Can Agricultural Technology Diffusion be Harnessed to Reduce Malnutrition? Experimental Evidence from Uganda

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FIRST DRAFT: May 27, 2016
REVISED DRAFT: June 20, 2018

This study uses a randomized saturation experiment and influential technology promoters to test strategies to promote diffusion of two highly nutritious agricultural crop technologies in Uganda to measure which approaches are most cost-effective at achieving high adoption rates. The crops are conventionally bred varieties of vitamin-A-rich orange sweet potato (OSP) and high-iron biofortified beans (HIB), distributed as an intervention to reduce vitamin A deficiency and anemia. The experiment included four treatment arms: three levels of randomized saturation of households with the crop technologies (control-0%, low-20%, and high-50%) and a treatment in which opinion leaders in farming and health identified through an election were invited to promote the technologies. Results show that being assigned to treatment in either the low or high saturation substantially increased the average probability of adopting the crops over the five seasons of the project and increased spillovers to neighboring households by 16-19%. There was no difference in spillover effects between the high and low saturation treatments. In addition, the low saturation treatment for high iron beans had a reinforcing effect on adoption by neighboring farmer group members who were also given access to the treatment, increasing their probability of adopting the crop by 14.9 percent in the last season of the project. The opinion leader treatment led to no more diffusion of either technology than in the control group.

[†] We gratefully acknowledge funding support from HarvestPlus. We also received helpful advice on the design of the study from Anna-Marie Ball, Sylvia Magezi, Charles Musoke, Howdy Bouis and other staff from HarvestPlus. Lucy Billings served as the Research Project Manager, overseeing all aspects of implementation of the diffusion experiments with implementing partners. Maha Ashour provided expert research support. Adam Trowbridge and Betsy Ness-Edelstein provided research support on costing analysis and fieldwork. Geoffrey Kiguli ably coordinated all field data collection. Our coauthor, Scott McNiven, passed away in 2013. It was his ideas that initiated these diffusion experiments and he was closely involved in the design of the study. His collaboration and friendship are greatly missed.

I. Introduction

Micronutrient malnutrition – low blood levels of essential vitamins and minerals including vitamin A, iron, iodine and zinc – is a leading global nutrition challenge. Despite substantial gains globally in reducing the share of poor households without enough food to eat over the past three decades, diets are of very low quality. Overall, malnutrition is responsible for fifty percent of all mortality in children under five years of age (Habicht et al., 2008), and economists have identified bundled interventions, including micronutrient provision, to reduce undernutrition in preschoolers as the number one solution deserving investment to address the greatest global challenges (Copenhagen Consensus 2012). Biofortification is a strategy to reduce micronutrient deficiencies by encouraging farmers to replace low-nutrient staple foods that represent a large share of calories in the diet with new staple varieties bred to be a dense source of essential nutrients in areas where micronutrient deficiencies are high. Biofortification has been identified as a promising strategy for increasing dietary intakes of micronutrients in children and women and reducing micronutrient deficiencies (Ruel and Alderman 2013), but it must first overcome the many problems constraining agricultural technology adoption in Africa. In particular, rates of adoption for biofortified crops must be high locally to substantially reduce rates of micronutrient deficiency because markets for biofortified crops are slow to develop among target populations. This suggest the need to identify strategies to promote broad diffusion of biofortified crops and foster technology spillovers for biofortification to be cost-effective as a public health intervention to reduce micronutrient deficiencies.

In this study, we use randomized saturation experiments and influential technology promoters to test strategies to promote diffusion of two biofortified crops in Uganda to measure which approaches are most cost-effective at achieving high adoption rates. The biofortified crops include conventionally bred varieties of vitamin-A-rich orange sweet potato (OSP) and iron-biofortified beans (high iron beans, HIB).[1] Field experiments conducted prior to this study demonstrated the effectiveness of introduction of OSP through farmer groups in Uganda for increasing dietary intake of vitamin A in children and women and improving vitamin A status in

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[1] Efficacy trials have shown that OSP improves vitamin A status in children (van Jaarsveld, 2006) and HIB improves iron status (Carvalho et al. 2012; Petry et al. 2012).

children (Hotz et al., 2012a).[2] In addition, these randomized controlled trials documented the presence of large spillover effects of the OSP technology from treated farmer group members to their untreated neighbors through existing information networks (McNiven and Gilligan 2013) and that these spillovers remained large four years after the initial introduction of the crop, which was two years after the project had ended (McNiven, Gilligan and Hotz 2016). The original field experiments on OSP in Uganda showed that the incremental cost of expanding the program was $44 per household based on the results of these pilot programs (de Brauw et al 2016). Annual costs per child per year may be half as much due to observed patterns of sustained adoption. The cost of distribution of vitamin supplements to children, a leading strategy to address vitamin A deficiency in Uganda, is only $5 per child per year, but coverage rates are below 70 percent and the program must be run annually. Nonetheless, for biofortification to be cost effective, strategies to promote broad technology diffusion are needed. The experiments in the current study were designed to test approaches to promote spillover effects.

This study has two contributions. First, we experiment with approaches to promote biofortified crop diffusion to identify the most cost-effective strategy to introduce biofortified crops in Uganda as a public health intervention to reduce vitamin A deficiency and anemia in children. Beans are a primary staple food throughout most of Uganda and sweet potato (white or yellow) is a primary staple in many areas. Vitamin A deficiency (VAD) and iron deficiency anemia are both important malnutrition problems in Uganda. VAD affects 28 percent of children under age 5 and 23 percent of adult women in Uganda (UBOS and ORC Macro 2001). Also, 49 percent of Ugandan children under age 5 and 23 percent of adult women suffer from anemia. Current leading strategies to address VAD in Uganda include biannual distribution of vitamin A supplements to children under 5 at Child Health Days and fortification of vegetable oil with vitamin A (UBOS and MEASURE DHS 2011). However, only 68 percent of targeted children receive vitamin A supplements during Child Health Days, and fortified vegetable oil is not available everywhere. Acute iron deficiency anemia for children and pregnant women is addressed primarily through supplementation at health clinics. This approach leaves large numbers of at-risk

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[2] A companion experimental study in Mozambique showed comparable effects of annual distribution of OSP with agriculture and nutrition trainings on dietary intakes of vitamin A in children under age 5 years (Hotz et al., 2012b), and a nonexperimental study showed that an intensive version of a similar intervention improved vitamin A status in children (Low et al. 2007). These studies expand the external validity for the impact of programs to promote OSP on vitamin A intakes and vitamin A status in children.

children and women untreated for anemia. Where biofortified crops are widely adopted, they may be more cost-effective at improving dietary intakes of vitamin A and iron over time than these other forms of treatment.

A second contribution of this study is to demonstrate the diffusion behavior in these spillover experiments for two distinct crop technologies with distinct agronomic characteristics. Spillover effects are essential to the success of technology adoption. Individuals who first obtain access to a technology may inform others of its benefits and other traits or may directly share the technology with others. These spillover effects through diffusion of the technology from initial adopters to their geographical neighbors or others in their information networks help to promote the spread of the technology at no additional cost to the intervention. Successful technology promotion relies on such word of mouth or direct sharing of technology to reach larger numbers of new users cost-effectively. Recognizing the importance of these spillover effects, many studies have begun to examine their role in promoting technology diffusion across a variety of economic contexts, including agricultural crop and input technology (Suri 2011; Feder, Just and Zilberman 1985), public health (Miguel and Kremer 2004) and communication technology (Aker and Blumenstock 2014; Aker 2011). Despite the importance of spillover effects, only recently have studies experimented with strategies to optimize spillover effects to identify the most cost-effective method of harnessing spillovers for technology adoption (Baird et al., 2016). Important factors that determine the size and duration of spillover effects include the rate of saturation of the target population with the initial introduction of the technology as well as the role of influential technology promoters, including early adopters, who are likely to speed the creation of spillover effects.

The spillover experiments reported here were designed to test how the saturation rate of communities with planting material for OSP and HIB affected adoption and diffusion in the same communities. Working with HarvestPlus, the organization supporting breading and introduction of biofortified crops, and their partners, OSP and high iron beans were introduced along with a limited set of messages on how to grow the crops and on their nutrition benefits, to farmer groups in randomly selected communities in the project “Developing and Delivering Biofortified Crops” (DDBC) in Uganda. This DDBC project model formed the comparison group for the experiments. In two other randomly assigned treatment arms, non-farmer group members were randomly selected to receive OSP and high iron beans planting material in low saturation (20 percent) and high saturation (50 percent) of the remaining community members. This randomized saturation design makes it possible to test the returns to saturation in producing spillover effects in the communities. In a fourth treatment arm, individuals identified during the community listing exercise before the baseline survey as opinion leaders in farming (2) and health (2) as well as individuals identified as “progressive farmers” or early adopters (2) were given enough planting material for an average sized farmer group, were trained on the agriculture and health messages, and were asked to promote the technologies in their communities. This model was included to test the role of these influential community members in generating spillover effects.

As an agricultural intervention with a public health objective to reduce malnutrition, biofortification requires high rates of adoption to be a successful strategy and eliminate the need for routine supplementation of the population with vitamin A, for example (Gilligan 2012). The RCT on the original introduction of OSP showed that most households in which children consumed OSP were growing the crop. There was very little market for the produce; rather, the typical method of accessing the crop was through own production, with OSP replacing roughly 40 percent of household’s planted area under conventional white or yellow sweet potato on average. This need for widespread adoption increases the importance of finding cost-effective strategies to optimize spillover effects within communities.

In the next section, we describe the DDBC intervention, the randomized saturation study design, and the data. We then introduce the estimation strategy for identifying the overall treatment and spillover effects, the presence of returns to higher rates of saturation, and identifying spillover effects on the treated farmer group members within the RS experiment. We also introduce the estimation strategy for comparing the opinion leader and progressive farmer treatment to the RS treatment arms. Next, we present the results of these experiments. We then introduce information on the cost of the strategies and discuss the implications of the results for cost effectiveness. Finally, we conclude with some reflections on harnessing spillovers for agricultural technology adoption and public health outcomes.

II. DDBC Intervention, Study Design, and Data

This section describes the DDBC intervention, study design, the study sample, and our core outcomes of interest.

a. DDBC Intervention

The HarvestPlus intervention, Developing and Delivering Biofortified Crops, is scaling up the delivery and promotion of biofortified orange sweet potato and high-iron beans in Uganda. The DDBC project was developed based on lessons from the pilot Reaching End Users (REU) project that took place in Uganda and Mozambique from 2007-2009. The REU project delivered biofortified provitamin-A-rich orange sweet potato (OSP) to 10,000 households in Uganda and 14,000 households in Mozambique. In both countries, the REU project was evaluated using a randomized control trial (RCT) with two treatment arms and a control. In Uganda, these intervention arms were randomly assigned across 84 farmer groups in 3 districts, Bukedea, Kamuli, and Mukono. The first treatment arm (Model 1) provided 20kg of sweet potato vines in the first season and intensive training on growing OSP and nutrition knowledge with some marketing support for a two year period. The second treatment arm (Model 2) was the identical to Model 1 for the first year, with reduced trainings and cost-savings in year 2. Two years after the intervention started the evaluation found the following: 66% of treated farmers vs. 5% of control still growing the crop; no significant difference in adoption between Model 1 and Model 2; large increases in mean dietary intake of vitamin A in children and women during the peak period of OSP harvest with a corresponding reduction in prevalence of inadequate vitamin A intake (30pp decline in children, and 25pp in adults); and among children with low serum retinol (< 1.05μmol/L) in blood samples at baseline, the prevalence of low serum retinol fell 9.5 percentage points in the treatment arms (Hotz et al, 2012).

The DDBC intervention aimed to scale up dissemination of OSP and distribute a variety of beans bred with elevated iron, referred to here as “iron beans,” in 13 districts in Uganda from 2011–2016, with funding support from USAID’s Feed the Future initiative. The project directly targeted 75,000 households and aimed to reach another 150,000 secondary beneficiary households through farmer-led diffusion of the crop, one of the core areas of research interest. The main intervention model was akin to a "Model 3" from the REU in that it was less intensive than the REU Model 2 because findings from the REU evaluation found no evidence of greater impact with the higher intensity intervention. Also, an analysis of the contribution of the nutrition trainings to the impact of the REU interventions indicated that similar impacts could be achieved with a much smaller investment in nutrition information dissemination (de Brauw et al., 2015). It was concluded that the cost-effectiveness of the interventions could be improved by simplifying and reducing the trainings. In communities assigned to participate in the DDBC project, OSP (15kg) and iron beans (2kg) planting material was distributed to households in one randomly selected farmer group from the community. These households also received modest trainings on how to grow and market the crops and on relevant nutrition information.

b. Study Design

The focus of the evaluation of the DDBC project is on effective strategies to promote diffusion of biofortified crops, and comparing the impact and costs of these strategies in driving adoption, diffusion, and health indictors such as vitamin A deficiency, prevalence of diarrhea, and dietary intake and frequency of consumption of foods rich in vitamin A and iron. The main DDBC project intervention, which utilizes farmer groups as the primary mode of diffusion, serves as the comparison group for this RCT. There are three additional treatment arms that investigate alternative modes of diffusion. The first two treatment arms, in addition to the core farmer group intervention, use a randomized saturation (RS) design where 20% (low saturation arm – LS) and 50% (high saturation arm – HS) of non-farmer group member households ("nonmembers") are also targeted with the intervention.[3] The remaining treatment arm involves selecting opinion leaders and progressive farmers (OL/PF) who were asked to select beneficiaries and distribute the crops in their communities (farmer groups were not treated in these communities). The four treatment arm design has the following structure:

1. Low Saturation (LS): Farmer group members and a random saturation covering 20% of non-farmer group member households received planting material and training

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[3] In the saturation component of the experiment, only households with children age 0-8 years old were targeted for the intervention. The reported saturation rates are for all nonmember households in the community. The average effective saturation rate of households with children in this age range was 37% for Low Saturation and 77% for High Saturation.

2. High Saturation (HS): Farmer group members and a random saturation covering 50% of non-farmer group member households received planting material and training
3. Opinion Leader and Progressive Farmer (OL/PF): An opinion leader or progressive farmer was asked to select beneficiaries and distribute the crop in their community. Farmer groups were not targeted.
4. Comparison: Farmer group members each received 15kg of OSP planting material and 2kg of HIB seeds, along with training

The two RS treatment arms aim to understand how the effectiveness and cost-effectiveness of adoption and diffusion of the crops varies by the intensity of treatment at the community level, while the OL/PF arm focuses on the role of influential members of a community in driving crop adoption and diffusion.[4]

c. Study Sample and Data Collection

As described in the DDBC Baseline Report (Ashour et al., 2013), the baseline survey consisted of two rounds of data collection, a Community Listing Exercise (CLE) conducted in July-August 2012 obtaining basic demographic and farming information about all available households living in the DDBC study communities and a more detailed baseline household survey (conducted in January-February 2013) covering a variety of topics related to farming and health.[5] The sample

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[4] Across all treatment arms, HarvestPlus also implemented a payback requirement in which beneficiary households were required to give back twice the amount of planting material that they received from the project (30 kg of OSP vines and 4 kg of HIB). In the OL/PF treatment communities farmers were considered primary beneficiaries if they received the crop directly from an OL or PF in first season 2013 and were expected to provide payback at the end of the season like primary beneficiaries in the other treatment arms. This payback requirement was intended to harness the substantial diffusion observed in the REU HarvestPlus project by providing a target level of diffusion intensity. As designed, the payback mechanism required that the planting material obtained through payback be shared with households in two communities outside of their own community to promote diffusion across communities. Interviews with the NGOs implementing the project revealed that NGOs differed in their approach to facilitating payback and some of the NGOs allowed within-community sharing to fulfill the payback requirement. Because randomization was stratified within the districts for which each NGO was responsible, the implementation of payback should be balanced across treatment arms.

[5] The CLE sample is a convenience sample of households available for interview on the day when the CLE was conducted. In smaller villages, households that were away from their homes due to work or travel on the day of the CLE were not interviewed. In larger villages, these households were omitted as were households in some neighborhoods of the village that could not be reached for interview due to lack of time. The endline CLE conducted a repeated convenience sample of those that were available for interview, attempting to revisit the subsection of larger villages that was interviewed during the baseline CLE.

includes 103 communities across 5 district strata.[6] The baseline CLE included 8,102 households. The baseline household survey sample targeted for interview 8 farmer group member households and 10 non-farmer group member households in each study community, leading to a baseline household survey sample of 1,821 households.

During the endline survey, the CLE and household surveys were conducted during the same fieldwork exercise. For the CLE component of the interview, an attempt was made to reinterview all baseline CLE households plus any other households available for interview in the community. In addition, a slightly more detailed household survey was administered to a sub-set of the households. Out of the baseline CLE sample of 8,102 households, 5,067 were interviewed in the endline CLE or household sample interview. This high rate of attrition (62.5 percent of households were reinterviewed) reflects the convenience sampling approach of the CLEs, in which, for cost reasons, the survey teams had to complete the interviews for each community in just one day. Also, in the study communities, an additional 3,875 households were available and interviewed during the endline CLE, leading to an endline CLE sample of 8,942 households.

The endline household survey component of the endline fieldwork involved screening selected households during the CLE interview for eligibility for the endline household survey sample. Those households that met the selection criteria were asked all of the questions in the CLE survey modules as well as additional modules about their farming practices and other outcomes. The sampling criteria for the endline household survey sample included sampling 18 households per community (cluster) that did not have any household members that were members of the DDBC project farmer group in that community.[7] In the LS and HS clusters, these 18 households were stratified to include 8 DDBC beneficiary households and 10 nonbeneficiary households. In the DDBC and OL/PF clusters, all 18 households were DDBC nonbeneficiaries. In addition, we restricted the sampling of these households to be those that had children under age 5, based on household demographics data from the baseline household or CLE survey and confirmed during

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[6] In the sample design, seven districts were grouped into five district strata: Kole, Gulu/Oyam, Maaaka/Rakai, Kamwenge, Kabale. Neighboring districts were grouped together in two cases to ensure that the sample had a sufficient number of project communities in the experiment in each stratum.

[7] In each community, we also sampled 6 households from the baseline household survey sample whose members were in the selected DDBC farmer group for that community for the endline household survey sample and had a child under 8 at baseline. In cases when less than 6 households were found that met these criteria the sample was reweighted to reflect this sampling framework.

the endline interview.[8] In some cases we found less than the required 8 DDBC beneficiary households and 10 nonbeneficiary households. As a result, we weight the sample by the ratio of the number of households in the sample design relative to the achieved sample, by beneficiary status. Households were randomly sampled for the endline household survey sample first from the baseline household survey sample, and then from the baseline CLE. As a result, we have baseline data for all households in the endline household survey sample, and this sample is the focus for our analysis. Appendix Table A1-Appendix Table A4 show that the baseline sample included in the analysis is well balanced for all four specifications used in the analysis (described in section III).

d. Outcomes

Our analysis focuses on the impact on adoption (by beneficiaries) and diffusion (to non-beneficiaries) of OSP and HIB. We construct three different variables per crop. The first looks at whether the household grew OSP (HIB) in any of the past five seasons, the second at whether the household grew OSP (HIB) in the past year (two seasons), and finally we look at whether the household grew OSP (HIB) during the most recent season. Constructing these three different variables per crop allows to look at both immediate and sustained adoption and diffusion.

III. Estimation Strategy

We analyze four main specifications in this analysis. We first focus on non-farmer group members in the two saturation (HS and LS) arms vs. the control group, before integrating farmer group members and the OL/PF treatment arm.

Our first specification estimates the pooled effect across the two treatment saturation arms, looking at both the direct treatment effect as well as the spillover effect using Equation 1:

$$Y_{ic} = \beta_0 + \beta_1 T_{ic} + \beta_2 S_{ic} + \varepsilon_{ic} \tag{1}$$

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[8] All households in the household baseline survey sample were selected from those households with at least one child under age 9. Most of these households had at least one child under age 5 at endline.

where T_{ic} measures the direct treatment effect among beneficiary non-farmer group members and S_{ic} measures the impact on the non-beneficiary non-farmer group members in either the HS or LS communities.

Focusing on the same group, our second specification separates out the two saturation levels so we can look at differences between the HS and LS in terms of the impact on the non-farmer group beneficiaries and the non-farmer group non-beneficiaries This specification can be seen in Equation 2.

$$Y_{ic} = \beta_0 + \beta_1 T(HS)_{ic} + \beta_2 T(LS)_{ic} + \beta_3 S(HS)_{ic} + \beta_4 S(LS)_{ic} + \varepsilon_{ic} \tag{2}$$

Our third specification focuses on adoption by farmer group members, as opposed to nonmembers, to understand whether treating other individuals in the community in any way reinforces adoption by farmer group members. Since all farmer group members were treated, this estimation will focus only on those directly treated:

$$Y_{ic} = \beta_0 + \beta_1 T(HS)_{ic} + \beta_2 T(LS)_{ic} + \varepsilon_{ic} \tag{3}$$

For our final specification we incorporate the OL/PF treatment arm and focus only on diffusion among non-member non-beneficiaries, comparing OL/PF to the other three arms. This specification is shown in Equation 4:

$$Y_{ic} = \beta_0 + \beta_1 S(HS)_{ic} + \beta_2 S(LS)_{ic} + \beta_3 S(OL/PF)_{ic} + \varepsilon_{ic} \tag{4}$$

All regressions control for the blocking used in the randomization in which each sample cluster was assigned to a block for randomization based on quantiles of the distribution of the baseline share of households growing OSP and the baseline share of households in the community that were members of the selected farmer group. Analysis of data from the REU project showed that households with previous experience growing OSP were significantly more likely to grow it in the current season. Some communities had limited exposure to OSP in the recent past, so we wanted to make sure to balance on this characteristic in the randomization. We also blocked the randomization on three quantiles of the share of households in the community that were members of the selected farmer group in order to balance the effect of having a large share of treated households on diffusion to nonmember households in smaller communities. We add two additional sets of controls to the analysis. First, we control for the share of the community that was in a farmer group and the size of the community population with children under 8. Second, we ran a stepwise regression using 12 explanatory variables (shown in Appendix Table 1-Appendix Table 4) that theory suggests should be predictive of crop adoption at follow-up and retained those variables that were significant at the 10% level. In the absence of a pre-analysis plan, this procedure largely removes the potential for rad hoc specification searching. The interacted adjustment produces, asymptotically and for finite samples, the most precise average treatment effect (Lin, 2013). This procedure led to the inclusion of vitamin A knowledge in all models and number of working age household members in the non-farmer group modules. Standard errors are clustered at the community level and stratified at the district level and samples are weighted to reflect the sampling strategy.

IV. Results

Table 1 presents the results of the RS experiments from equation (1), estimating the treatment effects on adoption (among treated non-farmer group members) and spillover effects on diffusion (among untreated non-farmer group members) of the pooled RS design on OSP and HIB over the three time periods. In the endline household survey sample, treated nonmember households in the RS treatments were significantly more likely to have grown OSP over the last five seasons (by 35.1 percentage points), over the last year (by 15.6 percentage points) or during the last season (by 14.2 percentage points) than untreated nonmember households in the DDBC treatment arm (control group).[9] This treatment effect reflects the average effect on nonmembers of gaining direct access to the OSP planting material through the project plus any additional spillover effect that occurs from having more neighbors with access to OSP in the RS treatments, above the average spillover effect on untreated nonmembers from treated farmer group members in the DDBC

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[9] This pattern of declining treatment effects reflects, in part, that the three time periods overlap and become progressively shorter. This does not necessarily imply a pattern of declining adoption over time.

treatment arm. As reported in Table 1, the spillover effects from farmer group members to nonmembers in the DDBC treatment arm were large, ranging from 37.6 percent for any of the last five seasons to 20.9 percent last season. This implies that the average OSP adoption rate in the treated nonmember RS sample was 73 percent over the five seasons of the project and held at 35 percent in the previous season.

Impact estimates also demonstrate the presence of larger spillover effects in the RS treatment arms. Untreated nonmember households in the RS treatments were significantly more likely to have grown OSP in each time period (by 16.0, 13.8 and 10.8 percentage points, respectively) than untreated nonmember households in the DDBC treatment arm. This indicates the presence of saturation effects. Households with a higher share of treated neighbors are more likely to have grown OSP. The size of the RS spillover effect is relatively stable over the three time periods. Although the treatment effect is substantially smaller in the more recent seasons in the recall interval, the spillover effect remains relatively constant at around 10 percentage points.[10]

The pattern of treatment and spillover effects for high iron beans is similar. Table 1 shows that treated nonmember households in the RS treatments were significantly more likely to have grown high iron beans over the last five seasons (by 35.7 percentage points), over the last year (by 9.3 percentage points) or during the last season (by 5.8 percentage points (insignificant)) than untreated nonmember households in the DDBC treatment arm. The average RS effect on diffusion of high iron beans led to a significant 18.5 percentage point increase in the probability that untreated nonmember households had grown high iron beans in the last five seasons compared to untreated nonmembers in the DDBC control group. This spillover effect was a significant 9.3 percentage points in the last year and a positive, but insignificant, 5.8 percentage points in the most recent season.

For OSP, the treatment effect was significantly larger than the spillover effect during the five season recall window, but insignificant during the last year and last season. For high iron beans, the treatment effect was always larger than the spillover effect, but the difference is never significant. When the treatment adoption and spillover diffusion are both significantly larger than in the DDBC control, but are not significantly different from each other, this suggests that distributing planting material to a larger number of nonmembers in the community has significant

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[10] The size of the treatment or spillover effects may not always decline as the recall interval shrinks because the counterfactual diffusion effect in the DDBC control treatment arm may be larger in some seasons than in others.

returns to diffusion, but that it may not matter who directly receives the biofortified crops. Both direct and indirect recipients of the technology are similarly affected in terms of their propensity to adopt the crop.

Table 2 presents the results from equation (2) reporting treatment and spillover effects by the Low Saturation and High Saturation treatment arms in the Randomized Saturation experiment. Results show significant treatment effects on OSP adoption by treated non-farmer group members in both the LS and HS treatments in each of the three time periods. Treatment effects are not significantly different between the LS and HS treatment arms. Spillover effects for OSP diffusion to untreated non-farmer group members are significant in all three time periods for the HS treatment and positive, but insignificant, for the LS treatment. The HS and LS spillover effects are significantly different from each other in the first two time periods, suggesting that there are significant positive impacts to saturation effects.

For high iron beans, the LS and HS treatment effects over the last five seasons are the same size and there is no significant difference between the LS and HS spillover effects over this period. However, over the last year and last season, the LS treatment effect is significantly larger than the HS treatment effect. The LS spillover effect in the last year is significant at 10.6 percentage points and positive (6.8 percentage points) but insignificant in the last season, and there are no significant spillovers in these two periods for the HS arm. This represents a reversal of the saturation effect for high iron beans in the last year of the project. There are two possible reasons for this. Self-reported data suggests that additional HIB were distributed in the LS arm and not in the HS arm after the 2013 drought. It is unclear why this occurred. Alternatively, it is possible that the very high rate of saturation in the HS treatment arm may have caused congestion in the market for high iron beans, or a different form of saturation in which it became unprofitable for many households to grow the beans when so many around them were doing so. The vast quantity of harvested beans, which can either be consumed, sold, or saved for planting in the next season, may have depressed the price of beans, discouraging future adoption by some households.

Next, we estimate equation (3) to examine the potential for spillover effects of the Randomized Saturation onto treated farmer group members. While coefficients are always positive (Table 3), we find no significant reinforcing impact of diffusion on treated farmer group members for OSP. Echoing the pattern of treatment and spillover effects for high iron beans in the last year and last season from Table 2, we find that the LS treatment lead to a significant spillover effect on treated farmer group members, increasing their probability of adopting high iron beans by 21.2 percent and 14.9 percent respectively. There was no comparable spillover effect from the HS treatment in those periods. The size of this effect is surprisingly large, but it provides further evidence of spillovers from one group of treated individuals to another in the same treatment arm.

Results so far have focused on the three RS treatment arms. The fourth treatment arm was included to test whether individuals identified by their peers in their own communities to be opinion leaders in farming or health or "progressive farmers" more prone to try new technologies would, by virtue of their influential role in their community, be more effective at promoting adoption of the biofortified crops than the DDBC dissemination model that relied on farmer group members in the community, with or without treatment of a random sample of their neighbors, as in the RS models. In the OL/PF treatment arm, these potentially influential promoters were given enough OSP and high iron beans planting material to provide the same quantity of planting material as would have been provided to an average sized farmer group in a community in the DDBC treatment arm. In this sense, the dose of the biofortified crop technologies provided was equal between the OL/PF and DDBC treatment arms. We tested the effectiveness of this OL/PF model against the other three treatment arms, estimating equation (4) on the sample of non-farmer group members in all four treatment arms. Results, presented in Table 4, show that opinion leaders and progressive farmers were not more effective at promoting adoption of OSP or high iron beans than farmer group members in the DDBC dissemination model. There is no difference in spillover effects between the OL/PF and DDBC treatment arms. Spillover effects in the HS treatment arms were significantly larger (at least weakly) than in the OL/PF treatment arm for both crops in all three time periods and spillover effects were larger in the LS treatment arm for HIB.

It may be the case that the OL/PF promoters were also members of the selected farmer group in the other treatment arms, so that they had access to the biofortified crop technologies and so were able to learn about their traits, experiment with them and promote them if they found them to be high quality. Although the OL/PF model provided these individuals with substantial quantities of the planting material to share, they likely faced communication and coordination costs in reaching a large number of households with the planting material, in part because they did not have the explicit commitment of their fellow farmer group members, for those that belonged to the farmer group in their communities. OL/PFs who were farmer group members in the DDBC treatment arms could coordinating diffusion activities with other members of their farmer group, who also had access to the technologies.

V. Cost-effectiveness

The results show that the saturation treatment arms created larger spillover effects on average for both OSP and high iron beans throughout the project, and that these effects were retained, if somewhat smaller, into the last season. The fact that higher treatment saturation leads to higher spillover effects on average shows that there are returns to saturation for promoting biofortified crop diffusion. However, the policy question for biofortification concerns whether higher rates of saturation are cost-effective. That is, does the additional technology diffusion that comes from providing a higher rate of saturation of a community with planting material justify the additional cost?

As part of these diffusion experiments, we worked with HarvestPlus and their NGO implementing partners to collect detailed information on all costs of delivering the OSP and high iron beans and the associated trainings (see Appendix A for a detailed description of the cost data). These costs included the cost of the planting material, transportation costs and training costs. In particular, we collected detailed information to determine differences in these costs across treatment arms. We also collected detailed information during the endline household survey interviews on the costs of participating in the project. Using these data, we are able to estimate the incremental cost of conducting the project in the LS and HS treatment arms relative to the DDBC treatment arm. We also estimated differences in cost between the OL/PF treatment arm and the DDBC treatment arm. This makes it feasible to estimate the cost per spillover beneficiary across all four treatment arms.

Table 5 provides the estimates per beneficiary community by treatment arm and Table 6 provides the estimates per individual beneficiary household per treatment arm. These estimates indicate that while total costs increase slightly from DDBC treatment to low saturation to high saturation, the costs per direct beneficiary are declining in the rate of saturation of the project within a community, so that average costs per direct beneficiary are lower in the LS and HS treatment arms than in the DDBC treatment arm in which only farmer group members received planting material and training. Because the LS and HS treatment arms also led to larger spillover effects which incur no additional costs to the project, this implies that the LS and HS treatments were more cost-effective than the standard DDBC treatment. Moreover, the size of the saturation spillover effects is large enough to suggest that these cost savings per total beneficiary are meaningful. To put it another way, the DDBC project would reach a larger number of total beneficiaries for the same cost by including in the project not only the members of the selected farmer group but also a large share of other households in the community. Our experiment also suggests that, at least in the case of OSP, the HS arm was more cost-effective than the LS arm.

Moreover, if the public health objective of these biofortification interventions is to reach a very high share of households in a community with children under age five, so that other costly interventions like Child Health Days would not be needed in these communities, there is strong evidence from this study to support the higher rates of saturation included in this experiment.

VI. Conclusion

These results provide justification for the HarvestPlus dissemination model that harnesses the motivation, coordination skills and scale of farmer groups to help promote adoption of biofortified crops in Uganda. McNiven and Gilligan (2013) found that community information networks played an important role in promoting diffusion of OSP during the previous REU project in Uganda. Nonmember households with at least one treated farmer group member in their information network were 19 percentage points more likely to adopt OSP in the first season of the project. This demonstrated the importance of access to planting material in the first season of the project but there were no returns to density of the treated information network in that season. At the end of the project four seasons after initial distribution of OSP, households with a larger share of treated farmer group members in their information network were significantly more likely to still be growing OSP; knowing at least 50 percent of the treated farmer group members increased the probability of growing OSP at the end of the project by 20 percentage points. This suggests returns to the density of the information network, and that over time information mattered more than access to planting material. These results suggested that an OL/PF treatment may be uniquely effective by finding the most influential nodes in the information network of members of the community. OL/PFs selected had both a large number of connections within the community information network and were also identified as being influential. Results from these DDBC experiments suggest that it was not only access to information that drove the sustained diffusion results in the REU—since opinion leaders were those who would be most effective at providing that information—but that scale and density of the information network were important. The influence held by opinion leaders and progressive farmers and their unique role as important hubs in the information network on farming and health is largely offset by scale of the farmer groups, which have more than three times as many members on average as the individuals enlisted as promoters in the OL/PF treatment. The REU results as well as those presented here suggest the presence of herd behavior or mimicry in supporting sustained adoption of these biofortified crop technologies.

References

Aker, Jenny. 2011. “Dial `A’ for agriculture: a review of information and communication technologies for agricultural extension in developing countries.” *Agricultural Economics* 42: 631-647.

Aker, Jenny C. and Joshua Blumenstock. 2014. “The Economics of New Technologies in Africa.” *Handbook of Africa and Economics*. Forthcoming, Oxford University Press.

Ashour, Maha, Daniel O. Gilligan, Scott McNiven and Lucy Billings. 2013. Impact Evaluation of the HarvestPlus Project Developing and Delivering Biofortified Crops in Uganda: Baseline Report. International Food Policy Research Institute.

Baird, Sarah, J. Aislinn Bohren, Craig McIntosh and Berk Özler. 2016. “Optimal Design of Experiments in the Presence of Interference.” *PIER Working Paper No. 16-025*.

Carvalho LM, Correa MM, Pereira EJ, et al. 2012. “Iron and zinc retention in common beans (*Phaseolus vulgaris* L) after home cooking.” *Food and Nutrition Research* 56: 15618‑23.

Copenhagen Consensus. 2012. Expert Panel Findings: Outcome Document. http://www.copenhagenconsensus.com/sites/default/files/outcome_document_updated_1105.pdf

de Brauw, Alan, Patrick Eozenou, Daniel O. Gilligan, Christine Hotz, Neha Kumar and J.V. Meenakshi. 2016. “Biofortification, crop adoption and health information: Impact pathways in Mozambique and Uganda.” Mimeo. International Food Policy Research Institute.

Feder, Gershon, Richard E. Just and David Zilberman. 1985. “Adoption of agricultural innovations in developing countries: A survey.” *Economic Development and Cultural Change* 33(2): 255-298.

Habicht, Jean-Pierre. 2008. “Comment: Malnutrition kills directly, not indirectly.” *The Lancet* 371: 1749-1750.

Hotz, Christine, Cornelia Loechl, Abdelrahman Lubowa, James K Tumwine, Grace Ndeezi, Agnes Nandutu Masawi, Rhona Baingana, Alicia Carriquiry, Alan de Brauw, JV Meenaksi, and Daniel O. Gilligan. 2012a. “Introduction of β-carotene rich orange sweet potato in rural Uganda resulted in increased vitamin A intakes among children and women and improved vitamin A status among children.” *Journal of Nutrition* 142(10): 1871-1880.

Hotz, Christine, Cornelia Loechl, Alan de Brauw, Patrick Eozenou, Daniel Gilligan, Mourad Moursi, Bernardino Munhaua, Paul van Jaarsveld, Alicia Carriquiry, and JV Meenaksi. 2012b. “A Large-Scale Intervention to Introduce Orange Sweet Potato in Rural Mozambique Reduces the Prevalence of Inadequate Vitamin A Intakes Among Children and Women.” *British Journal of Nutrition* 108: 163-176.

Gilligan, Daniel O. 2012. “Biofortification, Agricultural Technology Adoption, and Nutrition Policy: Some Lessons and Emerging Challenges.” *CESifo Economic Studies* 58(2): 405-421.

Lin, W., 2013. Agnostic notes on regression adjustments to experimental data: reexamining Freedman’s critique. Annals of Applied Statistics 7 (1), 295–318.

Low JW, Arimond M, Osman N, Dunguara B, Zano F, Tschirley D. 2007. “Orange-fleshed sweet potatoes increased vitamin A intake and serum retinol concentrations in young children in rural Mozambique.” *Journal of Nutrition* 137:1320-7.

McNiven, Scott C. and Daniel O. Gilligan. December 2013. “Networks and Constraints on the Diffusion of a Biofortified Agricultural Technology: Evidence from a Partial Population Experiment.” Mimeo. International Food Policy Research Institute.

McNiven, Scott C., Daniel O. Gilligan, and Christine Hotz. December 2016. Sustainability of impact: Dimensions of decline and persistence in adopting a biofortified crop in Uganda. International Initiative for Impact Evaluation (3ie) Impact Report 35.

Petry N, Egli I, Gahutu JB, Tugirimana PL, Boy E, Hurrell R. 2012. Stable iron isotope studies in Rwandese women indicate that the common bean has limited potential as a vehicle for iron biofortification. *Journal of Nutrition* 142: 492‑97.

Ruel, Marie, Harold Alderman and the Maternal and Child Nutrition Study Group. 2013. “Nutrition-sensitive interventions and programmes: how can they help to accelerate progress in improving maternal and child nutrition?” *The Lancet* 382: 536-551.

Suri, Tavneet. 2011. “Selection and comparative advantage in technology adoption.” *Econometrica* 79(1): 159-209.

Miguel, Edward and Michael Kremer. 2004. “Worms: Identifying impacts on education and health in the presence of treatment externalities.” *Econometrica* 79(1): 159-217.

UBOS (Uganda Bureau of Statistics) and MEASURE DHS. 2011. *Uganda Demographic and Health Survey, 2011*. Calverton, Maryland, USA: UBOS and MEASURE DHS.

UBOS (Uganda Bureau of Statistics) and ORC Macro. 2001. *Uganda Demographic and Health Survey, 2000–2001*. Calverton, Maryland, USA: UBOS and ORC Macro.

Van Jaarsveld PJ, Faber M, Tanumihardjo SA, Nestel P, Lombard CJ, Spinnler Benade AJ. 2005. “B-carotene-rich orange-fleshed sweet potato improves the vitamin A status of primary school children assessed with the modified-relative-dose-response test.” *American Journal of Clinical Nutrtion* 81:1080-7.

Table 1: Average Treatment and Spillover Effects in the Randomized Saturation Treatment Arms

	Dependent variable					
	(1)	(2)	(3)	(4)	(5)	(6)
	Orange Sweet Potato			High Iron Beans		
	Last Five Seasons	Last Year	Last Season	Last Five Seasons	Last Year	Last Season
Treatment	0.351***	0.156***	0.142***	0.357***	0.138***	0.123***
	(0.054)	(0.049)	(0.048)	(0.057)	(0.048)	(0.047)
Spillover	0.160***	0.138***	0.108**	0.185***	0.093**	0.058
	(0.057)	(0.053)	(0.050)	(0.060)	(0.047)	(0.039)
Mean in the control group	0.376	0.243	0.209	0.289	0.136	0.111
Number of observations	875	875	876	794	794	795
Prob > F(Treatment = Spillover)	0.000	0.737	0.523	0.003	0.343	0.171

Notes: The sample includes households in the endline survey sample who were also interviewed at baseline who were non-farmer group members in the randomized saturation treatment arms: High Saturation, Low Saturation and control (DDBC treatment arm). We restrict our sample to households with children under 8 at baseline. Each column reports a treatment or spillover effect as the share of households growing the crop in that period. Estimates on high iron beans exclude the sample from Kabale district, where the project did not distribute its variety of biofortified bush beans, which are not well suited to the higher elevations in that district. All models include dummy variables to control for experimental block randomization design according to district strata, two intervals of the share of households that previously grew orange sweet potato, and three intervals of the share of households in the community with at least one member in the selected farmer group. In addition, regressions control for the share of the community that was in a farmer group and the size of the community population with children under 8, and the two baseline variables that were predictive of adoption in the stepwise regression model: the number of working age adults and vitamin A knowledge. Standard errors in parenthesis are clustered at the community level and adjusted for stratification by district groupings. Samples are weighted to reflect the sampling strategy. Statistical significance of parameter estimates is indicated by: * 0.10, ** 0.05, *** 0.01.

Table 2: Treatment and Spillover Effects by Treatment Arm in the Randomized Saturation Treatment Arms

	Dependent variable					
	(1)	(2)	(3)	(4)	(5)	(6)
	Orange Sweet Potato			High Iron Beans		
	Last Five Seasons	Last Year	Last Season	Last Five Seasons	Last Year	Last Season
Low saturation treatment	0.337***	0.147**	0.154**	0.349***	0.233***	0.250***
	(0.078)	(0.065)	(0.063)	(0.071)	(0.064)	(0.063)
High saturation treatment	0.359***	0.160***	0.130**	0.362***	0.059	0.018
	(0.059)	(0.055)	(0.056)	(0.066)	(0.050)	(0.042)
Low saturation spillover	0.093	0.073	0.051	0.154**	0.106*	0.068
	(0.065)	(0.056)	(0.056)	(0.067)	(0.061)	(0.049)
High saturation spillover	0.228***	0.206***	0.167**	0.215***	0.083	0.052
	(0.069)	(0.074)	(0.066)	(0.076)	(0.053)	(0.046)
Mean in the control group	0.376	0.243	0.209	0.289	0.136	0.111
Number of observations	875	875	876	794	794	795
Prob > F(LS treatment = HS treatment)	0.786	0.844	0.734	0.869	0.013	0.001
Prob > F(LS spillover = HS spillover)	0.065	0.094	0.105	0.434	0.732	0.784

Notes: The sample includes households in the endline survey sample who were also interviewed at baseline who were non-farmer group members in the randomized saturation treatment arms: High Saturation, Low Saturation and control (DDBC treatment arm). We restrict our sample to households with children under 8 at baseline. Each column reports a treatment or spillover effect as the share of households growing the crop in that period. Estimates on high iron beans exclude the sample from Kabale district, where the project did not distribute its variety of biofortified bush beans, which are not well suited to the higher elevations in that district. All models include dummy variables to control for experimental block randomization design according to district strata, two intervals of the share of households that previously grew orange sweet potato, and three intervals of the share of households in the community with at least one member in the selected farmer group. In addition, regressions control for the share of the community that was in a farmer group and the size of the community population with children under 8, and the two baseline variables that were predictive of adoption in the stepwise regression model: the number of working age adults and vitamin A knowledge. Standard errors in parenthesis are clustered at the community level and adjusted for stratification by district groupings. Samples are weighted to reflect the sampling strategy. Statistical significance of parameter estimates is indicated by: * 0.10, ** 0.05, *** 0.01.

Table 3: Spillover Effects on Treated Farmer Group Members

	Dependent variable					
	(1)	(2)	(3)	(4)	(5)	(6)
	Orange Sweet Potato			High Iron Beans		
	Last Five Seasons	Last Year	Last Season	Last Five Seasons	Last Year	Last Season
Low saturation treatment	0.041	0.097	0.032	0.061	0.212***	0.149*
	(0.038)	(0.074)	(0.078)	(0.054)	(0.081)	(0.086)
High saturation treatment	0.057	0.077	0.053	0.102	0.031	0.007
	(0.035)	(0.071)	(0.071)	(0.064)	(0.073)	(0.083)
Mean in the control group	0.835	0.524	0.505	0.761	0.367	0.316
Number of observations	382	382	382	336	336	336
Prob > F(Low saturation = High saturation)	0.687	0.792	0.781	0.464	0.025	0.092

Notes: The sample includes treated farmer group members across the three saturation treatment arms who had a child under 8 at baseline.. All models include dummy variables to control for experimental block randomization design according to district strata, two intervals of the share of households that previously grew orange sweet potato, and three intervals of the share of households in the community with at least one member in the selected farmer group. In addition, regressions control for the share of the community that was in a farmer group and the size of the community population with children under 8, and the one baseline variables that was predictive of adoption in the stepwise regression model: vitamin A knowledge. Standard errors in parenthesis are clustered at the community level and adjusted for stratification by district groupings. Samples are weighted to reflect the sampling strategy. Statistical significance of parameter estimates is indicated by: * 0.10, ** 0.05, *** 0.01.

Table 4: Spillover Effects from the Opinion Leader/Progressive Farmer Treatment Relative to Farmer Group-led Dissemination in the Randomized Saturation Models.

	Dependent variable					
	(1)	(2)	(3)	(4)	(5)	(6)
	Orange Sweet Potato			High Iron Beans		
	Last Five Seasons	Last Year	Last Season	Last Five Seasons	Last Year	Last Season
Low saturation spillover	0.077	0.068	0.049	0.154***	0.106*	0.057
	(0.062)	(0.055)	(0.053)	(0.058)	(0.054)	(0.048)
High saturation spillover	0.212***	0.204**	0.163**	0.224***	0.091	0.045
	(0.071)	(0.078)	(0.072)	(0.080)	(0.056)	(0.046)
Opinion leader/Progressive farmer spillover	-0.008	-0.009	-0.009	-0.015	-0.036	-0.044
	(0.049)	(0.046)	(0.042)	(0.046)	(0.035)	(0.031)
Mean in the control group	0.376	0.243	0.209	0.289	0.136	0.111
Number of observations	868	869	870	798	799	800
Prob > F(LS spillover = OLPF spillover)	0.160	0.165	0.279	0.004	0.008	0.035
Prob > F(HS spillover = OLPF spillover)	0.003	0.009	0.024	0.004	0.031	0.060

Notes: The sample includes untreated non-farmer group members across all four treatment arms with children under 8 at baseline. All models include dummy variables to control for experimental block randomization design according to district strata, two intervals of the share of households that previously grew orange sweet potato, and three intervals of the share of households in the community with at least one member in the selected farmer group. In addition, regressions control for the share of the community that was in a farmer group and the size of the community population with children under 8, and the two baseline variables that were predictive of adoption in the stepwise regression model: the number of working age adults and vitamin A knowledge. Standard errors in parenthesis are clustered at the community level and adjusted for stratification by district groupings. Samples are weighted to reflect the sampling strategy. Statistical significance of parameter estimates is indicated by: * 0.10, ** 0.05, *** 0.01.

Table 5: DDBC implementation costs per beneficiary community by treatment arm (USD)

	DDBC	HS	LS	OL/PF
HarvestPlus project costs	864.04	864.04	864.04	864.04
Planting material	82.00	220.57	126.15	106.42
Field extension worker time	219.88	281.16	254.05	148.37
NGO transportation costs	166.30	210.30	181.88	149.25
All other NGO costs	613.28	575.78	619.14	502.99
Total	1,945.51	2,151.84	2,045.26	1,771.06

Table 6: DDBC implementation costs per individual beneficiary household by treatment arm (USD)

	DDBC	HS	LS	OL/PF
HarvestPlus project costs	50.48	17.21	30.24	36.77
Planting material	4.24	4.05	4.06	4.11
Field extension worker time	12.85	5.60	8.89	6.31
NGO transportation costs	9.72	4.19	6.36	6.35
All other NGO costs	36.39	11.82	22.02	21.82
Total	113.67	42.87	71.57	75.36

Appendix Table A1: Baseline Control Means and Balance for Non-Farmer Group Members (Pooled Model)

	Control Group Mean	Treatment Difference	Spillover Difference	p-value (Treatment-Spillover)
Panel A: Community Level Variables				
Share of Households that are Farmer Group Members	0.212	-0.009	-0.007	0.770
	(0.124)	(0.032)	(0.033)	
Number of Households with Children Under 8	59.680	-7.170	-6.020	0.341
	(29.018)	(7.053)	(7.035)	
Panel B: Household Characteristics				
Household Size	6.291	-0.184	-0.385*	0.335
	(2.281)	(0.208)	(0.199)	
Number of Working Age Household Members (aged 18-55)	2.171	0.001	-0.091	0.175
	(0.712)	(0.065)	(0.071)	
Household Head's Education (years)	6.283	-0.407	-0.344	0.868
	(3.237)	(0.412)	(0.474)	
=1 if Female Headed Household	0.114	0.009	0.085**	0.046
	(0.318)	(0.029)	(0.039)	
Panel C: Household Agriculture Experience				
=1 if Household Grew any Sweet Potato in Past 12 Months	0.930	-0.014	-0.044	0.284
	(0.255)	(0.026)	(0.035)	
=1 if Household Grew any Orange Sweet Potato in Past 12 Months	0.066	0.028	0.053	0.481
	(0.248)	(0.037)	(0.043)	
=1 if Household Grew any Beans in Past 12 Months	0.949	-0.021	-0.025	0.900
	(0.219)	(0.026)	(0.028)	
Total Land Area Cultivated in Past 12 Months (acres)	2.821	-0.383	-0.127	0.168
	(3.275)	(0.303)	(0.337)	
=1 if Household is Typically an Early Adopter of New Agricultural Technology	0.710	0.020	-0.066	0.097
	(0.454)	(0.046)	(0.052)	
=1 if Frequently Shares Crop Planting Material or Inputs with Other Households	0.382	-0.012	-0.081	0.144
	(0.487)	(0.045)	(0.051)	
Panel D: Household Health Knowledge				
=1 if Knows Vitamin A is Important for Health	0.525	0.044	0.050	0.887
	(0.500)	(0.058)	(0.065)	
=1 if Knows Iron is Important for Health	0.337	-0.050	-0.059	0.847
	(0.473)	(0.051)	(0.059)	

Notes: Mean differences statistically different than 0 at 99% (***), 95% (**), and 90% (*) confidence. Asterisks on the coefficients in columns (2) and (3) indicate significantly different than the control group, while in column (4) asterisks indicate a significant difference between the treatment and spillover groups. This baseline balance table corresponds to the pooled model shown in equation (1) The sample includes households in the endline survey sample who were also interviewed at baseline who were non-farmer group members in the randomized saturation treatment arms: High Saturation, Low Saturation and control (DDBC treatment arm). We restrict our sample to households with children under 8 at baseline. Column 1 shows the control group mean, column 2 the pooled treatment difference, column 3 the pooled spillover difference, and column four the p-value on the test for equality between the treatment and spillover difference. Standard errors in parenthesis are clustered at the community level and adjusted for stratification by district groupings. Samples are weighted to reflect the sampling strategy.

Appendix Table A2: Baseline Control Means and Balance for Non-Farmer Group Members (Slope Model)

	Control Group Mean	Treatment Difference		p-value Treatment (LS-HS)	Spillover Difference		p-value Spillover (LS-HS)
		Low Saturation	High Saturation		Low Saturation	High Saturation	
Panel A: Community Level Variables							
Share of Households that are Farmer Group Members	0.212	-0.029	0.009	0.299	-0.014	0.001	0.709
	(0.124)	(0.035)	(0.038)		(0.037)	(0.040)	
Number of Households with Children Under 8	59.680	-6.680	-7.603	0.903	-7.888	-4.071	0.616
	(29.018)	(8.329)	(7.708)		(8.227)	(7.722)	
Panel B: Household Characteristics							
Household Size	6.291	-0.202	-0.169	0.916	-0.385*	-0.385	0.999
	(2.281)	(0.269)	(0.252)		(0.224)	(0.284)	
Number of Working Age Household Members (aged 18-55)	2.171	-0.038	0.037	0.492	-0.131*	-0.049	0.460
	(0.712)	(0.094)	(0.074)		(0.067)	(0.109)	
Household Head's Education (years)	6.283	-0.108	-0.668	0.273	-0.62	-0.066	0.380
	(3.237)	(0.522)	(0.442)		(0.470)	(0.651)	
=1 if Female Headed Household	0.114	-0.025	0.039	0.107	0.039	0.133**	0.156
	(0.318)	(0.033)	(0.036)		(0.040)	(0.059)	
Panel C: Household Agriculture Experience							
=1 if Household Grew any Sweet Potato in Past 12 Months	0.930	-0.020	-0.008	0.768	-0.035	-0.055	0.736
	(0.255)	(0.034)	(0.032)		(0.035)	(0.055)	
=1 if Household Grew any Orange Sweet Potato in Past 12 Months	0.066	0.021	0.035	0.808	0.038	0.069	0.673
	(0.248)	(0.054)	(0.045)		(0.045)	(0.066)	
=1 if Household Grew any Beans in Past 12 Months	0.949	-0.043	-0.002	0.307	-0.017	-0.033	0.737
	(0.219)	(0.037)	(0.029)		(0.028)	(0.044)	
Total Land Area Cultivated in Past 12 Months (acres)	2.821	-0.621*	-0.172	0.203	-0.106	-0.149	0.926
	(3.275)	(0.334)	(0.361)		(0.388)	(0.429)	
=1 if Household is Typically an Early Adopter of New Agricultural Technology	0.710	0.094*	-0.045	0.029	-0.074	-0.059	0.850
	(0.454)	(0.049)	(0.059)		(0.055)	(0.075)	
=1 if Frequently Shares Crop Planting Material or Inputs with Other Households	0.382	-0.028	0.002	0.687	-0.076	-0.085	0.914
	(0.487)	(0.057)	(0.060)		(0.052)	(0.078)	
Panel D: Household Health Knowledge							
=1 if Knows Vitamin A is Important for Health	0.525	0.056	0.032	0.744	-0.015	0.119	0.172
	(0.500)	(0.069)	(0.068)		(0.071)	(0.090)	
=1 if Knows Iron is Important for Health	0.337	0.011	-0.103*	0.085	-0.086	-0.031	0.547
	(0.473)	(0.065)	(0.054)		(0.061)	(0.086)	

Notes: Mean differences statistically different than 0 at 99% (***), 95% (**), and 90% (*) confidence. Asterisks on the coefficients in columns (2) , (3), (5) and (6) indicate significantly different than the control group, while in column (4) asterisks indicate a significant difference between the low saturation and high saturation treatment arms, and in column (7) asterisk indicate a significant difference between the low saturation and high saturation spillover arms. This baseline balance table corresponds to the model shown in equation (2). The sample includes households in the endline survey sample who were also interviewed at baseline who were non-farmer group members in the randomized saturation treatment arms: High Saturation, Low Saturation and control (DDBC treatment arm). We restrict our sample to households with children under 8 at baseline. Column 1 shows the control group mean, column 2 the low-saturation treatment difference, column 3 the high saturation treatment difference, column 4 four the p-value on the test for equality between the low-saturation and high saturation treatment difference, column 5 the low-saturation spillover difference, column 6 the high saturation spillover difference, column 7 the p-value on the test for equality between the low-saturation and high saturation spillover difference Standard errors in parenthesis are clustered at the community level and adjusted for stratification by district groupings. Samples are weighted to reflect the sampling strategy.

Appendix Table A3: Baseline Control Means and Balance for Farmer Group Members

	Control Group Mean	Low Saturation	High Saturation	p-value (LS-HS)
Panel A: Community Level Variables				
Share of Households that are Farmer Group Members	0.22	0.067	0.001	0.417
	(0.129)	(0.800)	(0.039)	
Number of Households with Children Under 8	57.846	-11.665	-5.769	0.470
	(29.970)	(8.754)	(7.712)	
Panel B: Household Characteristics				
Household Size	7.14	-0.464	-0.346	0.754
	(2.416)	(0.342)	(0.353)	
Number of Working Age Household Members (aged 18-55)	2.389	0.07	0.067	0.986
	(0.958)	(0.129)	(0.139)	
Household Head's Education (years)	6.117	0.08	0.581	0.313
	(3.323)	(0.396)	(0.436)	
=1 if Female Headed Household	0.159	0.05	-0.011	0.377
	(0.367)	(0.074)	(0.060)	
Panel C: Household Agriculture Experience				
=1 if Household Grew any Sweet Potato in Past 12 Months	0.930	0.015	0.003	0.729
	(0.256)	(0.030)	(0.034)	
=1 if Household Grew any Orange Sweet Potato in Past 12 Months	0.111	-0.054	0.012	0.158
	(0.315)	(0.041)	(0.058)	
=1 if Household Grew any Beans in Past 12 Months	0.968	-0.02	-0.011	0.757
	(0.177)	(0.026)	(0.028)	
Total Land Area Cultivated in Past 12 Months (acres)	3.392	0.028	-0.498	0.162
	(3.546)	(0.477)	(0.418)	
=1 if Household is Typically an Early Adopter of New Agricultural Technology	0.780	0.015	-0.019	0.643
	(0.416)	(0.069)	(0.073)	
=1 if Frequently Shares Crop Planting Material or Inputs with Other Households	0.542	-0.186**	-0.127	0.416
	(0.500)	(0.077)	(0.077)	
Panel D: Household Health Knowledge				
=1 if Knows Vitamin A is Important for Health	0.669	0.045	0.008	0.622
	(0.473)	(0.076)	(0.078)	
=1 if Knows Iron is Important for Health	0.444	-0.045	-0.044	0.992
	(0.499)	(0.087)	(0.083)	

Notes: Mean differences statistically different than 0 at 99% (***), 95% (**), and 90% (*) confidence. Asterisks on the coefficients in columns (2) and (3) indicate significantly different than the control group, while in column (4) asterisks indicate a significant difference between the low and high saturation spillover groups. This baseline balance table corresponds to the farmer group model shown in equation (3) The sample includes households in the endline survey sample who were also interviewed at baseline who were farmer group members in the randomized saturation treatment arms: High Saturation, Low Saturation and control (DDBC treatment arm). We restrict our sample to households with children under 8 at baseline. Column 1 shows the control group mean, column 2 the low saturation spillover difference, column 3 the high saturation spillover difference, and column four the p-value on the test for equality between the low saturation and high saturation spillover difference. Standard errors in parenthesis are clustered at the community level and adjusted for stratification by district groupings. Samples are weighted to reflect the sampling strategy.

Appendix Table A4: Baseline Control Means and Balance for Non-Farmer Group Member (Spillovers, including OLPF)

		Spillovers				
	Control Group Mean	Low Saturation	High Saturation	OLPF	p-value (LS-OLPF)	p-value (HS-OLPF)
Panel A: Community Level Variables						
Share of Households that are Farmer Group Members	0.212	-0.014	0.001	0.021	0.424	0.673
	(0.124)	(0.037)	(0.040)	(0.043)		
Number of Households with Children Under 8	59.680	-7.888	-4.071	-5.142	0.709	0.876
	(29.018)	(8.227)	(7.722)	(7.568)		
Panel B: Household Characteristics						
Household Size	6.291	-0.385*	-0.385	-0.169	0.387	0.479
	(2.281)	(0.225)	(0.285)	(0.215)		
Number of Working Age Household Members (aged 18-55)	2.171	-0.131*	-0.049	-0.066	0.444	0.890
	(0.712)	(0.067)	(0.110)	(0.078)		
Household Head's Education (years)	6.283	-0.62	-0.066	-0.527	0.838	0.452
	(3.237)	(0.468)	(0.647)	(0.449)		
=1 if Female Headed Household	0.114	0.039	0.133**	0.012	0.524	0.046
	(0.318)	(0.040)	(0.059)	(0.032)		
Panel C: Household Agriculture Experience						
=1 if Household Grew any Sweet Potato in Past 12 Months	0.930	-0.035	-0.055	-0.047	0.737	0.892
	(0.255)	(0.035)	(0.055)	(0.028)		
=1 if Household Grew any Orange Sweet Potato in Past 12 Months	0.066	0.038	0.069	-0.006	0.275	0.232
	(0.248)	(0.045)	(0.066)	(0.029)		
=1 if Household Grew any Beans in Past 12 Months	0.949	-0.017	-0.033	-0.004	0.622	0.500
	(0.219)	(0.028)	(0.044)	(0.020)		
Total Land Area Cultivated in Past 12 Months (acres)	2.821	-0.106	-0.149	-0.042	0.891	0.831
	(3.275)	(0.387)	(0.426)	(0.436)		
=1 if Household is Typically an Early Adopter of New Agricultural Technology	0.710	-0.074	-0.059	-0.070	0.950	0.882
	(0.454)	(0.055)	(0.075)	(0.049)		
=1 if Frequently Shares Crop Planting Material or Inputs with Other Households	0.382	-0.076	-0.085	-0.095	0.754	0.905
	(0.487)	(0.052)	(0.077)	(0.044)		
Panel D: Household Health Knowledge						
=1 if Knows Vitamin A is Important for Health	0.525	-0.015	0.119	0.041	0.421	0.391
	(0.500)	(0.071)	(0.090)	(0.063)		
=1 if Knows Iron is Important for Health	0.337	-0.086	-0.031	-0.024	0.373	0.938
	(0.473)	(0.061)	(0.086)	(0.063)		

Notes: Mean differences statistically different than 0 at 99% (***), 95% (**), and 90% (*) confidence. Asterisks on the coefficients in columns (2) -(4) indicate significantly different than the control group, while in column (5) asterisks indicate a significant difference between the low saturation and OLPF spillover groups, and column (6) asterisk indicate a significant difference between the high saturation and OLPF spillover groups. This baseline balance table corresponds to the model shown in equation (4) The sample includes households in the endline survey sample who were also interviewed at baseline who were non-treatment non-farmer group members in the randomized treatment arms: High Saturation, Low Saturation, OLPF, and control (DDBC treatment arm). We restrict our sample to households with children under 8 at baseline. Column 1 shows the control group mean, column 2 the low-saturation spillover difference, column 3 the high saturation spillover difference, column 4 the OLPF spillover difference, column 5 the p-value on the test for equality between the low-saturation and OLPF arms, and column 6 the p-value on the test for equality between the high-saturation and OLPF arms. Standard errors in parenthesis are clustered at the community level and adjusted for stratification by district groupings. Samples are weighted to reflect the sampling strategy.

Appendix A: Costing Details

The aim of the costing exercise is to calculate the program cost by treatment arm in order to make comparisons of cost-effectiveness between treatment arms. HarvestPlus implemented the DDBC project in Uganda from 2011 to 2016 aiming to reach 225,000 beneficiary households across 13 districts of Uganda. We estimated costs for study beneficiaries as a share of total project costs for the relevant time period. We separate the costs of the NGO implementing partners from the HarvestPlus project costs in order to allocate costs by treatment arm. For the NGO implementing costs we used 2013 annual financial reports covering the period from January – December 2013 and interview data from NGO implementing partner staff. For the HarvestPlus costs we used the 2013 project summary report covering the same time period, the general ledger that details country office spending, HarvestPlus staff reports on the price paid to outgrowers for planting material in 2013, and reports on capital equipment purchases throughout the project.

NGO implementing partner costs

The DDBC project is managed by the HarvestPlus Uganda country program in partnership with six NGO implementers, each operating in a different region of the country. The study was conducted in five district clusters covered by four different NGO implementers: Community Enterprise Development Organization (CEDO), Africa 2000 Network (A2N), Samaritan's Purse (SP), and World Vision (WV). In order to assess project costs by treatment arm, we collected detailed cost information from each of the NGO implementers and calculated the cost of implementation by beneficiary community, the unit used for random assignment of treatment in the study design, and by individual direct beneficiary. We used NGO 2013 financial reports to document costs and collected information from project field extension workers (FEWs) to document the time spent on implementing the intervention in each study community and the estimated distance from the NGO office to each study community.

Because there was not a standard financial reporting template used across NGOs the cost categories are quite different by NGO. As a result we had to determine costs for each NGO by treatment arm first rather than aggregating by activity across NGOs before allocating costs to treatment arms. The drawback to this approach is that it becomes more difficult to refine cost estimates based on alternate scenarios with different levels of investment in the various project activities. However, it does not inhibit our ability to arrive at an aggregated cost by treatment arm for the purpose of the cost-effectiveness analysis.

We first determined which cost categories from the NGO budget would vary by treatment arm deciding that this should be limited to FEW time and transportation costs. We assumed that all other cost categories could be shared across beneficiary communities proportional to the number of communities covered by that treatment arm. We determined the proportion of costs that should be allocated to each treatment arm by dividing the number of communities assigned to the treatment by the total number of beneficiary communities in 2013 (including both communities covered in the first and second agricultural season) for each NGO.

For the two cost categories that vary by treatment arm we used alternative distributions for allocating the costs. We collected detailed information on FEW time and travel for each study community. For the transportation allocation we calculated total travel distance for each treatment arm multiplying the total number of visits to all communities in that treatment arm by the average distance from the NGO office to the study communities served by that NGO assuming that since treatment assignment was random the travel distance should be equal across treatment arms with a large enough sample. We arrived at the distance for non-study communities by using the average number of visits to the DDBC comparison treatment communities multiplied by the number of non-study communities and the average travel distance to all study communities. We then calculated the allocation of transportation costs for each treatment arm by taking the total travel distance for the treatment arm divided by the total travel distance for all beneficiary communities in 2013 and then multiplying by the total NGO 2013 transportation costs including vehicles value, driver salaries, insurance, and fuel. Even though community visits do not represent the full use of project transportation resources, we had no way to determine the total distance for other transportation uses such as administrative errands or trips to Kampala for strategic planning and procurements, which would have been distributed across all beneficiary communities equally. This means that any differences in transportation costs between treatment arms are likely exaggerated.

A similar process was used for determining the allocation of FEW salary to the different treatment arms. We asked extension works to estimate how many hours they spent on a number of specific activities in each of the study communities. We then added the total time across activities for each treatment arm in each NGO. We estimated the FEW time for non-research communities covered by each NGO in 2013 by using the average time reported on activities in the DDBC comparison communities multiplied by the number of non-research communities for each NGO. We then calculated the share of time devoted to each treatment for each NGO by dividing the total time recorded for the treatment arm by the total time across all communities including non-research communities in that NGO. We multiplied the budget line for FEW salaries by the time allocation share for each treatment for each NGO. As with the transportation allocation, we were not able to determine what proportion of the FEW time was spent on activities besides those working directly with the beneficiary communities. Other activities such as general project planning, reporting, and training should be divided equally by the number of beneficiary communities rather than according to the proportional distribution of time for the treatment arms. As a result the differences between treatment arms in cost of FEW time is likely exaggerated. Also worth noting, we aggregated all FEW salaries into a single line, which was divided among the treatment arms according to the calculated proportions. If differences in FEW pay is based on experience or skill and this was also considered in assigning which FEWs would cover the study communities with more challenging treatment arms, this could also have a very slight impact on the value of FEW time by treatment arm.

HarvestPlus costs

The HarvestPlus DDBC project involved a number of activities to support the wide distribution and adoption of biofortified crops is Uganda. Besides contracting, training, and overseeing NGO partners to implement the project in the target districts, the HarvestPlus Uganda staff directly supported the NGO partners with demand creation, marketing and product development, and monitoring and evaluation. The HarvestPlus project also facilitated seed systems for biofortified crop development and contracted outgrowers to produce planting material for distribution. Finally, the HarvestPlus staff was responsible for overall project management including planning and reporting, coordination with research partners, and participating in relevant national and global forums. For the purpose of this exercise we omit costs to support research activities. However, we include all other direct and indirect project costs.

We determined that the only HarvestPlus cost to vary by treatment arm is the value of the planting material. HarvestPlus paid outgrowers UGX 10,000 per 50 kg sack of OSP vines and

UGX 3,250 per kg of iron beans. Each beneficiary was given a half sack of vines and 2 kg of beans at a total value of UGX 11,500 (USD 4.48). We calculated the cost of planting material per treatment arm by multiplying the value of the planting material by the number of beneficiaries in each treatment arm for each NGO.

We divided total HarvestPlus project spending less the value of planting material for all 2013 project beneficiaries and less costs on research activities and payments to the six NGO implementing partners by the total number of project beneficiary communities in 2013. We arrived at the total treatment arm cost for each NGO by adding the transportation allocation, FEW time allocation, all other NGO costs, the value of planting material, and the share of HarvestPlus project costs. We then calculated the mean cost per community for each treatment arm across NGOs. It's worth noting that there is considerable variation in costs by NGO. It is likely that the international NGOs had larger budgets due to more overhead costs to support international country staff and a country headquarters office.