Local innovators in Uganda: Experimenting with improved seeds in a low adoption environment

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Abstract

We analyse the conditions under which the use of different agricultural technologies lead to an increase in productivity in Ugandan agriculture. We present a target-input model to conceptualize the adoption decisions of a new technology in which the optimal use of inputs is unknown. We use a nationally representative sample of Ugandan households to test the impacts of farmers' choices on a measure of farm productivity and a measure of persistence of innovation. We find little evidence that seed policy reforms implemented in Uganda in the past 20 years had any substantial impact on agricultural productivity or the commitment of most farmers to persist in using improved technologies.

Keywords: Green Revolution, Improved Seed, Seed Policy Reforms, Uganda

JEL Codes: O33, O34, Q12

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1. Introduction

Several studies focusing on the impact of the Green Revolution in Asia have found evidence that seed policy reforms and agricultural productivity are related (Morris *et al.*, 1998; Ramaswami, 2002; Gerpacio, 2003) and that seed policy reforms enhancing intellectual property rights (IPRs) have triggered an expansion of seed industry. Despite growing interest in IPR and seed market reform in recent years, it is still not clear to what extent emerging seed policy reforms and IPR regimes in developing countries have contributed to increasing crop productivity, improving access to inputs, and strengthening food security. Some authors have found that IPRs reduce yield-gaps across crops, although results vary by crop, by region, and even by the time-period analysed (Spielman and Ma, 2016; Swanson and Goeschl, 2014; Kolady *et al.*, 2012). Clearly, modern varieties are making a major contribution to ongoing productivity gains, even though the role of IPRs itself is less well understood (O'Gorman and Pandey, 2010).

Since Uganda's ascension to membership in the World Trade Organization (WTO) in 1995, there are at least two distinct legal systems in place regulating seed sales and plant breeding in the country: a) TRIPS 27(3)b, providing for plant variety protection for all nationally registered plants and seed varieties under international law; and b) national laws enshrining the right of farmers to make use of seed and plants legally released on the national market.[1]

The Plant Protection Act of Uganda (1994), as revised in 2006, is "*an Act to provide for the promotion, regulation and control of plant breeding and variety release, multiplication, conditioning, marketing, importing and quality assurance of seed and other planting materials and for other related matters*." Previous works conclude that the degree to which these objectives can be achieved depends on social interactions, such as social learning processes and the role of peer effects in the diffusion of new technologies (Waters-Bayers *et al.*, 2015). Eaton et al., (2006) highlight that, at the time of their study, public plant breeding in Uganda focused on open-pollinated varieties (OPVs) and had not yet resulted in a widespread use of public varieties by farmers, while the private sector was still insignificant in terms of breeding activity, and thus had also not contributed substantially to the nascent seed industry.

The policy and legislative innovation introduced in Uganda since the early nineties have largely failed to trigger any significant productivity improvements in the country. Uganda is characterized by extremely low adoption of new technologies, even simple ones, such as improved seeds and new varieties of crops (Bold *et al.,* 2017, Coromaldi, Pallante and Savastano, 2015) and mineral fertilizers (Sheahan and Barrett, 2017).

Why adoption rates are so low still remains somewhat of a mystery and it is broadly viewed as a central reason why the country has not embarked on a path of sustained economic growth and mass poverty is still widespread (Bold et al., 2017).

The goal of this paper is to understand if and under what conditions the use of different agricultural technologies (e.g. adopting only improved seeds, or improved seeds jointly with mineral fertilizers or pesticides) diffused and led to an increase in productivity in Ugandan agriculture.[2] The empirical analysis is based on four waves of data from a nationally representative sample of Ugandan households, collected from the 2009-2010 to the 2013-2014 cropping years.

In particular, we study how improved seed accessed through different networks perform relative to local seed. We study agricultural productivity by looking at crop yields, captured by the quantity of crop harvested per acre in the main growing season.

We further analyse what factors contribute to the continued adoption of new agricultural technologies, such as improved seed.[3]

The rest of the paper is organized as follows. Section 2 presents a conceptual framework to describe the adoption decisions and management of a new agricultural technology. Section 3 describes our empirical approach. In this section we present the data and some key statistics, and explain our econometric strategy. In section 4 we discuss the main empirical results. Section 5 concludes and discusses some of the policy implications of our findings.

2. Conceptual Framework

We present a simple model to conceptualize the adoption decisions and management of a new technology (for example, improved seed) in which the optimal use of inputs under the new technology is unknown and stochastic.[4] We follow closely the modified target-input model proposed in the seminal paper of Foster and Rosenzweig (1995), while emphasising how this model applies in our context. This model is well-suited to describe situations where farmers rely on peers or more formal public information dissemination to learn about input use, rather than just learning by experimenting about the profitability of adopting a new technology. Optimal input use is central to farmers' concerns in an environment subject to technological change, and there is suggestive evidence of learning from others (Foster and Rosenzweig, 1995). Waters-Bayer et al., 2015, for example, find that research and development in agriculture and natural resource management can be disseminated farmer-to-farmer through informal networks and spaces created for farmer-researchers and other farmers to meet and exchange, such as innovation fairs.

The optimal, or target input use on each plot *i* planted using improved seed by farmer j in each period t is:

$$\tilde{\theta}_{ijt} = \theta^{*} + u_{ijt} \tag{1}$$

θ^{*} is defined as the mean optimal use of inputs and u_{ijt} is a random variable $u_{ijt} \sim N(i.i.d)$ with variance σ_u^2, which is assumed known by the farmers. Farmers have also priors over θ^* that is $N(\hat{\theta}_{j0}, \sigma^2_{\theta j0})$. Yields per plot using traditional seed are known, and indicated as η_a. Farmers adopting improved seed for the first time face several uncertainties regarding the use of this new technology, as well as the use of complementary inputs, such as fertilizer, that allows for the highest expected discounted revenue. While the use of traditional seed does not require the joint application of mineral fertilizer, improved seed varieties. usually benefit substantially from their joint use. This enhances uncertainties regarding the optimal use of inputs when the new agricultural technology is adopted (Bold et al., 2017; Ogada et al., 2010; Marenya and Barrett, 2009). For this reason, yields per plot using improved seed (captured by η_h) are unknown at the beginning of the growing season. In the empirical application of this study we will test different decisions of the farmers in term of whether they use jointly or not different agricultural technologies.

The term A_j is the total number of plots cultivated by farmer j, and defining θ_{ijt} as the per plot actual input use, per plot yields from improved seed of the i^{th} plot most suitable for cultivating improved seed is:

$$\eta_a + \eta_h - \eta_{ah} \ \frac{i}{A_j} - \left(\theta_{ijt} - \tilde{\theta}_{ijt}\right)^2 \quad (2)$$

Where η_{ah} is the loss associated with using less suitable plots as the share of land cultivated with improved seed increases. In target input models the profitability of a new technology, grows over time because of knowledge accumulation.

Foster and Rosenzweig (1995) show that under the assumptions of the model, expected profits for farmer j at time t are:

$$\pi_{jt} = \left(\eta_h - \eta_{ah} \frac{H_{jt}}{2A_j} - \sigma^2_{\theta jt} - \sigma^2_u\right) H_{jt} + \eta_a \, A_j \ + \mu_j + \varepsilon_{pjt} \ (3)$$

Where $E_t\ (\varepsilon_{pjt}) = 0$ and p is the input price. μ_j captures land productivity variation within farmers. $\sigma^2_{\theta jt}$ is the variance of farmer j's posterior distribution over θ^*_j at time t and H_{jt}/σ^2_u

is the precision of the signal, which increases proportionately with the number of parcels on which the farmer plants new-technology seed (Foster and Rosenzweig, 1995: 1182). At the end of the harvest, the optimal use on each plot of total land *i* planted by farmer *j* using the new improved seed ($\tilde{\theta}_{ijt}$) becomes known, and each farmer *j* update his priors regarding the expected optimal input use θ^*. We assume that shocks are independent across space.[5] If the farmer observes not only his yields, but also his neighbours' plot-specific inputs, then the signal precision for the farmer will also depend on the share of land neighbours allocated to improved seed (Foster and Rosenzweig, 1995: 1182). In this setting, Bayesian updating can be used to write:

$$\sigma^2_{\theta jt} = \frac{1}{(1/\sigma^2_{\theta 0}) + (1/\sigma^2_u)\, S_{jt} + [\mathrm{n}/(\sigma^2_u + \sigma^2_k)]\, \bar{S}_{-jt}} \qquad (4)$$

Where $(1/\sigma^2_{\theta 0})$is the precision of farmer *j*'s prior at the beginning of the growing season (time 0); $(1/\sigma^2_u)$ captures own experience, and represents the precision of information obtained from each plot cultivated by *j*; S_{jt} is the cumulative number of plots cultivated by farmer *j* at time *t*, *n* is the number of farmer *j*'s neighbors, and $\mathrm{n}/(\sigma^2_u + \sigma^2_k)$ is the precision of information obtained from an increase in average cumulative experience of farmer *j*'s neighbours ($\bar{S}_{-jt}$).[6]

In this setting, the existence of learning by doing and network externalities (learning by others) affects the structure of the profit function, as well as the adoption decisions of farmer *j* at time *t*. In the empirical application we use the number of years of adoption of modern technology to proxy learning by doing.

Given a discount factor ϕ, farmer *j* will maximize his expected discounted profits at time *t*, facing the following unconditional maximization problem:

$$V_{jt} = \max_{H_{jx}} \mathrm{E} \sum_{x=t}^{T} \phi^{s-t} \pi\big(H_{jx}, S_{jx}, S_{-jx}, A_j, \mu_{j,} \varepsilon_{pjx}\big) \quad (5)$$

Foster and Rosenzweig (1995) indicate as S_{-jx} the vector of experience for other farmers in village j and show that the decision made by each farmer depends on his neighbours' past planting decisions, and his own expectations about future planting decisions.

In our context this result means that if most of the farmers have already adopted, and continue to adopt, improved seed, neighbouring farmers will see the results of the earlier experimentation with the technology, and learn from those successes and mistakes. On the other hand, if only few farmers have chosen improved seed yet, early adopters need to carry out several rounds of experimentation to learn the optimal combination of inputs. Since only about 12% of the plots in our sample are cultivated using improved seeds, the cost of adopting a traditional seed is lower than the cost of learning about the best growing conditions for improved seed. In this framework, we have path dependency and it matters what initial endowment and information sharing practices a rural community possesses.

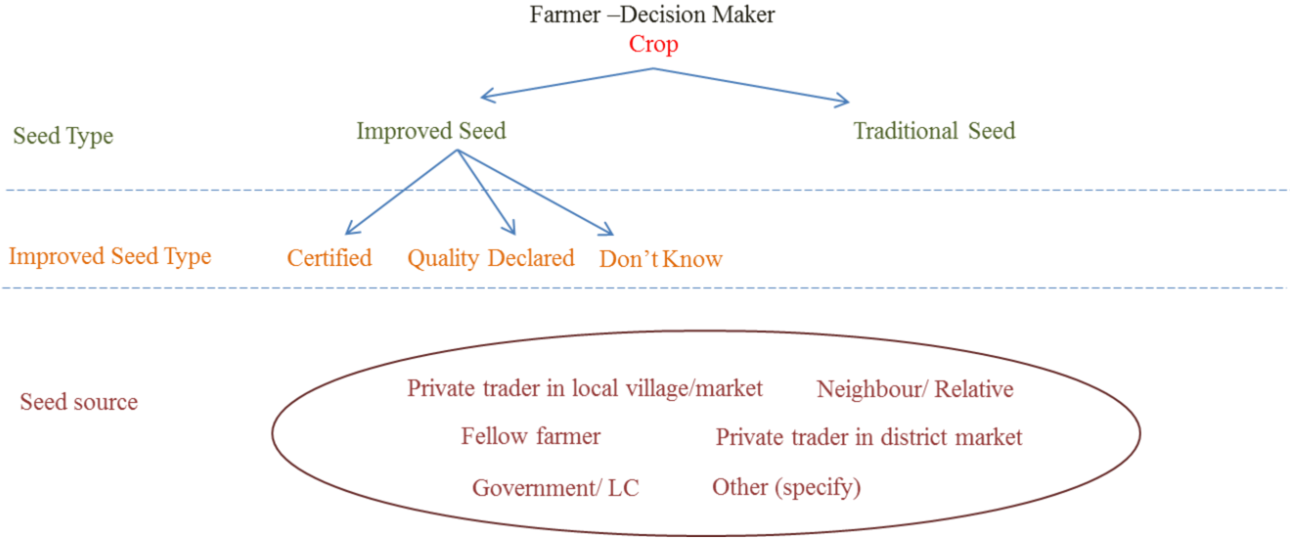
3. Empirical approach

3.1. Data

We use household data for rural agricultural households from the 2009/10, 2010/11, 2011/12 and 2013/14 waves of the Uganda National Panel Survey (UNPS).[7] The UNPS includes a nationally representative sample of households. This data provide detailed information on rural households' economic activities, their income and well-being.

The dataset collects information at plot level regarding the type of seed used (improved versus traditional), whether the seed was purchased or retained from previous growing seasons, the type of certification of the improved seed (certified, quality declared or unknown quality) and the source of seed.[8] Figure 2 shows the decision set concerning seed input use for the farm families in our sample:

Figure 2: Farm family decision set: seed inputs



Data was collected on crops planted by the household during the first cropping season (January-June) and second cropping season (July –December) on each plot on each parcel accessed by the household through ownership or user rights. We focus on the main agricultural season, as done in previous work (e.g. Sheahan and Barrett, 2017). Observations are at the plot level. We focus on five crops that are most frequently planted: maize, beans, groundnuts, sorghum and cassava. We also include cotton because of the large share of improved seeds compared to traditional seeds for this crop. Together these crops account for over 70% of the plots in our dataset cultivated using improved seeds. Maize is the main crop for which farmers use improved seed in our representative sample of Ugandan farmers. This crop is the most important crop in terms of household income and one of the most important crops for food security in Uganda. In absolute terms, maize occupies the largest area of all crops and it is grown by the largest number of households in Uganda. The total area planted to maize in 2012/13 was about 23% of the total crop area, and 63% of cereals area (UBOS, 2014). The *National Agricultural Research System* released in Uganda 50 maize varieties from 1960 to 2012, including 28 hybrids and 22 open-pollinated varieties (OPVs). The speed of introduction accelerated quickly after 1999, six years after the TRIPS Agreement and the release of the Seed and Plant Varieties Regulations.

We focus on purchased seeds. Farmers buy seed for only about 29% of plots in our sample. This means that they tend to save seed from previous cropping seasons. For each plot farmers have to state what type of seed (traditional or improved) she/he has bought (Table 1).

Table 1: purchased seed by seed type

	Frequency	%
Traditional	6,751	82.5
Improved	1,435	17.5
Total	8,186	100.0

Notes: Pooled dataset. Observations are at plot (area planted) level.

The vast majority of the sample only used local seed in the years under observation. Other studies confirm that Uganda is characterized by extremely low adoption rates of improved seeds and that the informal seed supply system controls 80% of the country's seed supply (Lwakuba, 2012).

District markets are used to provide almost twice the proportion of improved seed than of local seed (Table 2). Local markets, fellow farmers, neighbours and relatives supply 86% of traditional seed but less than 69% of improved seed.

Table 2: seed source by seed type

Traditional Seed		**Improved Seed**	
	% of responses		% of responses
Private trader in local village/market	66.5	Private trader in local village/market	51.8
Fellow farmer	18.0	Private trader in district market	24.0
Private trader in district market	12.7	Fellow farmer	16.3
Neighbour / Relative	1.4	Other	4.1
Government / LC	1.0	Government / LC	3.1
Other	0.5	Neighbour / Relative	0.8

Notes: Table based on question: Where did you buy most of this seed? Pooled dataset. Number of observations: 4,701. Observations are at plot (area planted) level.

We also explore the potential role of national certification laws – as a supplement to the information supplied within markets for different types of seeds.

The adoption of *certified* improved seed remains relatively low, comprising less than 39% of our sample (Table 3). The improved seed are mostly of declared quality, without formal certification.

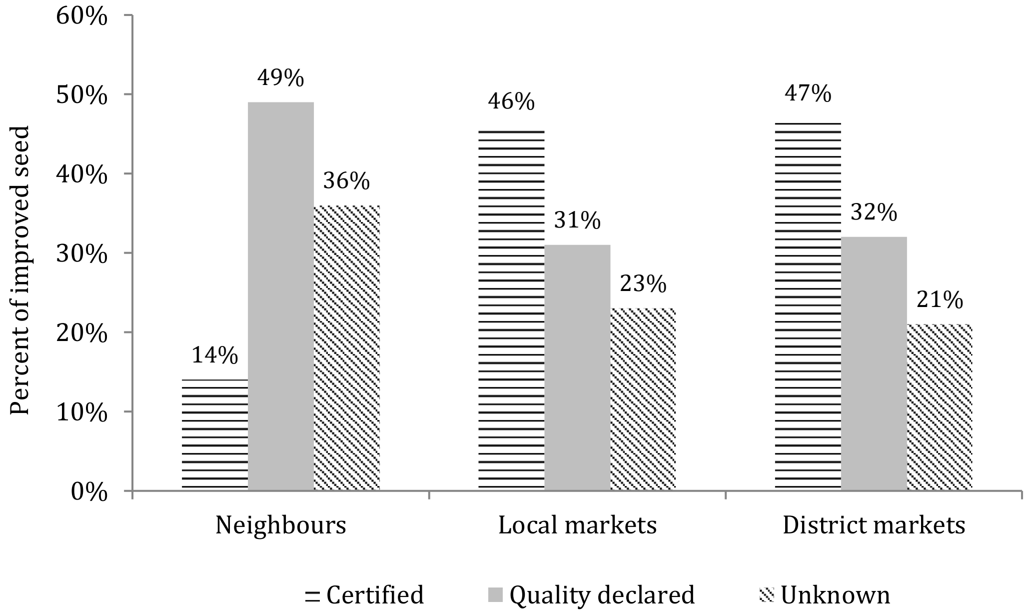
Table 3: Improved seed by certification type

	Frequency	%	Cumulated
Quality Declared	582	41.0	41.0
Certified	546	38.4	79.3
Don't Know	294	20.7	100.0
Total	1,422	100.00	

Notes: Pooled dataset. Observations are at plot (area planted) level.

Figure 3 shows farmers' choice of improved seed type by certification type and source. District markets are the main source of certified improved seeds. Only about 21% of the improved seed sourced at the district market are of unknown quality. This share rises slightly to 23% in local markets and to 36% if the source of the improved seed are neighbours or fellow farmers. Only about 14% of improved seed bought by neighbours or fellow farmers are certified. About half of the seed bought from neighbours are of quality declared certification type.

Figure 3: Farmer's choice of seed certification and source of improved seed



Notes: Pooled dataset. Number of observations: 823. Observations are at plot (area planted) level. The group "Neighbours" includes neighbours / relatives and/or fellow farmers.

The analysis of timing and frequency of improved seed adoption across four survey rounds reveals that less than 1% of the farmers in the sample adopt improved seed for all four main growing seasons. About 24% of the farmers report using improved seed for a single season.

Table 4 shows the transitional probabilities that a farmer switches to a new seed type in a given plot, from a main growing season to the next.

Table 4: Transitional probabilities of changing seed type

	Traditional	Improved	Total
Traditional	**85.4**	14.7	100
Improved	**45.4**	54.7	100
Total	72.3	27.7	100

Note: Table based on question: What type of seed did you purchase?

Looking at Table 4 we infer that about 85% of farmers planting traditional seed in a given plot will continue using such seed type in the next period, while only 15% of them will switch to improved seed in the next period. More than 45% of the sample that cultivated a plot with improved seed will switch to traditional seed in the next growing season.

In the next section we will present our estimation strategy.

3.2. Estimation strategy

We test the impacts of different farmers' choices on a measure of farm productivity (captured by the logarithm of crops output per acre) and on a measure of persistence of innovation (the number of years a farmer innovate). We analyse, in particular, three treatment choices made by the farmers:

i. Which agricultural technologies to adopt, if any. That is, whether farmers use only traditional seed or adopt improved seed, with or without fertilizers and/or pesticides;

ii. Where to buy improved seed;

iii. If improved seed are bought, for which type of certification, if any, to opt.

We conduct the empirical analysis with a treatment effect model in two stages. In the first stage, we estimate the determinants of the treatment choices through a multinomial logit model. In the second stage we look at how these choices affect farm productivity and the persistence of innovation.

In assessing these sets of decisions, we are concerned that there may be a self-selection process by which farmers belong to one decision group or another. Many factors can lead to a non-random selection of farmers. Because we are using non-experimental data we cannot rely on a Randomized Controlled Trial (RCT) approach, which is often identified as the best possible evaluation approach because it could eliminate selection bias (Imbens and Wooldridge, 2009). Instead, we use a treatment effect model, which is among the recommended approaches to address the challenge of establishing a counterfactual with non-experimental data. Furthermore, instead of the binary choice (e.g. simply adopt or not adopt a given agricultural technology) we look at the adoption decisions of the farmer in more detail. In the first set of choices, farmers can choose to adopt improved seed, or improved seed jointly with supplementary inputs such as fertilizers and/or pesticides. To capture this set of decisions, we construct a multinomial variable for the treatment choice, accounting for adoption of improved seed, improved seed with fertilizers, and improved seed with pesticides (with or without fertilizers).

The first set of treatment choices (TRT) are thus defined as follows:

$$TRT(1) = \begin{cases} 0 & if\ traditional\ seeds\ are\ used \\ 1 & if\ improved\ seeds\ are\ used\ without\ fertilizers/pesticides \\ 2 & if\ improved\ seeds\ are\ used\ with\ fertilizers \\ 3 & if\ improved\ seeds\ are\ used\ with\ pesticides\ (with\ or\ without\ fertilizers) \end{cases}$$

The impact of these treatment choices is tested on both the logarithm of output per acre. Our data analysis (Section 3.1) and previous literature (Bold et al., 2017) suggest the relevance of understanding farmers' decision regarding where to source their improved inputs. Notably, the source of the seed may correlate with the quality of the adopted technology. Bold et al., (2017), conclude that low quality inputs are rife in the local retail markets they surveyed. For this reason, we complement the analysis by constructing a separate treatment variable related to the source of improved seeds. In this specification farmers decide whether to purchase improve seeds from district markets, local markets, or obtain them from neighbours or fellow farmers.

The second set of treatment choices are thus defined as follows:

$$TRT(2) = \begin{cases} 0 & if\ traditional\ seeds\ are\ used \\ 1 & if\ improved\ seeds\ from\ local\ market\ are\ used \\ 2 & if\ improved\ seeds\ from\ district\ market\ are\ used \\ 3 & if\ improved\ seeds\ are\ from\ fellow\ farmers\ or\ neighbors \end{cases}$$

The impact of these treatment choices is tested on the logarithm of output per acre.

In the model, we construct counterfactuals of treatment, in order to correct for non-observed treatment effects on the non-treated, and non-treatment effects on the treated. We consider the case when all the variables that affect both treatment assignment and outcomes are observable by including control variables. In this case, we consider the outcome to be conditionally independent of the treatment.

Let $y_{i,\{0,1,2,3\}}$ denote the outcome (e.g., harvest output in kilograms per acre) of each plot depending on the treatment levels. d_i denotes the treatment choices of each plot. The treatment effect model estimates a set of conditional expectations (i.e., $E(y_{\{0,1,2,3\}}|d=0)$, $E(y_{\{0,1,2,3\}}|d=1)$, $E(y_{\{0,1,2,3\}}|d=2)$, and $E(y_{\{0,1,2,3\}}|d=3)$). Four of the conditional expectations are observable (i.e., $E(y_0|d=0)$, $E(y_1|d=1)$, $E(y_2|d=2)$, and $E(y_3|d=3)$) while the remaining expectations are not directly observable (i.e., $E(y_{\{1,2,3\}}|d=0)$, $E(y_{\{0,2,3\}}|d=1)$, $E(y_{\{0,1,3\}}|d=2)$, and $E(y_{\{0,1,2\}}|d=3)$).

The average treatment effect (ATE) is the average effect of treatment in the population:

$$ATE = \begin{cases} E(y_1 - y_o) \\ E(y_2 - y_o) \\ E(y_3 - y_o) \end{cases}$$

In order to estimate the average treatment effect, we construct models to estimate the outcome when improved seeds are used, and outcome when traditional seeds are used. Since the outcome variable logarithm of harvest output in kilogram per acre, is a continuous variable, we use a linear model for the outcome, by estimating the following models.

$$y_{\{0,1,2,3\}} = \boldsymbol{x}'\boldsymbol{\beta}_{\{\mathbf{0,1,2,3}\}} + \varepsilon_{\{0,1,2,3\}}$$

To estimate the treatment choice, we use a multinomial logit model, with the following specification where the latent variable is a logistic transformation of the multinomial treatment variable. The treatment assignment process is:

$$d = \begin{cases} 1 & if\ \boldsymbol{\Lambda}(\boldsymbol{w}'\boldsymbol{\gamma_1}) + \eta_1 > 0 \\ 2 & if\ \boldsymbol{\Lambda}(\boldsymbol{w}'\boldsymbol{\gamma_2}) + \eta_2 > 0 \\ 3 & if\ \boldsymbol{\Lambda}(\boldsymbol{w}'\boldsymbol{\gamma_3}) + \eta_3 > 0 \\ 0 & otherwise \end{cases}$$

$\boldsymbol{\Lambda}$ represents the logistic function and we define x as a vector of covariates that affect the outcome variable. These include variables related to information, market access, demographics, plot characteristics, and labour on plot, along with year fixed effects. W is a vector of covariates that affect the treatment assignment. Definitions for each variable included in this study and their descriptive statistics are presented in Table A1 and A2 in the Appendix.

Notably, $\boldsymbol{w}$ include variables related to information, market access, demographics, plot characteristics, and year fixed effects.

We make the conditional independence assumption by assuming that after conditioning on covariates, the potential outcomes are conditionally independent of the treatment. In the case of a binary treatment choice, the regularity conditions require that

$$E(\varepsilon_0, \varepsilon_1 | \boldsymbol{x}, \boldsymbol{w}) = 0$$
$$E(\eta_1 | \boldsymbol{x}, \boldsymbol{w}) = 0$$

The joint distribution of the error terms takes the following form.

$$\begin{pmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \eta \end{pmatrix} = N \left\{ \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} \sigma_0^2 & \rho_{01}\sigma_0\sigma_1 & \rho_{\eta 0}\sigma_0 \\ \rho_{01}\sigma_0\sigma_1 & \sigma_1^2 & \rho_{\eta 1}\sigma_1 \\ \rho_{\eta 0}\sigma_0 & \rho_{\eta 1}\sigma_1 & 1 \end{pmatrix} \right.$$

Conditional independence specifies that $\rho_{\eta 0} = \rho_{\eta 1} = 0$ which simplifies the joint distribution of the error terms. In this case unobserved shocks that affect the treatment does not affect the outcome, and unobserved shocks that affect the outcome does not affect the treatment.

$$\begin{pmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \eta \end{pmatrix} = N \left\{ \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} \sigma_0^2 & \rho_{01}\sigma_0\sigma_1 & 0 \\ \rho_{01}\sigma_0\sigma_1 & \sigma_1^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \right.$$

Furthermore, we specify the overlap assumption, where for each treatment level $\tilde{d}$, $0 < \Pr\left(d = \tilde{d} \middle| w\right) < 1$.

In order to account for the effect of a set of variables that determines selection into treatment groups, we use an inverted probability weighting approach to augment the effect of the counterfactuals. This approach incorporates a weighting scheme on the counterfactuals, by taking into consideration the probability of treatment selection based on a set of selection variables. Furthermore, to account for control variables of the outcome variable that may affect the treatment, we include a regression adjustment in the treatment effect model. Our outcome model or treatment model could be mis-specified. This "doubly robust" approach has been shown to be consistent as long as either the treatment model or the outcome model is correctly specified (Cattaneo, 2010).

We are also interested in evaluating whether treatment choices (in term of which technology bundles to adopt and from where to source the seeds) affect persistence of innovation in the household. We construct a second outcome variable representing years of innovation in the household, with values ranging from 0 to 4. Since this outcome variable is a count variable, we use a Poisson model for the outcome, instead of a linear model.

$$E(y_{\{0,1,2\}}|x) = \boldsymbol{e}^{\boldsymbol{\theta}'_{\{0,1,2\}}\boldsymbol{x}}$$

It has to be noted that to test the impact of treatment choices on the persistence of innovation, we restrict the dataset to improved seed. By doing this, we test the incremental effects of the use of improved seeds on persistence along with supplementary inputs such as mineral fertilizers. The treatment assignments for this second outcome variable are as follows.

$$d(1) = \begin{cases} 0 & if\ improved\ seeds\ are\ used\ without\ fertilizers/pesticides \\ 1 & if\ improved\ seeds\ are\ used\ with\ fertilizers \\ 2 & if\ improved\ seeds\ are\ used\ with\ pesticides \end{cases}$$

$$d(2) = \begin{cases} 0 & if\ improved\ seeds\ from\ local\ market\ are\ used \\ 1 & if\ improved\ seeds\ from\ district\ market\ are\ used \\ 2 & if\ improved\ seeds\ are\ from\ fellow\ farmers\ or\ neighbors \end{cases}$$

Finally, we look at the question of whether authenticity of the seed technologies is a key determinant in explaining average agricultural returns in Uganda (Bold et al., 2017). We expand this research question by testing the third treatment choice on the outcome variable "number of years of innovation." Our third treatment choice is:

$$d(3) = \begin{cases} 0 & if\ improved\ seeds\ with\ unknown\ quality\ are\ used \\ 1 & if\ improved\ seeds\ certified\ quality\ are\ used \\ 2 & if\ improved\ seeds\ with\ quality\ declared\ are\ used \end{cases}$$

4. Results

Table 5A shows the average treatment effect of the first set of treatment choices made by the farmers, that is, whether to use i. improved seeds used alone ii. improved seed with fertilizers, or iii. improved seed with pesticides, on our measure of farm productivity (the logarithm of harvest output per acre). Each of the treatments is compared with the use of traditional seed.

The results reported in Table 5A show that the use of improved seed alone enhanced the logarithm of crop output by 0.406 kilogram per acre compared to the output obtained from traditional seeds. This result is in line with Ahmed (2012) who suggests that the lack of improved maize varieties is one of the main reasons why Uganda is well below its production potential, given the cultivated area. Surprisingly, if improved seeds are used with fertilizers, this does not generate a statistically significant improvements in productivity. It should be noted that both an under or over use of inputs can reduce yields (Foster and Rosenzweig, 1995).

Table 5A: ATE improved seeds with alternative inputs bundles on ln(harvest output per acre)

Outcome variable: ln(harvest output per acre)	Coef.	
ATE		
Improved seed used alone	0.406***	(0.132)
Improved seed with fertilizers	0.364	(0.438)
Improved seed with pesticides	-0.636	(0.410)
Average output of traditional seed	3.006***	(0.048)
Outcome model controls		
Plot characteristics	Yes	
Labor in agriculture	Yes	
Market access	Yes	
Information	Yes	
Demographics	Yes	
Year fixed effect	Yes	
Number of observations	2,348	

Robust standard errors in parenthesis. *** p<0.01, ** p<0.05, * p<0.1

In Uganda the percentage of plots cultivated using jointly improved seed and mineral fertilizers is much lower than what has been reported in other Southern and Eastern African countries (Bozzola et al., 2018; Smale et al., 2015; Ogada et al., 2010; Marenya and Barrett, 2009). This suggests that Ugandan farmers, even those who are well-informed about modern production techniques, face significant barriers in accessing inputs, and that poor yields associated to the new technology may be related to non-optimal applications of complementary inputs.

The impact of adopting jointly improved seed with pesticides is also not statistically significant. This result is consistent with previous studies treating pesticides as damage control agents, rather than productive inputs such as land, fertilizers, seeds or water. Notably, pesticides are applied and managed to decrease the gap between potential and realized output rather than to raise the upper threshold for potential output (Lichtenberg and Zilberman, 1986).

Several factors are significant in predicting whether farmers choose to adopt traditional, improved seeds alone, or improved seeds jointly with fertilizers and/or pesticides (Table 5B).

Visits from the farmer to extension services emerge as a leading factor in adoption choices of improved technologies. In contrast, we do not find a significant effect from the number of visits of the extension services to the farm. This result supports the hypothesis that the farmers displaying a more proactive attitude towards information seeking are more likely to adopt improved seed.

Topography and soil quality are also important factors affecting the decision to adopt improved seeds and fertilizers. Previous findings have indicated that farmers tend to invest in soil conservation management on plots where the topography is steeper (Miheretu and Yimer, 2017; Asrat *et al.*, 2004; Wossen *et al.*, 2015). Our results seem to indicate that farmers are less likely to choose fertilizers or pesticides with improved seeds on plots less favourable because of steeper terrains.

Table 5B: Factors affecting the choice of improved seeds with alternative inputs bundles

	(1) Improved seed	(2) Improved seed with fertilizers	(3) Improved seed with pesticides
Information			
Number of visits from extension services	-0.018	0.032	0.082
	(0.036)	(0.068)	(0.066)
Number of visits to extension services	0.107***	0.148**	0.202***
	(0.032)	(0.064)	(0.058)
Market access			
Access to input market	-0.001	-0.030	1.088*
	(0.259)	(0.827)	(0.660)
Access to output market	0.286	0.219	-2.035***
	(0.279)	(0.911)	(0.421)
Demographics			
Gender	0.011	0.279	-0.686
	(0.143)	(0.334)	(0.501)
Household size	0.039**	0.065	0.047
	(0.020)	(0.040)	(0.049)
Education	0.169	0.613*	0.444
	(0.114)	(0.339)	(0.432)
Education squared	-0.007	-0.022	-0.015
	(0.007)	(0.018)	(0.024)
Age of household head	0.001	0.006	-0.014
	(0.004)	(0.009)	(0.013)
Plot characteristics			
Water source	0.661*	0.179	1.424
	(0.379)	(0.476)	(1.168)
Topography	-0.093	-0.545***	-0.655**
	(0.067)	(0.165)	(0.319)
Erosion	-0.128	1.283***	0.610
	(0.172)	(0.301)	(0.429)
Distance to home	0.111**	0.100	-0.171
	(0.052)	(0.114)	(0.134)
Plot size	-0.001	0.022	0.000
	(0.012)	(0.018)	(0.021)
Year fixed effects		Yes	
Number of Observations		2,348	

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.10

Table 6A shows that improved seeds purchased from a district market significantly enhance logarithm of harvest output with respect to traditional seed, while this effect is not statistically significant if seeds were purchased from local markets or from fellow farmers/neighbours. This result suggests that farmers who are willing or have the ability to travel longer distances obtain the best results in their fields in terms of output. The improved seed that are obtained when farmers travel to district markets are likely to be of a better quality and authenticity. However, we can expect that in such scenarios there is no, or a lower, learning externality in the system within the local markets. This finding is coherent with the theoretical framework presented in Section 2 applied to Ugandan agriculture, which is still characterized by low adoption.

Table 6A: ATE source of seeds on ln(harvest)

Outcome variable: ln(harvest output)	Coef.	
ATE		
Improved seed obtained from neighbour	-0.017	(0.718)
Improved seed obtained from local market	0.135	(0.214)
Improved seed obtained from district market	0.910**	(0.412)
Average output of traditional seeds	2.941***	(0.040)
Outcome model controls		
Plot characteristics	Yes	
Labor in agriculture	Yes	
Market access	Yes	
Information	Yes	
Demographics	Yes	
Year fixed effect	No	
Number of Observations	2,884	

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

When farmers make choices on where to acquire seeds (Table 6B), visit to the extension agents plays again a major role. Gender plays a role when deciding to travel far to district markets with women less likely to travel. Other studies looking at in East African countries found gender differences in accessing productive assets and inputs, which in turn affects average productivity levels of the two groups, with female producers generally obtaining lower agricultural yields (Covarrubias, 2015; Peterman *et al.*, 2014 and 2010; Quisumbing

1996). This finding has direct policy implications regarding the need to grant woman farmers better access to agricultural technologies, notably, Quisumbing (1996) shows that no significant differences in technical efficiency of male and female farmers are observed when differences in inputs are controlled.

Table 6B: Factors affecting the choice of markets for seeds

	(1) Neighbours	(2) Local Markets	(3) District Markets
Information			
Number of visits from extension services	-0.195	-0.025	0.050
	(0.129)	(0.056)	(0.047)
Number of visits to extension services	0.051	0.185***	0.175***
	(0.079)	(0.034)	(0.044)
Demographics			
Gender	0.353	-0.092	-0.731*
	(0.467)	(0.234)	(0.416)
Household size	-0.003	0.031	-0.006
	(0.075)	(0.027)	(0.036)
Education	0.308	0.028	-0.084
	(0.369)	(0.149)	(0.237)
Education squared	-0.018	-0.003	0.012
	(0.022)	(0.009)	(0.014)
Age of household head	-0.027**	0.010	0.005
	(0.014)	(0.007)	(0.009)
Plot characteristics			
Topography	-0.030	-0.064	0.117
	(0.245)	(0.100)	(0.150)
Erosion	0.237	0.077	0.157
	(0.587)	(0.231)	(0.390)
Distance to home	-0.299	0.054	0.044
	(0.251)	(0.089)	(0.128)
Plot size	0.030**	0.020	0.002
	(0.012)	(0.011)	(0.013)
Year fixed effects		No	
Number of Observations		2,884	

Notes: Robust standard errors in parenthesis. *** p<0.01, ** p<0.05, * p<0.1

Coherent with these result, we also find that farmers are more likely to innovate with more persistence (not to abandon the technology once adopted) when they adopt improved seeds in conjunction with fertilizers, while we do not find a statistically significant effect for join use of hybrids and pesticides (Table 7).

Table 7: ATE of fertilizers and pesticides on years of innovation

Outcome variable: years of adopting improved seeds within the household	Coef.	
ATE		
Improved seeds and fertilizers	0.429**	(0.199)
Improved seeds and pesticides	-0.109	(0.117)
Years of innovation using improved seeds only	1.629***	(0.046)
Outcome model controls		
Plot characteristics	Yes	
Labor in agriculture	Yes	
Market access	Yes	
Information	Yes	
Demographics	Yes	
Year fixed effect	Yes	
Number of Observations	542	

Notes: Robust standard errors in parenthesis. *** p<0.01, ** p<0.05, * p<0.1. Treatment model determinants omitted

Farmers show awareness that the type and authenticity of improved seed utilized might be a barrier to improved productivity, as the higher the probability that the inputs are not authentic, the lower is likely to be the adoption rates, a result found in Bold et al., 2017. Table 8 shows that our hypothesis is robust: farmers' relying on certified seeds (which are likely to be those willing to travel further as suggested by the statistics presented in Figure 3) are the innovators, less likely to drop adoption once they use once. We do not disentangle whether they use jointly fertilizers or not. Adopters of *quality declared* improved seeds also tend to continue adoption but the difference compared to "undeclared quality" is smaller, as expected.

Table 8: ATE of improved seed certification on years of innovation

Outcome variable: years of adopting improved seeds within the household	Coef.	
ATE		
Certified seeds	0.416***	(0.101)
Quality declared seeds	0.303***	(0.107)
Improved seeds of unknown quality	1.332***	(0.081)
Outcome model controls		
Plot characteristics	Yes	
Labor in agriculture	Yes	
Market access	Yes	
Information	Yes	
Demographics	Yes	
Year fixed effect	Yes	
Number of Observations	540	

Notes: Robust standard errors in parenthesis. *** p<0.01, ** p<0.05, * p<0.1. Treatment model determinants omitted

Several explanations might be offered for the result that traditional seed are not perceived to be inferior to modern ones: one reason is the problem of authenticity of seed, which supports the results in Bold *et al.,* (2017).

5. Conclusions, Policy Implications and Further Work

In this paper we show that in the case of Ugandan agriculture that the availability of improved seed and the implementation of seed policy reforms has not in itself been sufficient to provide the incentives needed to transform agricultural systems in the field.

Despite the implementation of seed policy reforms over the past 20 years, we uncover low productivity outcomes in the country. The implementation of "green revolution" strategies thus far has had limited success in Uganda, and there is little evidence that seed policy reforms have boosted agricultural productivity, a result also found in Dawson et al. (2016), Denning et al. (2009), Sserunkuuma (2005), and Evenson and Gollin, (2003).

Building on the work by Foster and Rosenzweig (1995) we presented a simple target-input model to conceptualize the adoption decisions and management of a new technology in which the optimal use of inputs under the new technology is unknown and stochastic. Within this framework, there is path dependency in the adoption process. Looking at a representative sample of Ugandan rural households, we found evidence of low adoption rates of improved seed, and of unfruitful experimentation with improved seed and complementary inputs in the local communities.

Theory indicates that substantial experimentation may be required in order to reach the productivity frontier with improved seed (by converging on the optimal combination of inputs). Our evidence indicates that experimenters have only achieved modest success in this initial stage, that the level of success when new technology is adopted is small and farmers often abandon the new technology after having adopted it for one growing season.

It is important to understand the socio-economic conditions of farmers who support innovation and embrace more productive agricultural practices, to encourage such groups to facilitate further adoption, and reduce barriers to adoption by other reference groups. We find evidences that a proactive attitude towards information seeking is a key characteristic of farmers who adopt improved seed. We also discuss the existence of important gender differences in terms of the accessibility of inputs.

The role of public policies in supporting experimentation is obvious and important. This research suggests that state and donors interventions in agricultural markets, while designed to enhance rural development and to correct existing market failures, must embrace a participatory approach and reinforce / support farmer-led research and information dissemination networks at local (informal) scale.

Appendix:

Table A1. Variables definition

Variable	Description
Logarithm of harvest output	Crop harvested in main growing season (kg) per acre of plot, transformed to non-zero, positive values, and applied logarithm
Years of innovation	Number of years the household uses improved seeds on any of their crop-plots. Ranges from 0 to 4 reflecting available of panel data
<u>Information</u>	
Number of visits from extension services	Number of times in the past 12 months someone from extension services (e.g., National Agricultural Advisory Services, input supplier, NGOs, cooperatives or farmer's associations, large scale farmers, etc.) visited any of the household's plots
Number of visits to extension services	Number of times in the past 12 months someone from the household visited any of the extension services (e.g., National Agricultural Advisory Services, input supplier, NGOs, cooperatives or farmer's associations, large scale farmers, etc.)
<u>Market Access</u>	
Agriculture input market	Whether a market selling agricultural inputs is available in the community: 0 = no, 1 = yes
Agriculture produce market	Whether a market selling agricultural produce is available in the community: 0 = no, 1 = yes
<u>Demographic</u>	
Age of household head description	Age of the household head in years at the time of survey
Gender of household head	1 = male, 2 = female
Highest level of education in household	Highest level of education achieved in the household: 0 = did not complete P1; 1 to 7 = P1 to P7 and post-primary specialized training; 8 to 13 = S1 to S6, including J1 to J3 and post-secondary specialized training; 14 = secondary education and above
Square term	Highest level of equation in the household, squared

of education	
Household size	Number of individuals within the household from household roster in each year
Plot characteristics	
Distance from plot to home	Travel time from homestead to this plot: 1 = less than 15 min; 2 = 15 to 30 min; 3 = 30 to 60 min; 4 = 1 to 2 hours; 5 = over 2 hours
Size of the plot	Size of the plot in acres taken from GPS. Farmer's estimation is used when GPS is not available
Source of water	Main water source to this plot: 1 = irrigated; 2 = rain-fed; 3 = swamp/wetland
Topography	Topography of this plot: 1 = flat; 2 = gentle slope; 3 = hilly; 4 = valley; 5 = steep slope
Erosion	Problems with erosion on this plot during the last completed season: 0 = no, 1 = yes
Labour	
Percent of household hours on agriculture	Percent of hours that the household spends on agriculture among other non-market activities over the last 7 days. Non-market activities include household activities such as collecting firewood, fetching water, constructing dwelling or farm, repairs, milling, handcrafts, and hunting or fishing.

Table A2. Summary statistics

VARIABLES	(1) N	(2) Mean	(3) SD	(4) Min	(5) Max
Outcome					
log of harvest (kg)	6,561	2.911	2.094	0	10.268
Treatment					
Seed choice with fertilizers/pesticides	8,186	0.224	0.549	0	3
Seed choice and certification	8,173	0.317	0.758	0	3
Seed choice and source of seeds	7,527	0.168	0.554	0	3
Controls					
Information					
Number of visits from extension services	6,252	0.497	1.692	0	18
Number of visits to extension services	6,246	0.634	1.909	0	17
Market access					
Agriculture input market	5,911	0.915	0.278	0	1
Agriculture produce market	5,911	0.922	0.268	0	1
Demographics					
Age of household head	7,994	46.035	14.314	14	102
Gender of household head	7,994	1.276	0.447	1	2
Education of household head	7,178	7.006	3.150	0	14
Education of household head (square)	7,178	59.014	48.779	0	196
Household size (quartiles)	7,994	2.316	1.120	1	4
Plot characteristics					
Distance from plot to home (categories)	8,143	1.813	1.147	1	5
Size of the plot	8,141	2.870	14.790	1	676
Source of water	8,134	2.001	0.172	1	3
Topography	8,132	1.676	0.940	1	5
Erosion (1=yes, 0=no)	8,126	0.211	0.408	0	1
Labour					
Percent of household hours on agriculture	5,726	0.560	0.245	0.012	1

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Notes

[1] Agricultural Seed and Plant Act (Cap. 28), 1994, also known as Seed and Plant Varieties Regulations, Plant Variety Release (PVR) laws or Plant Protection Act of Uganda, reviewed in 2006 under the name of Seed and Plant Act, 2006 (N. 3 of 2007).

[2] According to the standard definition used within the LSMS-ISA project *local seeds* are defined as seeds obtained locally and normally of local varieties. They can be own seeds or obtained e.g., from neighbours. They arethe most commonly sown/planted in Uganda,.

[3] Under the Plant Protection Act of Uganda (1994), "certified seed" means a class of seed produced under a certification programme that is usually produced from registered seed.

[4] Following Foster and Rosenzweig (1995) we refer to optimal input use as the combination of inputs that maximizes expected discounted profits. In the empirical application, we use, more simply but coherently with previous literature, agricultural yields. These are expressed as the logarithm of harvested output per acre for five selected crops.

[5] See Foster and Rosenzweig (1995) for a discussion of the implications of this assumption.

[6] Refer to Foster and Rosenzweig (1995) for a discussion on the restrictions on the profit effects of experience implied by this learning technology and for an extension to the case where Bayesian learning is applied to the case of a village-level shock to the optimal target each year.

[7] This dataset was implemented by the Ugandan Bureau of Statistics (UBOS) (www.ubos.org) as part of the World Bank Integrated Surveys on Agriculture project. For more detail regarding the survey, see: http://go.worldbank.org/D3ZAKU07K0.

[8] *Certified seed* is a legal term referring to government certification by the relevant authority. Certified seed is defined by the Plant Protection Act of Uganda (1994) as a class of seed produced under a certification programme that is usually produced from registered seed. *Declared quality* seed (QDS) indicates a class of seeds that requires minimum field inspection and certification standards for purity and germination, according to the QDS System, presented by FAO in 1993 and revised in 2006. The Ugandan legislations mentions for the first time QDS in the draft National Seed Policy of 2014. QDS are not yet considered part of the formal and regulated Ugandan seed sector. *Unknown quality* seed indicates seed that is known to be of an improved nature but without any further information on its provenance or character. Local seeds are seeds obtained locally and normally of local varieties. They can be own seeds or obtained e.g., from neighbours.