farmers in the R+V and the V groups applied the additional fertilizer mainly to maize.[20] Results presented in Table 2 Panel A show that the treatment effect on amount of fertilizer per acre is only slightly smaller on maize on the whole farm than on maize on the main maize plot. The effect on crops other than maize is small and not statistically significant both on the main maize plot and on the entire farm.[21]

In addition, the impacts on maize yields show that farmers are concentrating the additional fertilizer on the main maize plot. Results in Table 2 Panel C Column 2 show that the treatment effect on maize yields on the whole farm is not statistically significant.

The farmers in the R+V group may be concentrating the additional fertilizer on maize and on the main maize plot because they have received fertilizer recommendations for this crop and the main plot. However, farmers in the V group also concentrate additional fertilizer on maize. The reasons may be that maize is the most important crop and the main maize plot is the most important plot for the farmers' livelihoods.

Data on control villages enables us to test for spillover effects of treatment. Estimation of spillover effects may be biased since baseline maize yields are different for farmers in control villages than for farmers in other groups in the experiment. However, baseline maize yields are similar in control and treatment villages when we use village fixed effects (results available upon request). We do not expect to find spillovers since farmers who do not receive vouchers in the treatment villages do not increase their application of fertilizer, and indeed we do not find any evidence of spillovers, as we show in Table A.3. We present the regression specification that tests for spillovers in Appendix B.

We also estimate the effects of treatment on expected revenue from the increased yields. In 2016, only 67 farmers report selling maize in the market. We use the prices from these 67 sales to estimate the revenue that farmers did or could have generated by selling harvested yields in the market.[22] The specification is the same as in Eq. (2). We show the results in Table 2, Panel D. Farmers in the R+V group experience a statistically significant and economically consequential increase in revenue relative to the other treatment groups, even when we use the more conservative price, 25th quartile of the price distribution (results available upon request).

8. Explaining the results

In this section we analyze how decisions made by farmers assigned to different arms of the experiment with respect to participation in the project, use of vouchers, and choice of fertilizer help to explain the treatment effects.

8.1. Participation by farmers

Farmers who were assigned to the R+V and V treatments, the two groups that experienced statistically significant treatment effects, were more likely to attend meetings at which project staff communicated information about fertilizer and distributed fertilizer recommendations and vouchers. Table 3 shows that a much larger percentage of farmers who were in the R+V and in V groups attended the meetings, 86% and 80% respectively, compared to farmers in the R group, 63%, and in the control group in treatment villages, 51%.

Farmers in the R+V and V treatment arms were also more likely to visit the input dealers than were other farmers. In the former group, 82% of farmers visited the input dealer to purchase inputs and/or redeem the voucher for cash, and 68% did so in the latter group, while among farmers in the R group and in the control group in treated

[16] The specification that allows the plot to be different in 2014 and in 2016 includes farmers whose main maize plot is different between baseline and endline, who are excluded from the estimation of Eq. (2).

[17] The number of observations differ in column 6 of Panel A because some farmers no longer cultivated the maize plot that was their baseline main maize plot during the 2016 follow-up season. More specifically, of the 782 farmers, only 662 cultivated the same maize plot at baseline and endline. Of the 662 who cultivated the same main maize plot in both years, 5 responded that the size of their baseline main maize plot was 0 acres. Of the 782 farmers, 49 farmers report cultivating 0 acres of maize on their entire farm at endline.

[18] The results are almost identical when we regress the amount of fertilizer applied on treatment indicators at endline, as we show in Table A.2, Panel C. The reason for the identical results is that few farmers applied fertilizer at baseline.

[19] We obtain consistent results when we regress maize yields on treatment indicators at endline, as we show in Table A.2, Panel C.

[20] Respondents farm on average 1.97 plots at baseline.

[21] Farmers often also grow crops other than maize on part of their main maize plot.

[22] Table A.4 in the appendix shows the mean, median and 25th quartile prices by village and presents the number of observations by village. Prices exhibit considerable variation across villages, likely attributable in variation in the sales date (markets in the region exhibit considerable intra-annual variation in maize prices) and the small number of transactions observed. For villages which did not have sales, we use the sample mean price across the villages.

Table 2
Average treatment effects on application of fertilizer, dealer-reported fertilizer purchases, yields and revenue.

	(1) Recommendations only (s.e.)	(2) Recommendations + Vouchers (s.e.)	(3) Vouchers only (s.e.)	(4) Constant (s.e.)	(5) Control mean [std. dev.]	(6) Observations	(7) R^2
Panel A: Fertilizer application							
Fertilizer on maize on baseline main maize plot (kg/acre)	0.88 (0.99)	23.330*** (2.44)	10.046*** (3.34)	1.005 (1.10)	0.901 [5.857]	657	0.121
Fertilizer on crops other than maize on baseline main maize plot (kg/acre)	0.004 (0.02)	0.246 (0.25)	0.16 (0.16)	0.001 (0.08)	0 [0]	662	0.003
Fertilizer on maize on entire farm (kg/acre)	0.337 (0.61)	21.051*** (1.96)	10.082*** (3.28)	0.777 (1.05)	0.785 [5.474]	733	0.122
Fertilizer on crops other than maize on entire farm (kg/acre)	−0.271 (0.22)	0.519 (0.62)	0.441 (0.31)	−0.02 (0.19)	−0.022 [0.287]	733	0.004
Panel B: Fertilizer purchases							
UREA (kg)	0.01 (0.010)	25.991*** (1.171)	8.892*** (2.093)	−0.03 (0.665)	0 [0]	782	0.614
SA (kg)	−0.002 (0.003)	12.384*** (1.780)	0.862** (0.381)	0.02 (0.485)	0 [0]	782	0.387
Panel C: Yields							
Maize yields on baseline main maize plot (kg/acre)	−32.457 (50.372)	114.560** (52.086)	43.572 (50.559)	−121.209*** (35.919)	−133.29 [323.44]	548	0.018
Maize yields on entire farm (kg/acre)	8.879 (47.733)	92.775 (56.718)	−4.962 (56.829)	−208.649*** (34.142)	−208.93 [432.29]	733	0.007
Panel D: Revenue							
Revenue based on mean maize price (TzSh/acre)	21,639 (19,941)	54,309** (21,697)	24,212 (20,632)	120,523*** (14,665)	114,931 [124,026]	620	0.013

NOTES: Standard errors are in parentheses and are clustered at the village level. Regressions include village fixed effects. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table 3
Administrative data on take-up of treatments.

	Recommendations only	Recommendations + Vouchers	Vouchers only	Control	Control villages	Total
Panel A: Participation rates						
Total number of farmers (n)	191	203	198	190	268	1050
Attended SUA information and voucher dissemination meeting	63%	86%	80%	51%	21%	58%
Visited input dealer to redeem voucher for cash or make a purchase	24%	82%	68%	16%	5%	37%
Panel B: Proportion of farmers who purchased fertilizer						
Urea only	0%	43%	27%	0%	0%	14%
SA only	0%	0%	0%	0%	0%	0%
DAP only	0%	0%	0%	0%	0%	0%
Urea + SA	0%	49%	4%	0%	0%	10%
Redeemed entirely for cash value	N/A	8%	69%	N/A	N/A	.

NOTES: No farmer purchased a bundle of urea, SA, and DAP; Urea and DAP; or SA and DAP. Fertilizer purchases as reported by the input dealer.

villages the percentages were 24% and 16%, respectively. Nearly all farmers who attended dissemination meetings and received vouchers redeemed the vouchers.

Farmers in the R+V group were significantly less likely to redeem their vouchers exclusively for cash than were farmers in the V group. Only 8% of farmers in the R+V group requested exclusively cash from the dealer, as shown in Table 3 Panel B. Among the 92% who purchased inputs and received the remainder of the value of their voucher in cash, the average cash remainder was about 32% of the redeemable value of the voucher. More than two thirds of farmers in the V group fully redeemed the voucher for cash, purchasing no inputs.

Farmers who received recommendations plus vouchers also purchased a greater quantity of fertilizer than those who received only vouchers.[23] We estimate the impacts of treatment on amount of fertilizer purchased using the specification in Eq. (2) and amounts purchased that were reported by the agricultural input dealers in a sample that includes all treated households and control households in treatment villages. Farmers in the R+V group purchased approximately 26 kg more of urea and 12 kg more of SA than did farmers in the control group, who did not purchase any SA, as we show in Table 2, Panel B.[24] Farmers in the V group purchased approximately 8.9 kg more of urea and 0.9 kg more of SA than did farmers in the control group.

No farmers from the R nor the control groups purchased inputs from the dealers who visited the villages. With a single exception, only

[23] Some farmers who purchased fertilizer may not have applied all of the fertilizer to their plots. Table A.5 in the appendix compares the amount per acre of urea and SA purchased and the amount per acre applied by treatment group.

[24] Table A.6 shows the percent of farmers who purchased fertilizer as reported by farmers themselves.

farmers who received vouchers as a part of their treatment purchased fertilizer from the dealer.

8.2. The role of information

Plot-specific fertilizer recommendations may improve yields when coupled with vouchers through one or both of two mechanisms. First, the information increases farmers' propensity to apply fertilizer and the amounts applied, as shown in the previous section. Second, the farmers may be applying types of fertilizers that have a larger impact on yields.

The first way in which fertilizer recommendations may improve yields is that information about appropriate fertilizer types and amounts increases the likelihood that farmers will experiment to learn if fertilizer is profitable. Farmers who receive only vouchers may be concerned that they do not know which fertilizer they should apply and/or how much, despite knowing the recommendations made by the government extension service. The farmers may have tested the fertilizers recommended by the government in the past and found that they are not profitable. Past experience may be one reason why few farmers use fertilizer at baseline. Alternatively, the concern may be due to our intervention. Farmers may worry that they would buy the wrong fertilizer if they followed the extension service recommendations because they know that we are providing fertilizer recommendations to some farmers.

In fact, soil analysis results demonstrate that government recommendations do not address important nutrient deficiencies on the overwhelming majority of plots in the study. Government fertilizer recommendations for the region recommend urea and DAP to address deficiencies in nitrogen and phosphorus (NP limited) for maize cultivation. We find however that, a much larger proportion of plots are deficient in sulfur than in phosphorus, 91.6% versus 31.2% (Table 4). Moreover, while all plots are indeed deficient in nitrogen, nearly all are also deficient in sulfur. Farmers would not address the sulfur deficiency, nor deficiencies in several other important nutrients (Table 4), by following the government recommendations.

The second way in which information influences the results is that farmers in the R+V group bought different fertilizers than did farmers who only received vouchers, based on sales data reported by input dealers. The R+V farmers were more likely to buy fertilizers related to the specific nutrient deficiencies on their main maize plots as recommended by the project, in particular ammonium sulfate (SA), which addresses the sulfur deficiency. Among farmers in the R+V group, 49% purchased both urea and SA, 43% purchased urea only, and 8% did not purchase any fertilizer. Among farmers who received only vouchers, 27% bought only urea, 4% purchased SA and urea, and 69% did not purchase fertilizer but instead redeemed the voucher for cash (see Table 3, Panel B). No farmer in the V group purchased the bundle of fertilizers recommended by the government, urea and DAP, even though the recommended inputs cost the exact value of the voucher. No farmers in the other arms of the experiment purchased any fertilizer from the input dealer.

Farmers in the R+V group reaped larger yields relative to the control group most likely because more of them applied fertilizer that addressed their nutrient deficiencies, urea and SA, and potentially because they applied more fertilizer. Farmers in the V group may not have obtained higher yields than the control group because urea alone may be insufficient to raise yields, and potentially because they applied smaller amounts.

However, farmers only tested the benefits of applying urea and SA or urea alone. The behavioral response was insufficient for us to assess the benefits of the full heterogeneity in recommendations. There was considerable variation in types of fertilizers recommended to farmers whose soils were deficient in sulfur because of accompanying deficiencies in other nutrients. With one exception, only farmers who were NS-limited and received the recommendation to use SA and urea applied fertilizer to address the sulfur deficiency though not all of the farmers who received this recommendation applied SA (see Table 5). Farmers did not buy more expensive combinations of fertilizer that addressed other combinations of nutrient deficiencies possibly because the costs of those fertilizers for 0.5 acres exceeded the amount of the voucher.[25]

9. Policy implications

9.1. Profitability of fertilizer

An approximate cost–benefit analysis suggests that application of fertilizer is highly profitable for farmers even without any fertilizer subsidy given appropriate information about soil deficiencies. In a scenario in which the extension service relies on targeted soil testing to improve regional recommendations and farmers do not pay for individual soil tests, a farmer who applies the average amount of SA and urea in our sample could increase her/his profits by about 47,000 Tanzanian shillings (TzSh) on a one-acre farm.[26] This amount represents about nine days of work at the median daily wage of 5000 TzSh. If farmers bear the costs of soil tests of their individual plots, the profits gained from applying the average amount of SA and urea in the sample applied by those farmers who applied both are approximately 37,000 TzSh on a one-acre farm, or about seven days of work at the median daily wage.

The estimates are based on the increase in revenue from maize yields estimated for the R+V group divided by the fraction of farmers in the R+V group who applied SA and urea, 0.49. The lack of a treatment effect on yields in the V group suggests that application of urea alone does not increase yields. Therefore, the treatment effect on revenue in the R+V group is likely to be the result of fertilizer investment by those farmers who applied SA and urea. Very few farmers apply fertilizer and none apply SA at baseline. Therefore, the amount applied at follow-up represents an increase due to the intervention.

Farmers in the R+V group increase their revenue by 54,300 TzSh per acre on average, based on panel D in Table 2; therefore, farmers who apply SA and urea + SA increase their revenue by about 110,800 TzSh per acre. Farmers who applied both SA and urea, applied an average of 24 kg/acre of each. The respective prices reported by the input dealer are 1400 and 1200 TzSh/kg, for a total cost of 62,400 TzSh.[27] The cost of applying fertilizer may also include cost of labor and cost of time and transportation to procure the fertilizer. We find no statistically significant effect of the R+V and V interventions on the amount of labor, as shown in Table A.8 in the appendix; therefore, we ignore this component. We estimate the cost of procuring fertilizers by allowing for two hours of travel time valued at the median daily wage of 5000 TzSh to be a total of 1250 TzSh.

The costs that farmers would bear for tests of soil on their individual plots are somewhat speculative given that such services are rare in practice. The cost of the analyses for a soil sample per plot using the SoilDoc kit is approximately 7000 TzSh (including the fixed costs of the equipment and the costs of reagents and other per-test supplies). Extension agents can carry out the soil tests. An agent would be likely to carry out tests on multiple plots on one trip to a village. We compare costs per soil test if the agent can complete 10 soil tests in one day, as an upper bound on costs of soil testing, and costs if the agent can complete 20 soil tests in one day, as a lower bound. The daily salary

[25] Farmers also do not seem to respond to differences in the amount of fertilizer recommended. As Table 4 shows, the only fertilizer for which the recommended amount differs across farmers is urea. The amount of urea applied by farmers in the R+V group does not depend on whether the recommendation advised 25 or 35 kg, as we show in Table A.7.

[26] The per acre profit on a larger farm would be slightly larger since the transportation cost required to obtain fertilizer is a one-time, fixed cost.

[27] Fertilizers are typically sold in 25 or 50 kg bags, and prices were reported accordingly. We took the price per 25 kg bag and divided it by 25 to get the price per kg.

Table 4
Prevalence of soil nutrient deficiencies by treatment, recommended fertilizers, and costs.

Deficiency	Recommended fertilizers (per 1/2 acre)	Total cost (TzSh)	Control	Vouchers only	Recommendations only	Recommendations + Vouchers	Total
Nitrogen	35 kg Urea	57,000	0.8%	0.8%	1.5%	0.8%	3.8%
Nitrogen + Sulfur	25 kg Urea + 25 kg ammonium sulfate (SA)	65,000	12.9%	15.0%	14.2%	14.6%	56.6%
Nitrogen + Phosphorus	25 kg Urea + 25 kg diammonium phosphate (DAP)	80,000	0.1%	0.4%	0.0%	0.1%	0.6%
Nitrogen + Phosphorus + Sulfur	25 kg Urea + 40kg minjingu mazao	85,000	6.6%	6.4%	5.5%	6.1%	24.7%
Nitrogen + Potassium	35 kg Urea + 25 kg muriate of potash (MOP)	99,000	0.0%	0.0%	0.0%	0.1%	0.1%
Nitrogen + Potassium + Sulfur	35 kg Urea + 25 kg sulfate of potash (SOP)	107,000	1.3%	0.8%	1.5%	1.2%	4.7%
Nitrogen + Phosphorus + Potassium	25 kg Urea + 25 kg DAP + 25 kg MOP	122,000	0.0%	0.0%	0.1%	0.1%	0.3%
Nitrogen + Phosphorus + Potassium + Sulfur	25 kg Urea + 50kg Yara Mila	145,000	1.4%	0.8%	1.2%	2.3%	5.6%

NOTES: % as a share of total soil samples in treatment villages, n = 782.

Table 5
Urea and Urea+SA application rates by nutrient limitations.

	Recommendations + Vouchers				Vouchers only	
	Mean fertilizer applied (kg/acre) on baseline main maize plot if applied urea only	Mean fertilizer applied (kg/acre) on baseline main maize plot if applied urea and SA	% of farmers in recommendations + voucher group who applied urea only	% of farmers in recommendations + voucher group who applied urea and SA	% of farmers in voucher group who applied urea only	% of farmers in voucher group who applied urea and SA
Nitrogen	29.22	6.25	1.5%	0%	0.5%	0.5%
Nitrogen + Sulfur	25.97	45.31	30.5%	19.7%	12.6%	1.5%
Nitrogen + Phosphorus	25.00	0.00	0.5%	0%	0.00%	0.00%
Nitrogen + Phosphorus + Sulfur	25.46	45.00	12.8%	0.5%	7.6%	0.00%
Nitrogen + Potassium	0.00	100.00	0.5%	0.5%	0.00%	0.00%
Nitrogen + Potassium + Sulfur	79.13	31.25	2.5%	0.5%	1.5%	0.00%
Nitrogen + Phosphorus + Potassium	0.00	0.00	0%	0%	0.00%	0.00%
Nitrogen + Phosphorus + Potassium + Sulfur	24.93	0.00	3.4%	0%	0.00%	0.0%

of an extension agent is about 18,200 TzSh in our study area. Average transportation costs per day total 10,000 TzSh. The resulting cost per soil test is not very sensitive to the number of tests that the agent carries out per day. The cost per soil test if the agent can conduct 10 tests in one day is about 10,000 TzSh, while it is about 8500 TzSh if s/he can carry out 20 tests per day. The net benefits reported above use the higher number.

A number of factors could influence the response of yields to fertilizer, the value of the increase in yields, the costs of applying fertilizer, and the costs of soil testing. The above estimates are approximations. The decline in value of yields relative to our calculations would have to be 61% or more to eliminate the profits generated by the increase in fertilizer use. The costs of applying fertilizers could increase by 150% before the fertilizers would become unprofitable.

Farmers realize the profits approximated above without any fertilizer subsidy. However, farmers appear to be unwilling to invest in fertilizers without financial assistance. Financial incentives that would be sufficient to increase investment in fertilizer depend on the reasons why farmers do not purchase fertilizer without a voucher. Given time to learn about profitability of fertilizer, improved access to credit or smaller financial incentives, such as those tested in Duflo et al. (2011), could suffice.

9.2. *The benefits of plot-specific information*

Our results are strong evidence that the Tanzanian extension service should add SA to the list of recommended fertilizers in Morogoro rural given that 95% of the tested plots are deficient in sulfur with the caveat that we do not know if SA will be equally effective in the presence of additional, unaddressed nutrient deficiencies as it was for farmers whose soils were deficient in nitrogen and sulfur and who used urea and SA. The study cannot evaluate the potential benefits of following fertilizer recommendations that vary across plots within a village because farmers did not apply the more expensive fertilizers whose application would address such variation.

Further work is needed to determine at what temporal and spatial scales soil testing would be most efficient. Some soil characteristics such as organic matter content and cation exchange capacity change slowly but others, like nitrate, phosphorous, pH and sulfur can change more quickly in response to management. Heterogeneity is driven by geological variation, landscape orientation (hill top, backslope or valley bottom), and by variation over time in use and management practices. Variation in soil nutrient deficiencies is considerable within villages; almost a third of the overall across-village variation for some measured nutrients. Fig. 4 displays variation within villages in nitrogen, potassium, phosphorus, and sulfur. The red lines indicate the threshold value of the nutrient at which a plot is deemed deficient in our assessment.

10. Conclusion

Our results show that plot-specific fertilizer recommendations increase fertilizer use and maize yields substantially among smallholder maize farmers but only when vouchers that cover the cost of the increase in fertilizer accompany the recommendations. Farmers who receive only vouchers are much less likely to purchase and apply fertilizer than are farmers who receive both recommendations and

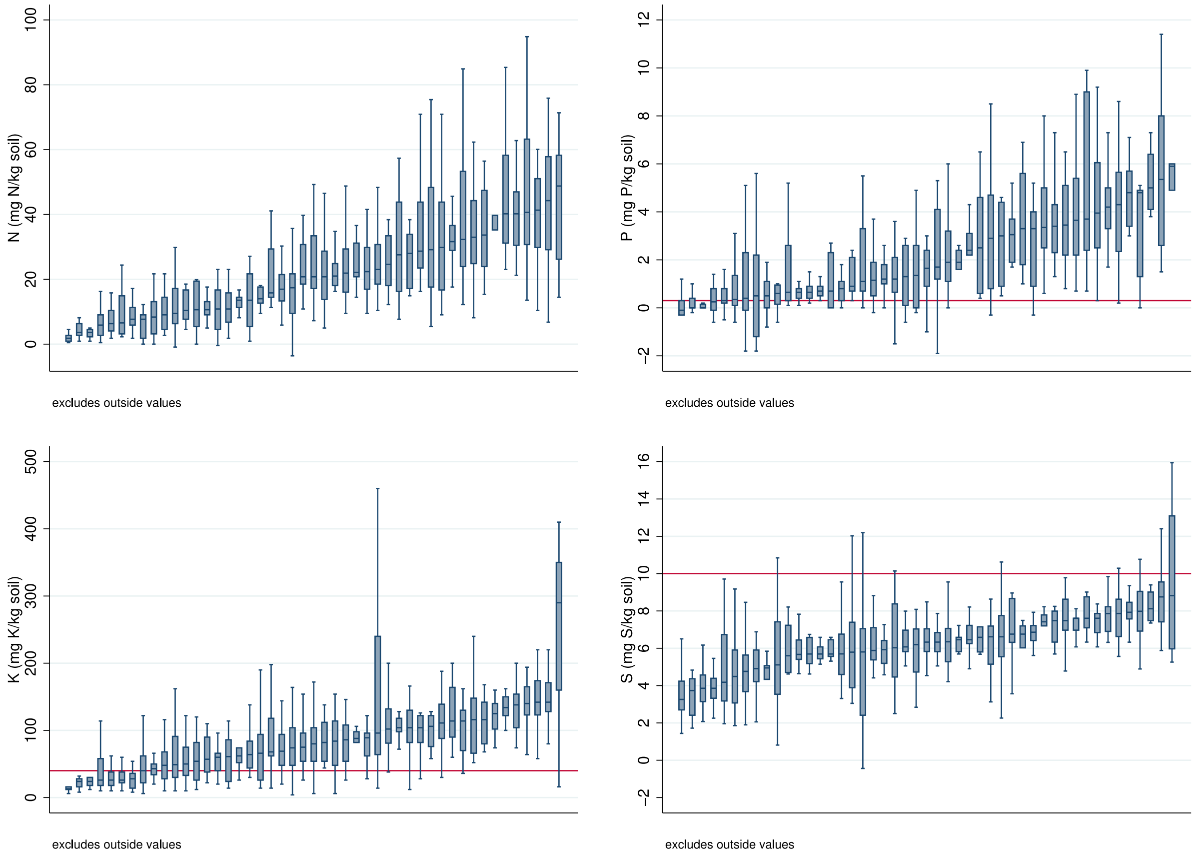

Fig. 4. Distribution of nitrogen (N), potassium (K), and phosphorus (P) on study maize plots by village. NOTE: Red lines indicate thresholds below which a fertilizer recommendation would include application of a given nutrient. There is no threshold for nitrogen (N) as all farms were recommended to apply urea. Outliers are excluded. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

vouchers, and they apply fertilizers that address only one of their soil deficiencies. Farmers who receive recommendations alone experience the same outcomes as the control group.

We find that the application of fertilizers recommended for the majority of participants by the project, SA combined with urea, has a large impact on maize yields and is likely to be profitable even without any subsidy for the costs of fertilizer and even if farmers have to pay for the costs of the soil test. Farmers who receive only vouchers and do not apply fertilizer may be correct in their assessment that applying fertilizer according to extension service recommendations, without knowing soil deficiencies on their plot, is not profitable. Farmers in this group who do apply fertilizer, apply only one of the fertilizers recommended by the extension service, urea, which does not improve yields. We do not know if the combination recommended by the extension service, urea and DAP, would increase yields since no farmers apply this combination, but we do know that the combination does not address most farmers' soil deficiencies. Farmers who receive recommendations alone and do not apply fertilizer are foregoing a profitable investment. These farmers are either unable to purchase fertilizer, or they prefer not to invest given uncertain returns.

One policy implication is that programs that provide plot-specific fertilizer recommendations together with assistance with purchasing fertilizer should improve farm productivity and profits. The assistance with financing fertilizer should be designed more optimally than are the vouchers in our study, for example following Duflo et al. (2011). A second implication is that using soil tests to update and improve regional fertilizer recommendations may be sufficient to achieve the same impacts as result from plot-specific tests, depending on the trust that farmers would have in fertilizer recommendations provided by extension services. Building trust may be a challenge where farmers do not have confidence in recommendations provided by extension services currently.

Further research is needed to identify reasons why farmers do not invest in fertilizer even when they do have plot-specific information. The results of this study combined with ongoing research suggests that one reason may be limited farmer ability to finance fertilizer purchases. We are examining how use of fertilizer and maize yields evolve over three years following the original study, once the vouchers are no longer available but all farmers have received fertilizer recommendations for their main maize plot (Tamim et al., 2021). By 2019, three years after the end of the original study, application of fertilizer and yields are almost back to baseline levels, i.e., we observe very little fertilizer use, in each treatment group and in the control group. The farmers experienced a pronounced drought during the year of the intervention, 2016. The intervention enabled farmers in the recommendation and voucher group to maintain yields similar to the previous year, while farmers in other treatment groups saw large declines in yields. The profit realized from higher yields may have been sufficient to manage the drought but potentially not sufficient to set aside cash to increase investment in inputs in the following years. Inability to sustain greater fertilizer inputs may have returned the farmers to the pre-intervention yields and insufficient resources to invest in fertilizer in subsequent seasons. Other potential reasons for lack of a longer-term impact require further research.

Future research should examine the optimal design of financial incentives to continue investing in fertilizer and how long such incentives may need to continue. Farmers may need temporary assistance with purchasing fertilizer only while they learn whether fertilizer is profitable, or the constraints on investing may persist in the absence of reforms such as improved saving and/or credit services. The role

Table A.1
Verification of random assignment to treatment: Control group consists of control farmers in treatment villages and control villages.

	(1) *n*	(2) Control	(3) Vouchers only	(4) Recommendations only	(5) Recommendations + Vouchers	(6) *F-test p-test*
Panel A: Baseline variables						
Total land held by household (acres)	1050	5.219 (0.287)	0.046 (0.522)	0.234 (0.529)	−0.289 (0.518)	0.864
Total land cultivated by household (acres)	1050	3.603 (0.172)	0.005 (0.313)	0.267 (0.401)	−0.379 (0.311)	0.377
HH marketed maize (1=Y)	841	0.338 (0.024)	−0.015 (0.045)	−0.018 (0.047)	−0.019 (0.044)	0.960
Share of land in maize	1050	0.576 (0.012)	−0.010 (0.023)	−0.026 (0.023)	−0.009 (0.023)	0.744
Size of baseline main maize plot (acres)	1050	2.512 (0.131)	−0.142 (0.238)	0.453* (0.241)	−0.082 (0.236)	0.140
Female headed household (1=Y)	1050	0.175 (0.017)	0.022 (0.032)	0.003 (0.032)	−0.061 (0.031)	0.121
Head completed at least elementary school (1=Y)	1050	0.679 (0.022)	0.018 (0.040)	0.028 (0.040)	−0.014 (0.039)	0.801
Applied mineral fertilizer to maize (1=Y)	1050	0.007 (0.004)	0.004 (0.007)	0.004 (0.007)	−0.002 (0.007)	0.890
Used improved maize seeds (1=Y)	1050	0.225 (0.019)	−0.033 (0.035)	−0.031 (0.035)	−0.013 (0.034)	0.728
Quantity of mineral fertilizer applied to baseline main maize plot (kg/acre)	1045	0.023 (0.118)	0.434** (0.215)	0.244 (0.217)	−0.003 (0.213)	0.170
Maize yields on entire farm (kg/acre)	1050	450.38 (19.98)	34.60 (36.38)	−9.65 (36.84)	35.71 (36.06)	0.567
Maize yields on baseline main maize plot (kg/acre)	915	440.81 (15.80)	−76.95*** (28.24)	−23.26 (29.36)	−78.19*** (28.02)	0.008
Hotelling F-statistic			0.166	0.110	0.229	
Panel B: Attrition						
Soil Analysis baseline (2014)	1050	0.945 (0.009)	0.004 (0.017)	0.039 (0.017)	0.029 (0.017)	0.0687
2nd Baseline in August 2015	1050	0.854 (0.019)	−0.071 (0.034)	−0.131 (0.034)	−0.080 (0.033)	0.0008
Endline in August 2016	1050	0.939 (0.011)	0.006 (0.021)	−0.012 (0.021)	−0.002 (0.020)	0.906

NOTES: Columns 3-5 report the coefficients of respective treatment indicators from an OLS regression of each baseline variable or attrition on all three treatment indicators. Standard errors are clustered by village and are in parentheses (standard deviations for mean values in column 2). Column 6 reports the *p*-value for the F-test that coefficients for all treatment indicators are jointly equal to 0 for each baseline variable. Hotelling's F-statistic is for a test of equality of the means of all baseline variables jointly between each treatment group and the control group.

that subsidies offered only when farmers have cash available, such as in Duflo et al. (2011), can play should be clarified.

An important question for future research concerns the resolution at which soil tests should be conducted to inform recommendations. The farmers adopted recommendations that applied to 95% of main maize plots, and therefore could be simply integrated into regional recommendations. However, the project found considerable variation in soil deficiencies within as well as across villages. Future research should investigate whether application of fertilizers that is responsive to various degrees of heterogeneity in the recommendations would be more profitable than the behavior observed in our experiment, in which farmers did not respond to the heterogeneity in recommendations.

Research should also investigate the design of soil testing services for medium and small farmers. One option is to test the effectiveness of integrating soil testing with SoilDoc into the function of extension services. Another is to investigate whether farmers can use SoilDoc on their own with appropriate training and how the necessary training could be offered. Groups of farmers could purchase the SoilDoc kit, possibly resulting in broader access to information than poorly financed extension services would provide.

Further research should investigate the pervasiveness of the combination of heterogeneous soil conditions and funding constraints. It would be helpful to understand under what conditions interventions similar to the one in this study improve outcomes.

CRediT authorship contribution statement

Aurélie P. Harou: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Malgosia Madajewicz:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing - review & editing, Funding acquisition. **Hope Michelson:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Funding

Table A.2
Average treatment effects on application of fertilizer and yields (with control villages, baseline/endline main maize plot, cross section)

	(1) Recommendations only (s.e.)	(2) Recommendations + Vouchers (s.e.)	(3) Vouchers only (s.e.)	(4) Constant (s.e.)	(5) Control mean [std. dev.]	(6) Observations	(7) R^2
Panel A: Fertilizer application and yields, with control villages							
Fertilizer on maize on baseline main maize plot (kg/acre)	0.88 (0.97)	23.330*** (2.40)	10.046*** (3.28)	0.829 (0.81)	0.901 [5.857]	884	0.121
Fertilizer on crops other than maize on baseline main maize plot (kg/acre)	0.004 (0.02)	0.246 (0.25)	0.16 (0.16)	0.001 (0.06)	0.0 [0.0]	889	0.003
Fertilizer on maize on entire farm (kg/acre)	0.337 (0.60)	21.051*** (1.93)	10.082*** (3.23)	0.785 (0.77)	0.785 [5.474]	984	0.122
Fertilizer on crops other than maize on entire farm (kg/acre)	−0.271 (0.22)	0.519 (0.61)	0.441 (0.30)	−0.008 (0.14)	−0.021 [0.287]	984	0.004
Maize yields on baseline main maize plot (kg/acre)	−32.457 (49.61)	114.560** (51.29)	43.572 (49.79)	−140.49*** (26.89)	−133.29 [323.44]	721	0.018
Maize yields on entire farm (kg/acre)	8.879 (47.00)	92.775 (55.85)	−4.962 (55.96)	−199.18*** (25.04)	−208.93 [432.29]	984	0.007
Panel B: Fertilizer application and yields, baseline/endline main maize plot							
Fertilizer on maize crop on main maize plot (kg/acre)	0.847 (0.97)	23.555*** (2.28)	10.519*** (3.36)	1.057 (1.18)	0.889 [5.821]	666	0.125
Fertilizer on crops other than maize on main maize plot (kg/acre)	−0.018 (0.02)	0.213 (0.22)	0.161 (0.17)	0.013 (0.07)	0.0 [0.0]	666	0.003
Maize yields on main maize plot) (kg/acre)	−36.438 (43.38)	110.458** (50.36)	31.81 (53.98)	−117.326*** (34.08)	−122.62 [368.05]	593	0.016
Panel C: Fertilizer application and yields, cross section							
2016 fertilizer on maize on baseline main maize plot (kg/acre)	1.276 (1.262)	23.264*** (2.415)	10.542*** (3.306)	0.98 (1.137)	0.905 [5.815]	662	0.119
2016 fertilizer on crops other than maize on baseline main maize (kg/acre)	0.004 (0.018)	0.246 (0.248)	0.16 (0.162)	0.001 (0.076)	0.0 [0.0]	662	0.003
2016 fertilizer on maize (kg/acre)	0.624 (0.793)	21.046*** (1.957)	10.576*** (3.253)	0.783 (1.093)	0.799 [5.469]	733	0.121
2016 fertilizer on crops other than maize (kg/acre)	0.011 (0.010)	0.747 (0.553)	0.418 (0.309)	0.00 (0.156)	0.0 [0.0]	733	0.005
2016 maize yields on baseline main maize plot (kg/acre)	29.169 (29.724)	119.402*** (39.057)	44.158 (39.708)	250.53*** (24.915)	240.04 [245.90]	620	0.017
2016 maize yields of entire farm (kg/acre)	12.599 (33.652)	120.073** (43.594)	43.439 (42.484)	237.017*** (28.249)	235.80 [286.47]	733	0.02

NOTES: Standard errors are in parentheses and are clustered at the village level. Regressions include village fixed effects. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table A.3
Spillover effects of fertilizer application on maize plot.

	(1) Fertilizer on maize on baseline main maize plot (kg/acre)	(2) Fertilizer on maize on baseline main maize plot (kg/acre)	(3) Fertilizer on maize on entire farm (kg/acre)	(4) Fertilizer on maize on entire farm (kg/acre)
Recommendations only	1.535 (1.003)	1.772* (0.979)	0.305 (0.533)	0.296 (0.599)
Recommendations + vouchers	23.765*** (2.346)	24.002*** (2.367)	21.083*** (1.928)	21.074*** (1.969)
Vouchers only	10.421*** (3.342)	10.658*** (3.329)	10.011*** (3.204)	10.002*** (3.206)
Control in Trt Villages (D)		0.582 (0.474)		−0.023 (0.569)
Constant	0.556*** (0.214)	0.319* (0.190)	0.798*** (0.293)	0.807* (0.424)
Observations	884	884	984	984

Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

Table A.4
2016 maize selling price, by village (TzSh).

	Mean price	Median price	25th quartile price	n
Bamba	286	286	71	2
Bwakira Juu	357	375	321	3
Dalla	625	625	625	1
Dete	463	500	425	4
Gozo	963	550	500	6
Kibangire	286	357	200	5
Kikundi	491	450	232	4
Kisaki	456	500	357	7
Kiwege	.	.	.	0
Kiziwa	314	300	250	7
Kolelo	500	500	500	2
Kongwa	750	750	750	1
Magogoni	.	.	.	0
Matuli	650	650	650	2
Mbwade	469	500	375	7
Milengwelengwe	424	375	375	5
Mtamba	282	282	214	2
Pulambili	.	.	.	0
Sesenga	434	464	375	6
Tulo	467	500	400	3

NOTES: No sales were made in the villages of Kiwege, Magogoni or Pulambili.

Table A.7
The effect of quantity of urea recommended (25 v. 35 kg) on applied urea (kg/acre).

	Urea applied on baseline main maize plot (kg/acres)
Urea recommended 35 kg	0.603 (0.652)
Recommendations only	0.967 (0.651)
Recommendations + Vouchers	13.472*** (1.673)
Vouchers only	6.798*** (1.758)
Urea recommended 35 kg X Recommendations + Vouchers	1.334 (2.695)
Constant	0.133 (0.573)
N	662
R-square	0.15
Urea applied (kg/acres) mean	5.958
Urea applied (kg/acres) std. dev.	14.512

NOTES: This table reports the coefficients from an OLS regression of urea applied on the baseline main maize plot on the treatment indicators, an indicator variable for whether the recommendation included 35 kg of urea, and an interaction term of the recommendation and voucher treatment times the indicator variable for whether the recommendation included 35 kg of urea. Standard errors are in parentheses and are clustered at the village level. Regressions include village fixed effects. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

acquisition. **Cheryl A. Palm:** Conceptualization, Methodology, Investigation, Writing – review & editing, Funding acquisition. **Nyambilila Amuri:** Investigation. **Christopher Magomba:** Investigation. **Johnson M. Semoka:** Investigation. **Kevin Tschirhart:** Formal analysis, Investigation, Data curation, Visualization. **Ray Weil:** Conceptualization, Writing – review & editing.

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Table A.5
Fertilizer purchases reported by farmer and reported by dealer compared to amount of fertilizer applied (kg/acre).

	Recommendations only		Recommendations + Vouchers		Vouchers only		Control		Control Villages	
	Mean (kg/acre)	*n**	Mean (kg/acre)	*n**	Mean (kg/acre)	*n**	Mean (kg/acre)	*n**	Mean (kg/acre)	*n**
Urea purchase reported by farmer (kg)	0.424	16	20.394	141	8.622	65	0.559	14	0	17
Urea purchase reported by dealer (kg)	0	0	25.94	187	8.838	62	0	0	0.186	1
Urea applied as reported by farmer (kg/acre)	0.439	11	7.044	116	5.074	56	0.258	6	0.331	10
SA purchase reported by farmer (kg)	0	14	6.681	65	0.668	16	0.279	13	0	17
SA purchased reported by dealer (kg)	0	0	12.43	99	0.883	7	0	0	0	0
SA applied as reported by farmer (kg/acre)	0.071	1	2.336	47	0.299	4	0.142	3	0	0

NOTES: *n** denotes number of farmers who purchased/applied fertilizer.

Table A.6
Percent of farmers who purchased fertilizer, as reported by farmers themselves.

	Recommendations only	Recommendations + Vouchers	Vouchers only	Control	Control Villages
Urea (D)	1.5%	13.4%	6.2%	1.3%	1.6%
SA (D)	1.3%	6.2%	1.5%	1.2%	1.6%
DAP (D)	1.3%	1.8%	1.2%	1.0%	1.6%
Minjungu (D)	1.3%	2.6%	1.0%	1.0%	1.6%
CAN (D)	1.3%	1.5%	1.0%	1.0%	1.6%

NOTES: (% of total farmers in the sample, n = 1050).

Table A.8
Treatment effects on labor use.

	(1) Respondent work days	(2) Household members work days	(3) Hired work days	(4) Draught work days	(5) Labor costs (TzSh)
Recommendations only	−4.521	−20.332	0.327	0.000	−3483.158
	(4.843)	(22.560)	(0.621)	(0.079)	(8564.302)
Recommendations+ Vouchers	−0.063	−15.060	0.345	−0.041	9663.013
	(4.618)	(20.704)	(0.438)	(0.078)	(12990.959)
Vouchers only	−1.256	−21.102	0.417	−0.020	4306.074
	(4.564)	(20.890)	(0.583)	(0.032)	(7907.613)
Constant	33.624***	40.456**	1.737***	0.133***	40208.455***
	(2.746)	(16.092)	(0.359)	(0.037)	(7096.605)
Observations	652	651	671	671	224
R^2	0.002	0.004	0.001	0.001	0.014

Standard errors are in parentheses and are clustered at the village level. Regressions include village fixed effects. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

alone. This study is registered in the AEA RCT Registry and the unique identifying number is: "AEARCTR-0005470".

Appendix A

See Tables A.1–A.8.

Appendix B. Spillovers of treatment impacts

The information treatment could benefit farmers who were not assigned to treatment in the treated villages. Farmers share information about production and learn from their neighbors (Conley and Udry, 2010; Bandiera and Rasul, 2006). Even though soil deficiencies are heterogeneous, there is scope for farmers to share the fertilizer recommendations that they receive from the project. About half of the plots in this study have the same soil nutrient deficiencies as their nearest neighbor and 58% have the same nutrient deficiencies as their second nearest neighbor. Also, nearly all farmers' plots in the sample are deficient in sulfur. Therefore, sharing the information that everyone has received the recommendation to apply sulfur would benefit all farmers.

We test whether the benefits of treatment spill over to control households in treated villages. We estimate Eq. (2) but we include a binary variable that takes a value of 1 if the farmer resides in a treated village and is assigned to a control group. The omitted group are farmers in control villages. The regression is the following:

$$\Delta y_i = \alpha_0 + \sum_{i=1}^{3} \beta_i T_i + \delta_1 C_1 + \epsilon_i \quad (3)$$

As in equation, (2), Δ_i are differences between outcomes in 2016 and 2014 for the variables of interest, T_i are the treatment groups, and C_1 are the control farmers located in treated villages. The test for spillovers tests the null hypothesis that $\delta_1 = 0$.

We find no evidence of spillovers, as we show in Table A.7. The coefficients may be biased due to difference between control villages and treatment groups with respect to baseline maize yields. Nonetheless, the lack of spillover effects is not surprising since there is no statistically significant treatment effect on farmers in group R.

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