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TRANSFER OF IMPROVED VARIETIES IN INFORMAL MARKETS AND THE DIFFUSION OF EMBEDDED INNOVATION: EXPERIMENTATION WITH GENETIC RESOURCES IN UGANDA

Martina BOZZOLA, Tim SWANSON, Helena TING

Transfer of Improved Varieties in Informal Markets and the Diffusion of Embedded Innovation: Experimentation with Genetic Resources in Uganda

Bozzola Martina[1], Tim Swanson[2], Helena Ting[3]

Abstract

We look at the diffusion of seed technology among Ugandan farmers. We present a target-input model to conceptualize the adoption decisions of a new technology in which the best use of inputs is unknown. In this framework, there is path dependency in the adoption process. We show that the group of innovators is well-defined but too small to overcome the system's inertia. We find little evidence that seed policy reforms implemented in Uganda in the past 20 years boosted agricultural productivity, largely on account of a lack of local experimentation and inadequate use and diffusion of new seed varieties.

Keywords: Improved Seed, Seed Policy Reforms, Peer Effects, Uganda

JEL Codes: D10, O33, O34, Q12

[1] Corresponding Author. Research Fellow, AECP Group, ETH, Zurich (CH) mbozzola@ethz.ch

[2] Professor of Economics, Graduate Institute (IHEID), Geneva (CH) tim.swanson@graduateinstitute.ch

[3] Research Assistant, Centre for International Environmental Studies, Graduate Institute (IHEID), Geneva (CH) helena.ting@graduateinstitute.ch

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1. Introduction: no innovation without experimentation.

This study looks at the ways in which rural households in Uganda select and experiment with improved seed in their planting and production decision-making, under a regulatory system that allows for different types of legal protection to be in place simultaneously. We are interested in the diffusion of seed technology among rural Uganda farmers, who have access to improved seed either through their familial or community social networks, or through formal markets (for example, private or government traders). In addition, we are interested in the characteristics of those who might be first adopters in improved seed and the paths in which information are transmitted throughout the community.

Since Uganda's membership in the World Trade Organization (WTO),[1] there are at least two distinct legal systems in place regulating seed sales and plant breeding in that country: a) TRIPS 27(3)b, providing for plant variety protection for all nationally registered plants and seed varieties under international law;[2] and b) national laws enshrining the right of farmers to make use of seed and plants legally released on the national market (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 (No. 3 of 2007)).[3] With little modifications over the previous legislation, the 2006 Act establishes the National Seed Board under the Ministry of agriculture and provides for the control (variety testing, release and registration) of the placing on the market in Uganda of propagative material, plants and parts of plants intended for the propagation and multiplication of a variety. The Board may grant breeders rights for a variety of seed. The 2006 Act also establishes the National Variety Release Committee and the National Seed Certification Service. The first reviews and maintains the National Variety List. The second is responsible for reviewing, adjusting, maintaining and enforcing seed standards. The Act also defines offences relating to the placing of seed on the market.

During the latter part of the last decade, there has been much discussion concerning the potential conflicts between these two legal regimes, but both have existed simultaneously throughout this time.[4]

There is growing interest among public policy-makers, corporate decision-makers and other actors in the agricultural sector in the topic of seed market and intellectual property rights' (IPRs) policies. However, it is not clear to what extent emerging and evolving seed policy reforms and IPR regimes in developing countries are contributing to increasing crop productivity, improving food security and reducing market imperfections. Some authors have found in aggregate that IPR does in fact reduce yield-gaps across most crops, although results are variable by crop, by region, and even by time-period analysed (Spielman and Ma, 2016; Swanson and Goeschl, 2015). Clearly, modern varieties are making a major contribution to ongoing productivity gains, even though the role of intellectual property itself is less well understood (O'Gorman and Pandey, 2010).[5] Our goal is to examine in closer detail how institutions matter in shaping the flow of traits within a particular context. Why do local conditions matter in the global flow of value from an informational resource, such as the traits in modern agriculture? This is a crucial issue for purposes of seed diffusion and technology adoption in the agricultural sector in developing countries. 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; Pray and Nagarajan, 2009) and that seed policy reforms enhancing intellectual property rights have triggered an expansion of the seed industry. These positive consequences of seed reforms have often been explained by the fact that such reforms reduce the likelihood of firms losing proprietary control over their seed when releasing new seed material (Pray et al., 2001; Pray and Ramaswami, 2001; Kolady et al., 2012). In general, these studies have found a positive influence of seed policy reform on private investment in seed R&D but few studies have linked this positive investment to actual improvements in productivity. However, findings tend to be country and crop specific, and depend significantly on (a) the methods used to test these hypothetical relationships and (b) the type and quality of the data (Kolady et al., 2012).

Ainembabazi and Mugisha, (2014) provide specific evidence on the case study we wish to examine, that is, the adoption of agricultural technologies in rural Uganda. This study found that adoption of modern varieties follows a U-shaped pattern in which adoption and experience are related. The authors argue for increasing the experiential or knowledge base of farmers (through advancing extension services and training, for example), in order to encourage adoptions. We agree with the outcome of this study, but focus on an issue that remains unexamined within it: how do local institutions deal with incoming technologies in order to consider and evaluate them for possible adoption? We consider how local institutions develop to deal with widely considered problems. In this regard, our study is most closely related to an expanding area of recent work that examines how social networks and local groupings function to enable technology adoption in agriculture. See, for example, Liverpool-Tasie et al., 2012. We are interested in the question of how existing local and traditional Ugandan institutions might endogenously arise in order to provide this experiential and knowledge base to encourage adoptions, rather than how it might be generated externally.

There are many reasons why traits incorporated into plants at the highest level of R&D might not make it into local production systems in Africa. One possibility is that the traits do not fit well with local conditions (*efficiency*). Another possibility is that the information on the traits does not diffuse far down the lines of production (*information*). A third possibility is simply the inertia of existing systems: the tendency of local producers to rely on technologies they know and have experience with (*experimentation*).

Local institutions are not straightforward to analyse, but they may be important parts of the mechanism for adoption and transfer of innovation. From the laboratory to the market, improved seeds travel through fragmented distribution networks, and these networks tend to become increasingly complex and opaque as they arrive at local villages. Therefore, seed policy reforms that focus on upstream activities of research and development may or may not lead to positive productivity results at the farm level, depending on whether the traits contained in the improved seed are actually spread within the local production system.

In this study, we do an informal analysis of data from Uganda, from surveys conducted in 2009-2010, 2010-2011 and 2011-2012, to look at how households select and make use of improved seed in their production and plant-breeding decisions, considering that in this time period Ugandan farmers operated under at least two distinct legal systems regulating seed sales and plant breeding. We wish to explore how the legal systems interacted with the production systems to address the problems of diffusion indicated above.

The Plant Protection Act of Uganda (1994), as revised in 2006, provides that it 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*".[6] The economic literature suggests that the degree to which these objectives can be achieved depends on social interactions: social learning processes and the role of peer effects in the diffusion of new technologies.[7]

This study focuses on the role of innovators and their experimentation in the incorporation of useful traits into a local production system.[8] It does so by considering how individual farmers and households have made use of certified varieties in their breeding and production decisions.[9] The aim is to understand who imported traits into their own production, and how these non-local traits performed relative to other seeds within the production system. We explore the way that experimentation generates information within the local community, and whether incentives exist to diffuse for that information to others. In short, what role does the phenomenon of local experimentation play in the advancement and diffusion of innovation?

2. Conceptual Framework

We present a simple model to conceptualize the adoption decisions and management of a new technology (for example, improved seed varieties) in which the best use of inputs under the new technology is unknown and stochastic. We follow closely the modified target-input model proposed by the seminal paper of Foster and Rosenzweig (1995), emphasising how this model applies in our context. Optimal input use is central to farmers' concerns in an environment subject to technological change, and there appears to be some suggestive evidence of learning about the best use of inputs from others (Foster and Rosenzweig, 1995). This model is also well suited to describe situations where farmers rely on peers or more formal public information dissemination to learn about inputs use, rather than just learning on profitability of adoption of a new technology.

The optimal use of each plot *i* planted using the improved seed varieties by farmer j in each period t is:

$$\tilde{\theta}_{ijt} = \theta^* + u_{ijt} \quad (1)$$

θ^* is defined as the mean optimal use of inputs and $u_{ijt} \sim N(i.i.d)$ with variance σ_u^2, which is assumed known by the farmers. Farmers have also priors over θ^* that are $N(\hat{\theta}_{j0}, \sigma_{\theta j0}^2)$. Yields per plot using traditional seed varieties are known, and indicated as η_a. Farmers adopting hybrid seed for the first time face several uncertainties regarding the use of this new technology, as well as regarding the optimal use of complement inputs, such as fertilizer. For this reason yields per plot using improved seed are unknown at the beginning of the growing season. While the use of traditional seed varieties does not require the joint application of mineral fertilizer, hybrid seeds are usually adopted together with mineral fertilizers. This enhances uncertainties regarding the optimal use of inputs when the new agricultural technology is adopted (Bozzola et al., 2016, Sheahan, 2011; Ogada et al., 2010; Marenya and Barrett, 2009).[10]

Given A_j 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:

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

Where η_{ah} is the loss associated with using less suitable plots as the share of land cultivated with improved seed varieties increases. In target input models the profitability of a new technology, such as hybrid seed grows over time because of knowledge accumulation.[11]

Adopting improved seed varieties involves the cost of experimentation with new seed types and their complementary inputs. Farmers need to use the right amount of complementary inputs, such as fertilizers, to get the most benefit from adopting improved seed varieties.

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

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

Where E_t (ε_{pjt})=0 and p is the input price. μ_j captures land productivity variation within farmers. $\sigma^2_{\theta jt}$ is the variance of farmers' j posterior distribution over θ^*_j at time t. 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 variety ($\tilde{\theta}_{ijt}$) becomes known, and each farmer *j* update his priors regarding the expected optimal input use θ^*. We assume that shocks are independent across space.[12] If the farmer observes not only his yields, but also his neighbours' plot-specific input used on plots planted with the new technology (seed), then the signal precision for the farmer that year will also depend on the share of land neighbours allocated to improved seed varieties (Foster and Rosenweig, 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 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 neighbours, and $\mathrm{n}/(\sigma^2_{u} + \sigma^2_{k})$ is the precision of information obtained from an increase in the average of the cumulative experience of the farmer j's neighbours $(\bar{S}_{-jt})$.[13]

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.

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

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

Foster and Rosenweig, 1995 indicate as S_{-jx} the vector of experience for other farmers in village j and write:

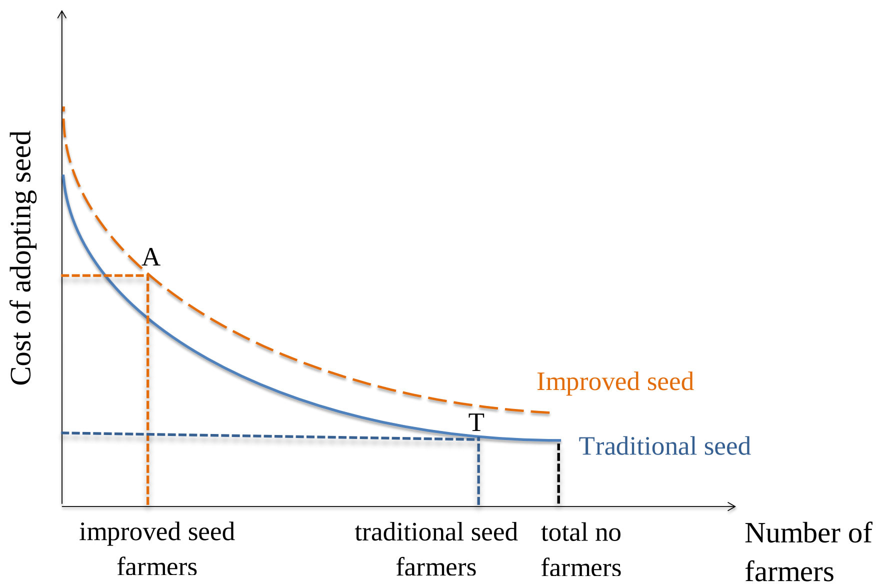
$$V_{jt} = \max_{H_j} \mathrm{E}\left[\left(\eta_h - \eta_{ah}\frac{H_{jt}}{2A_j} - \sigma^2_u - \frac{1}{(1/\,\sigma^2_{\theta 0}) + (1/\,\sigma^2_{u})\, S_{jt} + [\mathrm{n}/\,(\sigma^2_{u} + \sigma^2_{k})]\, \bar{S}_{-jt}}\right) H_{jt} + \eta_a A_j + \mu_j + \varepsilon_{pjt}\right] + \phi V_{jt+1} \qquad (6)$$

The last two equations show that the decision made by each farmer depends on his neighbours' past planting decisions, and his own expectations about future planting decisions.[14]

The model indicates that there is an important form of inertia controlling the shift from the old technology to the improved technology. Only when farmers learn enough to converge upon the optimal combination of inputs do improved seeds perform much better than traditional seeds (and hence provide a signal that efficiency lies in that direction). By contrast, farmers have substantial knowledge and experience concerning the optimal use of traditional seeds, given a long history of prior use. This means that a low level of adoption and experimentation may be insufficient to provide any signal leading to more widespread adoption. A substantial amount of *experimentation* is important to move the new technology toward the productive frontier in the new environment. Widespread *adoption* is critical to diffuse the information on the new technology's use and efficiency across the community.

This means that, if most of the farmers in an area have already adopted improved seed, neighbouring farmers are then able to see the results of the earlier experimentation with the technology, and learn from those successes and mistakes. On the other hand, if no one has chosen improved seed yet, early adopters need to carry out several rounds of experimentation to learn the optimal combination of inputs. Figure 1 illustrates the potential for inertia within such a system, by presenting the costs of adoption of improved and traditional seed as a function of the number of farmers using them.

Figure 1: Cost of seed adoption in the presence of learning externalities



The cost functions are drawn so that the cost of adopting traditional seed is always lower than the cost of adopting improved seed, for a given number of farmers.[15] The simple model described in Figure 1 has two equilibria: one in which everyone is using traditional seed varieties (we can assume with low levels of production) and the other where everyone has adopted the improved seed (with higher productivity levels). However, starting from an existing pool of traditional farmers (for example at point T), the improved seed are not adopted. Historically, only traditional seeds were available so many farmers have already chosen them. We draw Figure 1 so that the share of adopters and non-adopters over the total number of cultivated plots is a reasonable representation of the shares in our sample, where about 86% of plots are cultivated with traditional seed varieties and only the remaining 14% with improved seed (see Section 3.1). Since most of the farmers are using the old varieties, the cost of adopting a traditional crop is lower (point T) than the cost of learning about the best growing conditions for improved seed (point A). A new farmer who is deciding on what to cultivate next year will choose to go with the old seed varieties. This results in inertia in the use of traditional seed (or slow take-up if we change this basic model to allow for some heterogeneity among farmers). In this framework, history plays a key role in the process of adopting a new technology. We have path dependency and it matters what initial endowment and practices a rural community possesses. Sufficient investments in experimentation and diffusion are required to overcome this inertia.

It is this friction against switching between the two seed "systems" that concerns proponents of technological change in more traditional agricultural communities. The existence of such R&D system inertia can prevent the rapid movement toward the more optimal production system. We focus here on the role of certain individuals within such a system as the experimenters/innovators who perform the initial function of acquiring new traits, and attempting to move them into new locales. Who are they? How do they operate? What hurdles do they have to overcome in order to move the production system toward efficiency? We are also interested in whether the experimentation undertaken by these innovators is adequate to move the local production toward efficiency. Does local experimentation provide information and incentives for widespread adoptions of the new seed?

Therefore, in this study we are interested in identifying how individual types of farmers engage in the experimentation and innovation required to incorporate new information into a local production system, and thus the role of such farmers in incorporating and diffusing information between the modern system and the traditional one. The better these individual innovators operate in moving information between systems, the less a multiplicity of systems matters. The less efficient these innovators are, the more this pluralism produces friction. The presence of learning externalities also provides a justification for policy intervention. For example, if the government gives a temporary subsidy for adoption of improved seed, or approves laws supporting property rights for innovators, then we might move from the old variety equilibrium to the improved seed equilibrium. In the next section, we explore both the nature of such experimenters within the production system, as well as its capacity to move it in the direction of more modern, efficient seed technologies.

3. An Informal Application to the Ugandan Seed Market

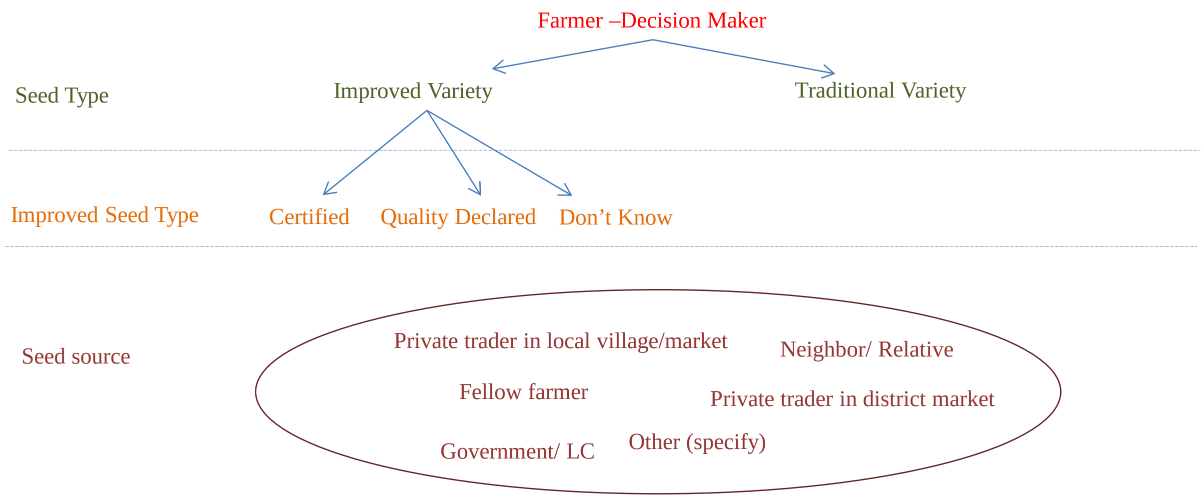
3.1. Adoption Decisions

In this section we present an informal analysis of the Uganda data regarding the patterns of seed purchase by the farmers in our sample. This analysis sheds lights on some underlying characteristics of the access to improved seed varieties. We use data for rural agricultural households from the 2009/10, 2010/11 and 2011/12 waves of the Uganda National Panel Survey (UNPS).[16] The UNPS includes a nationally representative sample of households.

The dataset collects information at plot level regarding the type of seed used (improved versus traditional varieties) whether the seed was bought or retained from previous growing seasons, the type of hybrid seed used (certified, quality declared or unknown) and the source of seed.[17] Most of the existing literature shows the importance of social learning after a new technology has been adopted (Conley and Udry, 2010; Bandiera and Rasul 2006; Munshi, 2004; Besley and Case, 1994; Foster and Rosenzweig, 1995). However, as our conceptual framework suggests (Section 2), when thinking about the decision of a farmer to adopt a new technology, it is important to consider whether the individual in question is the first in his cohort to adopt such a technology. These are the experimenters who are so important to the translocation of new traits to other production systems. It is also interesting to know whether the adopter continues to use the new technology in the next growing season or whether he/she switches back to the traditional one. That is, does the innovator continue to invest in experimentation, or simply assess the characteristics in a single trial? Experimentation of course has its costs, and so these indicators of commitment to innovation (the risk of bringing in new traits, the commitment to multiple years of experimentation) are indicators of a class of individuals who are investing heavily in the enterprise of innovation (in addition to production).

Figure 2 shows the decision set concerning input use for the farm families in our sample:

Figure 2: Farm family decision set: seed inputs



Farmers in our sample were asked if they *purchased* the seed for a given crop planted in a plot. Farmers declared buying seed for only about 28% of the plots in our sample. Farmers tend to save seed from previous cropping seasons, and the share of purchased seed is low, varying from 23% of the plots cultivated with hybrid seed in 2010 to 34% in 2011 (it was 30% in 2009). Furthermore, *improved* seed varieties were used in only 14% of the plots.[18]

For those plots where seed were purchased, we analyse the purchasing rates by seed type, separating i. traditional, ii. improved and iii. undeclared seed type.

When farmers use an *improved* seed variety, they normally buy it (83% of the instances in our sample). Only in about 17% of the cases farmers rely on *improved* seed varieties that have *not* been bought. These statistics might suggest that farmers adopting improved seed are relying on private traders and markets instead of family or fellow farmers' networks. This insight is confirmed from the data shown in Table 1. Notably, the district markets are used more as a source for the importation of new traits by a small contingent of farmers, while the locality (local market, local farmers) is used for the diffusion of traits by the vast majority of farmers. The fact that district markets are used to provide twice the proportion of improved seed than of traditional seed is indicative of the function of these larger markets in supplying more modern technologies. The local market supplies 63% of traditional seed but less than 50% of improved seed, demonstrating that the local market more often than not serves to reinforce the use of traditional seed varieties between local farmers.

Table 1: Bought seed - seed source by seed type

Traditional Seed		**Improved Seed**	
	% of responses		% of responses
Private trader in local village/market	63.07	Private trader in local village/market	48.55
Fellow farmer	20.52	Private trader in district market	26.38
Private trader in district market	13.08	Fellow farmer	16.40
Neighbour / Relative	1.76	Other	4.72
Government / LC	0.97	Government / LC	3.12
Other	0.60	Neighbour / Relative	0.80
N=5,162		N=1,123	

Table based on question: Where did you buy most of this seed?

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

The PVR laws (1994) established an authority known as the *National Seed Certification Service*, responsible for the design, establishment and enforcement of certification standards, methods and procedures. In 1993 the Parliament also established the National Agricultural Research Organization (NARO), to coordinate public agricultural research and development activities in all aspects of crops, fisheries, forestry, and livestock. NARO is the leading public organization responsible for research and development in the seed market. It is responsible to run the national research program, which is the main source of new crop varieties. NARO competes directly with national and international private seeds companies in developing new varieties. However, the adoption of *certified* improved seed remains relatively low, comprising only one third of our sample (Table 2). The improved seed are mostly of *declared quality*, without formal certification. The low uptake of *improved seed varieties* might be related, among other adoptions barriers, to some strict conditions imposed under the Agricultural Seed and Plant Act, for example the provisions related to *plant breeding and registration of breeders*; *on multiplication and licensing* and on *seed marketing*.[19] Furthermore, in their 2006 study, Eaton et al., find that in Uganda public plant breeding had not yet resulted in a widespread use of public varieties by farmers, and because it concentrated on open-pollinated varieties (OPVs), it had not contributed to the nascent seed industry. The authors also highlight that at the time of their study the private sector was still insignificant in terms of breeding (Eaton et al., 2006). Similarly, Ahmed (2012) 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.[20]

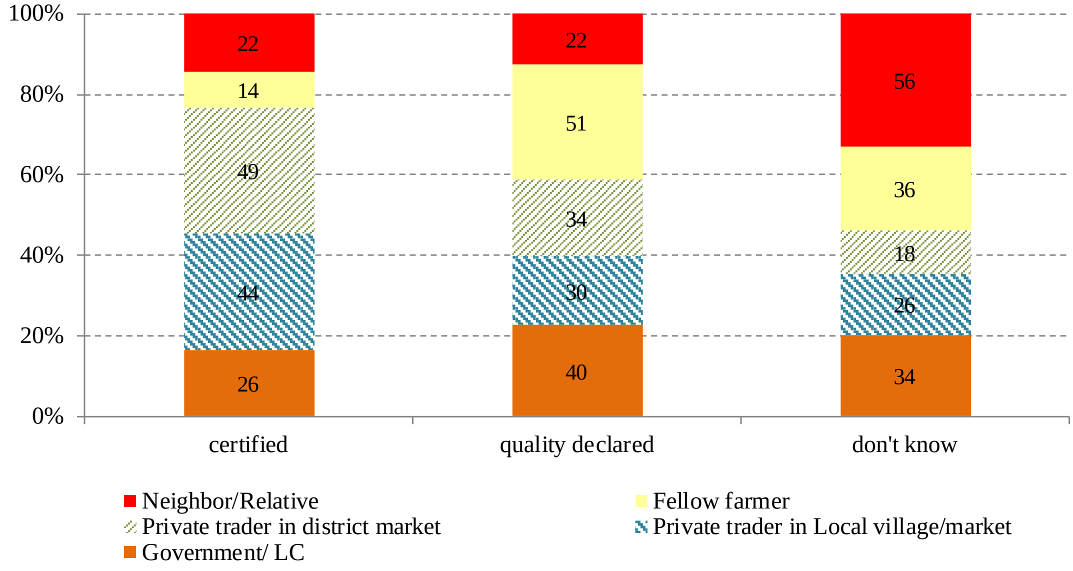
In about 24% of the answers provided in our sample, farmers declare a lack of knowledge regarding what type of improved seed they used in a given plot. These statistics highlight that poor information and awareness regarding the type and authenticity of improved seed utilized might still be a barrier to adoption, 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., 2015.

Table 2: Improved seed by type

	Frequency	%	Cumulated
Quality Declared	804	43.06	43.06
Certified	622	33.32	76.38
Don't Know	441	23.62	100.00
Total	1,867	100.00	

Figure 3 presents farmers' responses regarding the *type* of *improved* seed they adopt, disaggregated by seed's source. This figure reveals some interesting patterns. Farmers access *certified* improved seed mostly through traders in district (48.7%) or local (44.3%) markets. When farm families access improved seed through fellow farmers these are mainly (50.6%) of *quality declared* (with no formal certification) or even *unknown quality* (36%). The latter figure is even higher (55.6%) when the fellow farmer owns contiguous land or is a family member. In only 14% of the instances when improved seed were obtained through fellow farmers, the seed were certified.

Figure 3: Improved Seed type by seed source (percentage)



According to the Uganda Bureau of Statistics (2014) Ugandan farmers grow about 16 major crops. These include cereals (maize, millet, sorghum, rice); root crops (cassava, sweet potatoes, irish potatoes); pulses (beans, cow peas, field peas, pigeon peas); oil crops (groundnuts, soya beans, sim sim); plantains and coffee. Maize is the main crop for which farmers use improved seed varieties in our representative sample of Ugandan farmers. This crop is not only the crop with the highest number of plots cultivated with improved seed varieties, but it is also the most important crop in terms of household income and one of the most important crops for food security.[21] 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 more than 1.1 million ha (about 23% of the total crop area, and 63% of cereals area), the total production was 2,748,000 tons (UBOS, 2014).[22] The other main crops for which farmers use improved seed varieties in our sample are cassava, beans, groundnuts, and cotton. Together these five crops account for over 70% of the plots in our dataset cultivated using hybrid seed.

The analysis of timing and frequency of improved seed adoption in the three years under analysis reveals that less than 0.2% of the farmers in the sample adopt improved seed varieties for three consecutive years, while 1.5% of the farmers in the sample adopted improved varieties twice in the years under study. About 10% of the farmers reported using improved seed for a single season. The vast majority of the sample (more than 88% of respondents) only used traditional varieties in the years under observation.[23] Thus, the more traditional seed sector still contributes over 80% of the seed within the local production system (Lwakuba, 2012).[24] The proportion of farmers who may be termed "experimenters" is very low indeed, less than 2% of the sample.

Table 3 shows the transitional probability that a farmer switches to a new seed type in a given plot, from a main growing season to the next.

Table 3: Transitional probabilities of changing seed type

	Traditional	Improved	Total
Traditional	**90.48**	9.52	100
Improved	**50.27**	49.73	100
Total	82.20	17.80	100

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

From the data presented in Table 3 we infer that 90.5% of farmers growing traditional varieties in a given plot will continue using such seed type in the next period. However, about 9.5% of farmers will adopt improved seed varieties in the next period. About half of the sample that cultivated a plot with improved seed will switch to traditional seed in the next growing seasons. This is indicative of a lack of commitment to experimentation, perhaps because of the increased costliness that more than one season of experimentation may imply. In any event, it is clear that experimentation is occurring at a low level (about 1% of farmers) and without a significant amount of commitment (50% for one year only).

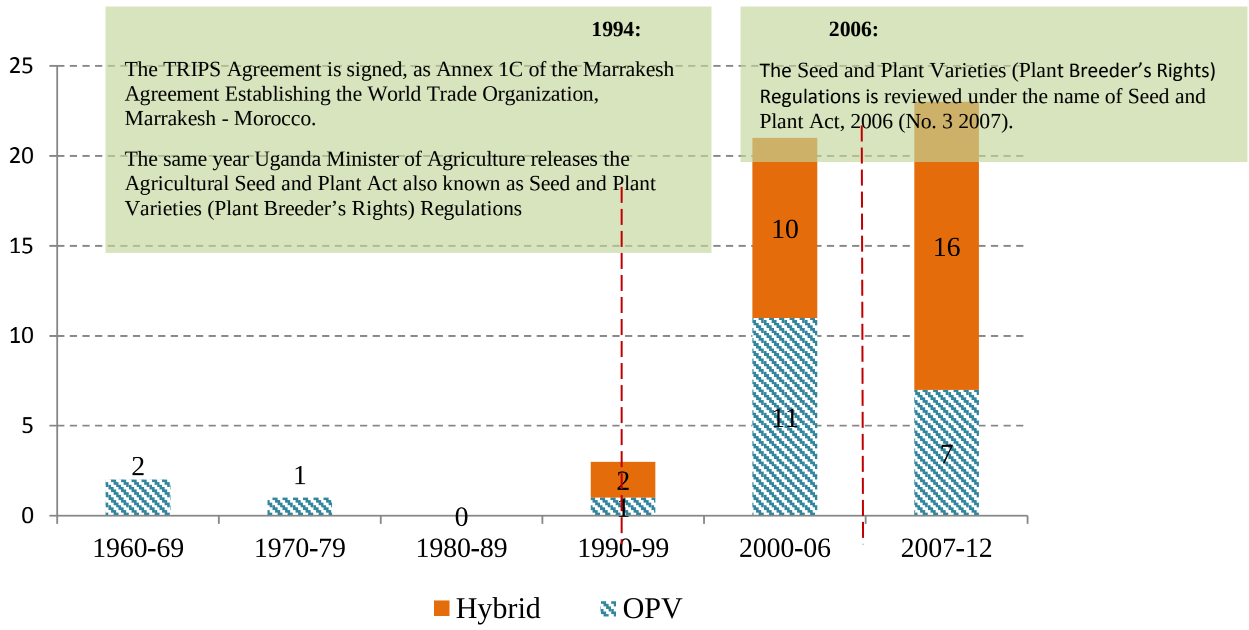
It is interesting to note that farmers relying on improved seed types which are certified or of *quality declared* will very seldom (in less than 9% of cases) agree to buy improved seed of unknown type in the following growing seasons (Table 4). However, most of the farmers who rely on improved seed of unknown type in a growing season will move to seed of declared quality in the next growing season (53.3%), which indicates that farmers might invest time and resources in accessing better information for their improved seed input, and felt unsatisfied by improved seed of unknown type. This might confirm results in Joughin, 2014 who refers to high reporting of seed counterfeiting by Ugandan farmers and in Bold et al., 2015 who finds that hybrid maize seed purchased in local Ugandan markets contains less than 50% authentic seed, and that such low quality results in negative average returns, which in turn might hinder adoption rates.

Table 4: Transitional probabilities of changing type of *improved* seed

	Certified	Quality declared	Don't Know	Total
Certified	**60.00**	32.00	8.00	100
Quality declared	26.92	**65.38**	7.69	100
Don't Know	20.00	**53.33**	26.67	100
Total	43.96	45.05	10.99	100

Although the Seed and Plant Act had the noble intent of enshrining the right of farmers to make use of seed and plants legally released on the national market, more than 20 years after its adoption, these statistics hint at the existence of substantial market failures across Uganda in the access and use of *certified* improved seed varieties. Farm level data seems to confirm this finding despite some evidence that since 2000 the number of maize open pollinated maize varieties (OPV) and hybrids released in Uganda have increased (Figure 4). Notably, the *National Agricultural Research System* in Uganda released 50 maize varieties from 1960 to 2012, including 28 hybrids and 22 OPV. The speed of introduction accelerated quickly after 1999, six years after the TRIPS Agreement and the release of the Seed and Plant Varieties Regulations.[25]

Figure 4: Number of open pollinated maize varieties and hybrids released in Uganda



Source: Drought Tolerant Maize for Africa (DTMA) Project and authors elaboration

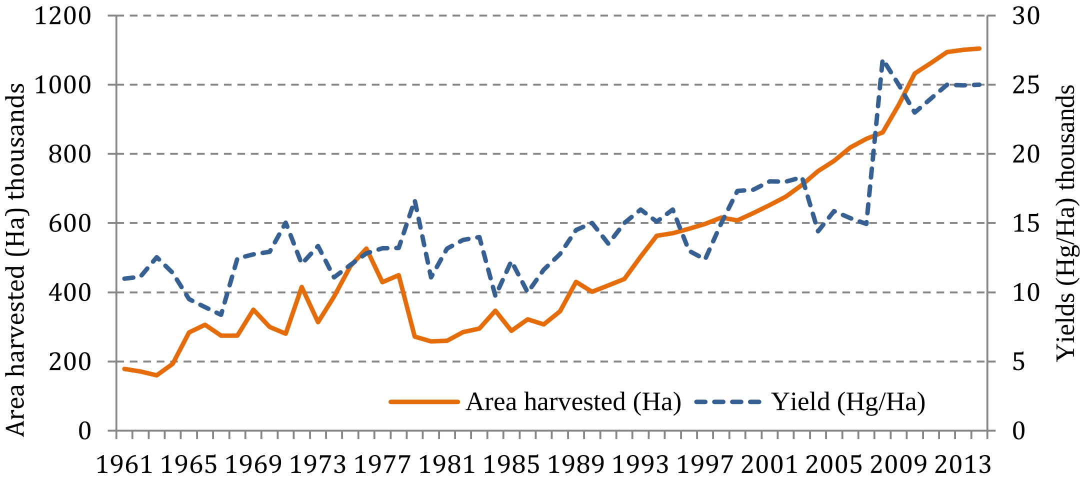
Our dataset allows us to locate farm families according to different geographical and social dimensions (such as geographical districts and belonging to a given parish). About 50% of farmers adopting improved seed for at least two years are concentrated in four counties only: three contiguous counties in the East of the country, close to the Kenyan border and Mount Elgon[26] (Bubulo, Kongasis and Budadiri counties) and one in the Northwest of the country, bordering the white Nile River (Obongi county). However, we have to count 35 counties if we want to include about half of the farmers adopting improved seed varieties either only once or never during the triennium of analysis. Previous literature shows that the choice of the reference group matters in understanding patterns of social learning and technology adoption. This result seems confirmed in our data analysis. 34% of farmers adopting improved seed for at least two years belong to the Bagisu ethic group, which constitute 5% of the Ugandan population.[27] There are 48 ethnic groups represented in the Uganda National Panel Survey, and less than 40% of these groups have at least one member who adopted improved seed varieties for 2 or 3 years.[28] This concentration of innovators (farm families using hybrid seed for at least two of the three year under study) suggests the existence of learning externalities, and possibly heterogeneity in seed market access across the country. Bandiera and Rasul, 2006 find that farmers' adoption decisions are correlated both to the choices of their network of family and friends and to those among their religion, but not to those in other religion groups (Bandiera and Rasul, 2006: 871). In this regard, it is interesting to highlight that religion is rather concentrated within this group, with the Anglican religion being predominant, professed by about 46% of people belonging to this group (UBOS, 2002).

In the next section we will address the issue whether evidence exists that the introduction of improved seed in the market has boosted the productivity of the agricultural sector. We will further try to identify patterns in productivity outcomes of plots cultivated with improved seed varieties, looking more specifically at outcome differentials between innovators and those relying predominantly on traditional seed varieties.

3.2. Improved seed varieties and productivity outcomes

Empirical and theoretical evidence on the green revolution in Asia and OECD countries shows that seed policy reforms and agricultural productivity are related and that the seed industry has strongly benefited from seed policy reforms enhancing intellectual property rights. However, results based on empirical applications in Sub-Saharan Africa are inconclusive. Figure 5 shows the evolution of maize yields (including both traditional and improved varieties) and total area planted with maize in Uganda since 1961. Maize production is historically characterized by very low yields. Since the early nineties, both area and total maize production increased dramatically. However, only between 2007 and 2008 the country has experienced a significant increase in maize yields. That is, most of the total production increase that occurred in the last 30 years has been caused by area expansion rather than yields improvement (Ahmed, 2012), despite significant productivity gains that could be expected after the seed reforms brought forward by the WTO TRIPS 27(3) b and national laws, such as the Agricultural Seed and Plant Act (Cap. 28), 1994.

Figure 5: Uganda Maize plant area and yields from 1961 to 2013



Source: Authors elaboration using data FAOSTAT, 2016

We have previously discussed how new legislation seed policy reforms enhancing intellectual property rights aimed to increase agricultural productivity, and we noted that the speed of introduction of improved maize seed varieties accelerated quickly after 1999. Looking at aggregated country data including both production from hybrid and traditional maize varieties, our data analysis does not confirm a delayed but rapid and significant growth in agricultural yields after seed policy reforms. Given the timing of adoption of these policies, (Figure 4), we can infer that these reforms may have triggered a moderate increase in maize yields since the early nineties. The spike in productivity in 2007 to 2008 is interesting; however, our data does not allow examining in detail its determinants. Since 2012, maize yields have been stagnating once more, falling between 2.8 and 3.0 metric tons/hectare: a quantity still low but at higher level than historical yields. Ahmet (2012) shows that regardless of the farm sizes, Uganda's maize yields levels from 1990 to 2012 have been low, generally between 1.0 and 1.8 metric tons/hectare (Ahmet, 2012).

We now turn to farm-level data to compare the agricultural productivity of plots cultivated with traditional seed to that of plots grown with improved seed, looking at total harvest output and plot areas planted in our sample.

We find little evidence that there is a positive productivity trend in our sample, but we do find that improved seed leads to demonstrably higher yields than those produced with traditional seed varieties in 2010/11 and 2011/12 (Table 5). In 2009 agricultural yields from improved seed varieties were lower than yields from traditional varieties, a result largely due to data from Maize, which is the crop accounting for the majority of hybrid seed use in our dataset.

Table 5: Plot area and yields by seed type and year

		Plot area (acres)	Yields (kg/acre)	No. Plots
2010	Improved	0.39	760	186
	Traditional	0.37	602	962
2011	Improved	0.42	743	156
	Traditional	0.32	666	919

Within improved seed categories, we expect that yields from certified seed to be higher than that of *quality declared* or *unknown quality*; however, this is not confirmed by the data. The yields for the *certified* improved seed are not higher than those of the other categories in 2009 and 2010, and only appear higher in 2011. This trend is evident for all crop types and for Maize in particular (Table 6 and Table 7).

Table 6: Plot area and yields by category of improved seed

		Plot area (acres)	Yields (kg/acre)	No. Plots
2009	Certified	0.45	859	152
	Quality declared	0.52	666	88
	Unknown	0.7	1,139	65
2010	Certified	0.35	713	73
	Quality declared	0.44	1,075	65
	Unknown	0.35	401	46
2011	Certified	0.38	1,138	49
	Quality declared	0.41	478	79
	Unknown	0.49	804	28

Table 7: Maize plot area and yields by category of improved seed

		Plot area (acres)	Yields (kg/acre)	No. Plots
2009	Certified	0.46	917	141
	Quality declared	0.43	795	57
	Unknown	0.33	1,208	40
2010	Certified	0.36	711	67
	Quality declared	0.37	1,511	39
	Unknown	0.36	581	29
2011	Certified	0.34	1,259	41
	Quality declared	0.37	659	44
	Unknown	0.63	683	15

The lack of robust evidence that improved seed performs better than traditional varieties would be likely to be one of the reasons for the low adoption rates in our sample. In general, this lack of incentive to switch to more modern technological systems is a basic cause of inefficiency in developing country agriculture. It is evidence of the inertia that exists within traditional agricultural societies to remain so.

Several explanations might be offered for the result that traditional varieties 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., 2015. Another is the poor information an adopter might have on the optimal growing techniques. Furthermore, even well informed farmers might face serious constraints in their access to complementary inputs such as fertilizers. When hybrid seed fails to deliver the expected higher yields, an earlier adopter might abandon experimentation and decide to revert to traditional seed. Furthermore, farmers might not experiment in improved seed if they observe in their community that these seeds fail to deliver the expected higher yields, with respect to traditional varieties, for which the production function is well known by the farmer. The negative news could spread within the community, leading to lower adoption of improved seed.

In short, this case study demonstrates that there is inertia to remain within the traditional technological system (traditional seed varieties) and that there is little positive feedback to those attempting to innovate outside of this system. For reasons we explore in the next section, the innovation system here is not providing sufficient positive feedback to enable this society to move in the direction of the superior technology. As a final outcome, in this sample of households, we do not find evidence that the percentage of households using improved seed increases over time.

3.3. Innovators and traditionalists: a comparison of farmer type

Why is it that the innovation system within this society is incapable of generating sufficient positive feedback to the use of the modern technology? We wish to understand how innovation occurs within a traditional society by exploring the nature of the "innovators" within it, in order to better understand the nature of experimentation and innovation in a traditional agricultural society.

We do this by investigating some underlying socio-economic characteristics and productivity outcomes in those plots farmed by innovators and compare them with those of plots cultivated with traditional seed varieties, or cultivated with improved seed only for one year. We look at the five main crops for which farmers in our dataset use improved seed varieties in our sample and we define i*nnovators* as those rural households using *improved* seed, in a given plot, for more than one growing season. These five crop categories are maize, cotton, cassava, beans and groundnuts, as discussed in Section 3.1. Table 8 shows the distribution of innovators and traditionalists in our dataset. The majority of the population did not purchase improved seed in any of the three year for any of their plots. This group accounts for about 88% of the total plots in our sample. Farmers used improved seed only in one of the observed three years in about 10% of plots, and less than 2% of the plots were cultivated with improved seed for two or more growing seasons. Given the way we define *innovators* in our analysis (farmers adopting improved seed for at least two main growing seasons out of the three for which data are available), they are a very small subset of the overall farmers population.

Table 8: Distribution of innovators vs. traditionalists

Innovator category	Frequency	Percent
Never	11,755	88.44
One year	1,317	9.91
Two or more years	219	1.65
Total	13,291	100

The three main ethnicities represented in our samples are: Langi (13.88%), Baganda (11.35%) and Iteso (8.93%). The same three ethnicities are predominant among traditionalists, but not among innovators (with the exception of the Iteso ethnic group). Bagisu farmers represent 33.96% of the innovators, followed by Sabiny 12.74% and Iteso 10.85%. The Bagisu ethnic group thus dominates not only the adopters group (see Section 3.1) but among the adopters, it is predominant in the innovators group. As discussed, this ethic group represents only 5% of the total Ugandan population, it is concentrated geographically and predominantly of Anglican religion.

The mean age for innovators' households is lower than that of traditionalists. Our data analysis also suggests that innovators obtain, on average, higher levels of education compared to the traditionalists. For example, the percentage of household who completed the seventh and last year of primary school as highest level of education is higher for innovators.[29] We observe the same pattern for higher levels of education: for example, the highest level of education for 8.0% of innovators is post-secondary level training, while only 4.6 % of traditionalists completed the same schooling level. Overall, the average school expenses are higher for the innovator group than for the traditionalist group.

Several studies based on empirical applications in East African countries show 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). For example, Quisumbing (1996) shows that no significant differences in technical efficiency of male and female farmers are observed when differences in inputs are controlled for. Most of the household heads in the sample are male. As expected, in our representative sample of Ugandan farmers the percentage of women's headship is more than three times lower in the innovators groups (6.3%) than in the traditionalist group (20.7%).

Innovators also tend to use more organic and inorganic fertilizers and more pesticides, as these inputs (particularly mineral fertilizers), are often used jointly with improved seed varieties. Innovators experiment with improved seed, and at the same time, use jointly other agricultural technologies. Nonetheless, the percentage of plots cultivated using jointly hybrid seed and mineral fertilizers is much lower than what has been reported elsewhere, mainly with data from Kenya (Bozzola et al., 2016; Smale et al., 2015; Sheahan, 2011; Ogada et al., 2010; Marenya and Barrett, 2009). This, once again, suggests that Ugandan farmers 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.

Comparing the main sources of income of traditionalists and innovators, the share of traditionalist households for which non-agricultural income is the main source of overall income is higher than in the innovators group (17% and 15% respectively). Traditionalists rely more on remittances than innovators, but the percentage of innovators whose main source of income are activities such as commercial farming, property and transfer other than remittances is higher than the percentage of traditionalists in the same category (6% versus 4%).

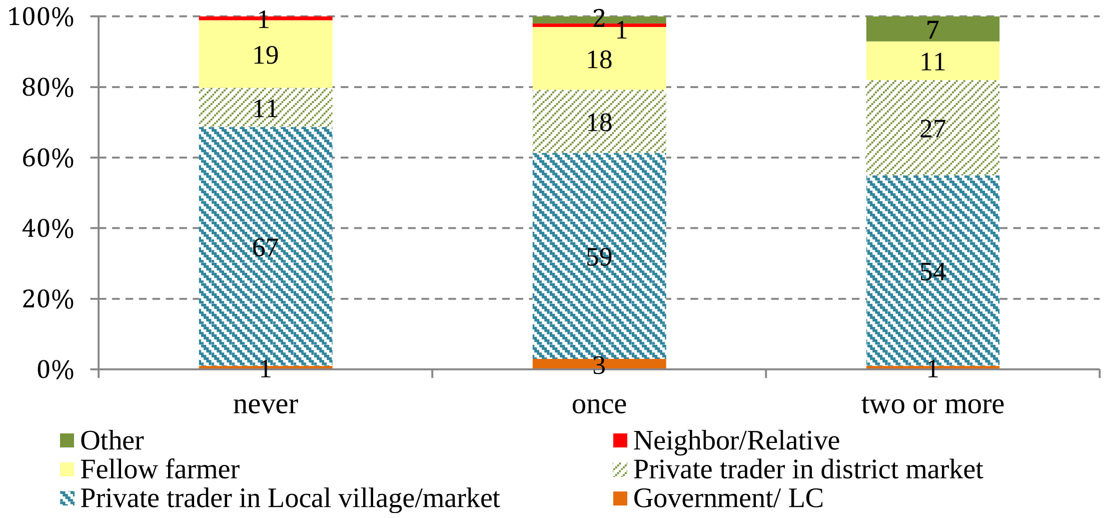
Table 9: Sociodemographic profile of innovators vs. traditionalists

Innovator category	Never	One year	Two or more years
Household mean age	22.66	22.43	19.77
HH Head Gender (% female)	20.7	17.4	6.3
HH size (no. of people)	7.72	7.81	8.36
HH head completed primary school (P.7) (% HH)*	18.12	17.66	19.25
HH head did some schooling, but not completed P.1 (% HH)	1.11	1.03	0.53
HH school expenses in previous 12 months (UGX)	650,197	499,642	659,450
Use of fertilizers (% plots)			
Organic fertilizers	3.54	5.05	4.57
Inorganic fertilizers	0.88	4.42	13.24
Pesticides and herbicides	3.46	8.02	11.47
Main source of income (% of plots)			
Subsistence farming	62.83	61.93	63.68
Wage employment	13.82	12.36	12.74
Non-agricultural	15.13	18.07	16.98
Remittances	4.19	2.39	0.47
Others (commercial farming, property, other transfers)	4.03	5.25	6.13

*data based on question: What is the highest level of education obtained?

We further compare the sources of seed purchases of innovators with the ones of traditionalists. We find that overall innovators tend to purchase more from district markets while reducing their purchase from local markets and fellow farmers. As discussed in Section 3.1 this could indicate that innovators are more willing to invest time and resources to travel to district markets, in order to buy improved seed varieties. Figure 6 outlines the source of seed purchased by different farmers groups, pooling the five crops under observation in this section.[30]

Figure 6: Source of Seed Purchased by Innovators and Traditionalists



In terms of the plot area, we identified in our data farmers who used improved seed at least once tend to plant their crops in larger plots, but we do not find evidence that the share of land planted with hybrid seed is constantly growing in the analysed triennium. This could mean that farmers adopting improved seed tend to do so in larger plots.[31] Table 10 shows the plot area by type of adopters.

Table 10: Plot area (acres) by farmer type

Farmer type	2009	2010	2011	Total
Never adopt	0.31	0.33	0.26	0.30
Number of plots	4,047	3,864	3,844	11,755
Adopt once	0.52	0.36	0.41	0.44
Number of plots	536	428	353	1,317
Adopt	0.58	0.36	0.34	0.44
Number of plots	84	82	53	219

The farmer uses improved seed varieties: never (never adopt), only once (adopt once) or more than once (adopt) in a given plot.

Given our analysis of innovators, we are able to say that there is evidence of the existence of a small but distinct group of farmers who conduct the vast majority of the experimentation and innovation within this society. As few as 1% of the farmers in the study undertake systematic importation of traits from outside the locality and from more diverse sources, and these innovators have traits themselves indicative of their distinctive character. The diminishingly small number of innovators (as a proportion of the community) may explain the low rate of technological change in Uganda. Other explanations may also be possible, such as the difficulty of moving traits across legal systems. Both frictions are potentially evident here, although the Uganda database lacks adequate richness to explore the problem in further detail.

In general we have attempted to show that the availability of modern varieties is not in itself sufficient to translate into incentives to move toward that system. There are many reasons why there is inertia within a traditional agricultural society, for it to remain technologically traditional. The specific aspect on which we have focused is on the need for an "innovator" class of individuals responsible for the experimentation and innovation required to generate the positive examples that attract interest to the new technology. We have identified this class, and indicated the characteristics indicative of its existence; however, we are also able to see that it is too small of a group to generate adequate positive feedback to overcome technological inertia. For this reason, we believe the two systems of technology continue to exist, and little incentive exists to switch between the two.

4. Conclusions, Policy Implications and Further Work

In this paper we have presented a simple target-input model to conceptualize the adoption decisions and management of a new technology in which the best 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 find evidence of low adoption rates of improved seed varieties, and of unfruitful experimentation with improved seed in the local communities.

Despite the implementation of seed policy reforms over the last 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). Our findings also support the literature showing that identifying relevant reference groups matters in order to understand patterns of social learning and technology adoption, a finding which may have important policy implications in a country like Uganda, characterized by over 55 legally recognized ethnic groups.

Most importantly, we isolate the way in which modern technologies (embedded in improved seeds) are trans-located to local production environments, through the offices of a class of farmers who we have termed “experimentalists” and “innovators”. These are the set of local farmers more likely to go longer distances (to district markets) in order to acquire newer, improved varieties. The role of this group is to overcome local technological inertia by experimenting with these improved varieties under local conditions. Theory indicates that substantial experimentation may be required in order to reach the productivity frontier with new varieties (by converging on the optimal combination of inputs). Our evidence indicates that experimenters have only modest success in their initial experimentation, that the level of experimentation is small (about 1.5% of farmers), and that commitment to experimentation is not strong (about 50% experiment with a specific variety for only one year).

For this reason, the level of experimentation in local production environments is insufficient to generate the signals required to engender adequate numbers of adoptions in the locality. Without significant numbers of adoptions, the knowledge base needed to communicate experience with, and the efficiency of, the modern technology. The initiation of the process of peer learning and positive social interaction requires this initial group of experimenters to make an adequate investment to move the system out of its traditionalist inertia – and we find no evidence that this level of investment in experimentation is in fact occurring.

It is important to understand the socio-economic conditions of farmers who support innovation and embrace more efficient agricultural practices, to encourage such groups to facilitate further adoption, and reduce barriers to adoption by other reference groups. Our initial analysis of the group of local innovators suggests that education may be an important factor to look at when analysing patterns of adoption of new agricultural technologies. We also discuss the existence of important gender differences in accessing productive assets and inputs. The role of public policies in supporting experimentation and trans-location of traits to local environments is obvious and important. In general, we identify the crucial role of the "innovators" within a society, and indicate that it is crucial to support them in their efforts to expand and integrate technologies in traditional societies.[32]

Appendices:

Appendix 1

Text of ANNEX 1C to the AGREEMENT ON TRADE-RELATED ASPECTS OF INTELLECTUAL PROPERTY RIGHTS

SECTION 5: PATENTS

Article 27 - Patentable Subject Matter

1. Subject to the provisions of paragraphs 2 and 3, patents shall be available for any inventions, whether products or processes, in all fields of technology, provided that they are new, involve an inventive step and are capable of industrial application. Subject to paragraph 4 of Article 65, paragraph 8 of Article 70 and paragraph 3 of this Article, patents shall be available and patent rights enjoyable without discrimination as to the place of invention, the field of technology and whether products are imported or locally produced.

2. Members may exclude from patentability inventions, the prevention within their territory of the commercial exploitation of which is necessary to protect *ordre public* or morality, including to protect human, animal or plant life or health or to avoid serious prejudice to the environment, provided that such exclusion is not made merely because the exploitation is prohibited by their law.

3. Members may also exclude from patentability:

(a) diagnostic, therapeutic and surgical methods for the treatment of humans or animals;

(b) plants and animals other than micro-organisms, and essentially biological processes for the production of plants or animals other than non-biological and microbiological processes. However, Members shall provide for the protection of plant varieties either by patents or by an effective *sui generis* system or by any combination thereof. The provisions of this subparagraph shall be reviewed four years after the date of entry into force of the WTO Agreement.

Appendix 2

Drought Tolerant Maize for Africa (DTMA) varieties developed in Uganda 2007 -2013 classified by Fisher et al. 2015

Table A1. Drought Tolerant Maize for Africa (DTMA) varieties developed in Uganda 2007 - 2013

Release name	Year of release	Hybrid/ OPV	Maturity range[1]	Grain yields (tons/ha)	Special/additional traits[2]
Longe 9H	2009	Hybrid	Intermediate	6.0 – 8.0	Resistant to MSV, NLB & GLS
Longe 10H	2009	Hybrid	Intermediate	> 8.0	Resistant to MSV, NLB & GLS
Longe 11H	2009	Hybrid	Intermediate	6.0 – 8.0	Resistant to MSV, NLB & GLS
UH 5051	2012	Hybrid	Intermediate	5.0 – 7.0	Suited to mid-altitudes
UH 5052	2012	Hybrid	Intermediate	5.0 – 7.0	Suited to mid-altitudes
UH 5053	2012	Hybrid	Intermediate	5.0 – 7.0	Suited to mid-altitudes
VPMAX	2012	OPV	Intermediate	3.0 – 5.0	
UH5354	2013	Hybrid	Intermediate-late	> 8.0	Suited to mid-altitudes
UH5355	2013	Hybrid	Intermediate-late	> 8.0	Suited to mid-altitudes

[1] Maturity Range: Extra early = those maturing in less than 100 days; early = 100-110 days; early/intermediate = 110-120 days; intermediate = 125-135 days; late = 135-145 days.

[2] Acronyms: maize streak virus (MSV), northern leaf blight (NLB), and grey leaf spot (GLS).

Source: Authors Elaboration from Supplemental Resource 2 in Fisher et al., 2015 and DTMA project, 2013

Appendix 3

Figure A.3.1 Source of Seed Purchased by Innovators and Traditionalists: Maize

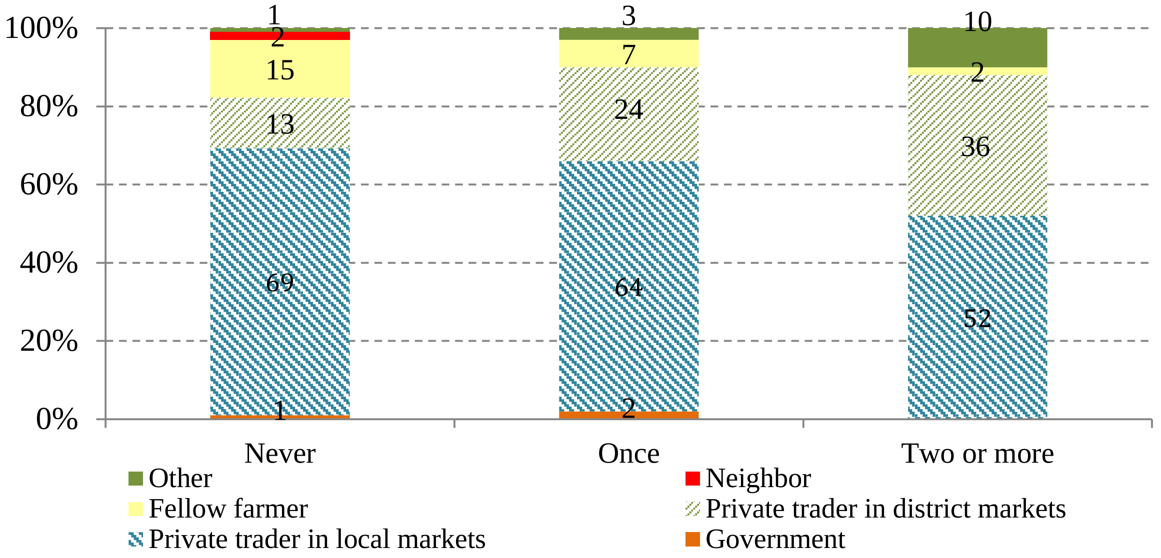
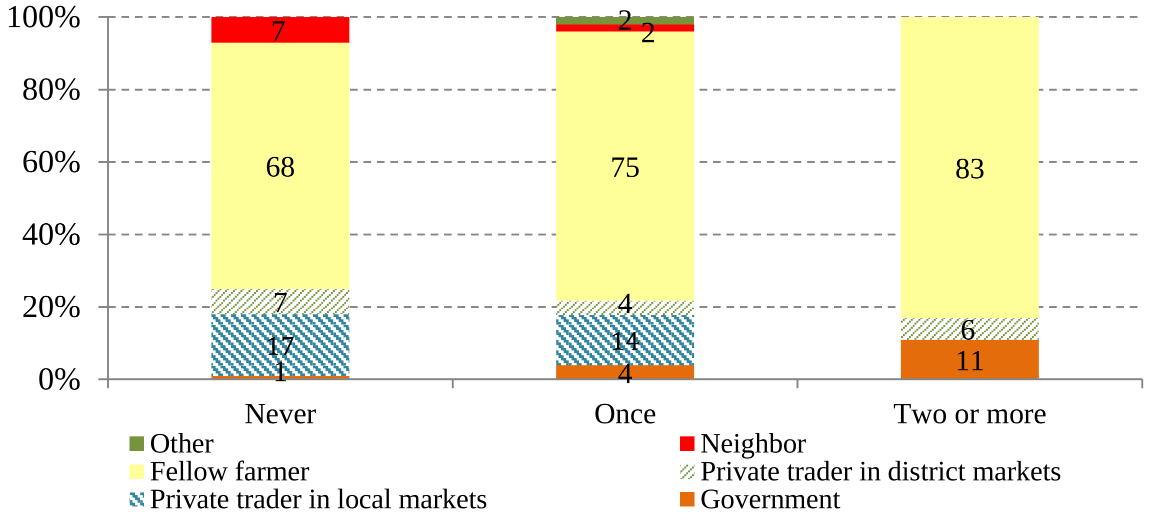


Figure A.3.2 Source of Seed Purchased by Innovators and Traditionalists: Cassava



Notes

[1] Uganda has been a WTO member since 1 January 1995 and a member of the General Agreement on Tariffs and Trade (GATT) since 23 October 1962.

[2] See Appendix 1.

[3] Other laws, regulations, administrative and technical procedures that govern seed production and distribution in Uganda include: The Uganda's National Seed Policy (2014), The Agricultural Chemicals (control) Act of 2006, The Adulteration of Produce Act, Cap.27; The Cotton Development Act, Cap 30; the Uganda Coffee Development Authority Act, Cap 325; the Uganda National Bureau of Standards Act, 1983; the Export Promotions Board Statute, 1996; the National Environment Act, CAP 153 and the National Agricultural Research Act, 2005 (Barnett et al., 2011).

[4] This situation continued at least until new plant variety protection was finally passed in December 2013.

[5] O'Gorman and Pandey (2010) find that 22% of modern productivity gains may be attributed to modern varieties, but that this result varies regionally and is much lower in Africa. One of our goals is to explain how and why this variability in outcome might obtain in various regions and in varying institutional contexts.

[6] Under the PVR laws, it is necessary for all seed importers and breeders to obtain *national certification* of varieties prior to release, and the farmers would turn to these suppliers in order to secure new characteristics in their own production and breeding programs in their local markets, most often from private traders.

[7] Although the importance of social learning in agriculture is well established in the literature, only recently has the literature addressed the importance of identifying the effects of learning separately from other determinants of adoption. Some studies have addressed the role of peer effects and social learning in the diffusion of new technologies (Conley and Udry, 2010; Bandiera and Rasul, 2006; Munshi, 2004).

[8] In this article, the terms *innovators* and *experimenters* are used as synonyms to identify the group of farmers who undertake most of the seed experimentation.

[9] 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.

[10] For example, Bozzola et al., 2016, analysing data of a representative sample of Kenyan farmers, found that in about 90% of the plots where maize hybrid seed are planted during the main rainfall season, mineral fertilizers were also applied.

[11] In this, target-input models differentiate themselves from another model on learning spillovers in agriculture, developed by Besley and Case (1993 and 1994), in which the profitability of adoption (rather than the optimal use of inputs) is uncertain and exogenous. The reader shall refer to Foster and Rosenweig (1995) for the exposition of the formal model. Mushi (2004) provides an interesting extension to the model, deriving formally the implications for adopters of hybrid seed varieties and acreage allocation with experimentation (Mushi, 2004, Appendix A).

[12] The reader shall refer to Foster and Rosenweig (1995) for a discussion on the implications of this assumption.

[13] Refer to Foster and Rosenweig (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.

[14] Foster and Rosenweig (1995) provide further insights on how the inclusion of strategic behaviour in the model would capture the influence of neighbours' characteristics on farmer adoption and on the effects of learning externalities on adoption decisions.

[15] Our results would not change, but they would be even stronger if we assume that the cost of adopting improved seed is always lower than the cost of adopting traditional seed, for a given number of farmers.

[16] 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. The survey is conducted in two visits in order to better capture agricultural outcomes associated with the two cropping seasons of the country. For more detail regarding the survey, see: http://go.worldbank.org/D3ZAKU07K0.

[17] *Certified seed* is a legal term referring to government certification by the relevant authority, and so we assume that respondents knew when purchased seed had such government certification. Notably, 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 is assumed to indicate a class of seeds that requires minimum field inspection and certification standards for variety purity and germination, according to the Quality Declared Seed System, presented by FAO in 1993 and revised in 2006. The Ugandan legislations mentions for the first time Quality Declared Seed (QDS) in the draft National Seed Policy 2014. QDS are not yet considered part of the formal and regulated Ugandan seed sector. *Unknown quality* seed is assumed to contrast with declared quality, and so indicates seed that is known to be of an improved nature but without any further information on its provenance or character.

[18] This percentage includes both bought and retained improved seed.

[19] See articles 7, 8 and 10 Ch. 28 of the Agricultural Seed and Plant Act, 1994 and following modifications in articles 9, 10 and 12 in the revised Seed and Plant Act, 2006 (No. 3 of 2007).

[20] Together with the lack of improved maize varieties, the author lists as main factors causing low yields: low soil fertility, erratic rainfall patterns and drought stress during some seasons.

[21] Traditionally, Uganda has been the most important food exporter in Central and East Africa, particularly of maize to Kenya (Benson et al., 2008). Matooke (cooking banana), cassava, and sweet potato are the main sources of calories. These crops are not extensively traded. Wheat and rice are the main food imports from global markets (Benson et al., 2008).

[22] The other main crops for which farmers use improved seed varieties in our sample are cassava, beans, groundnuts and cotton. Together these five crops account for over 70% of the plots in our dataset cultivated using hybrid seed.

[23] We provide in Section 3.3 a more detailed discussion on different farmer types, dividing our sample by the number of years farmers adopt improved seed varieties in a given plot.

[24] These numbers support the literature on adoption of modern crop varieties by smallholders in Sub-Saharan Africa (SSA) indicating low rates of adoption and lack of sustained use of seemingly advantageous farm technologies (Fisher et al., 2015; Kijima et al. 2011; Eaton et

al., 2006). Furthermore, studies indicate that smallholder farmers in SSA have made insufficient or no adjustments to reduce impacts of increasing temperature and/or decreasing precipitation, even when they are generally aware of local environmental changes and perceive adverse changes in climate (Bozzola et al., 2016; Fosu-Mensah et al., 2012; Gbetibouo et al., 2010). In the case of Uganda, Fisher et al., 2015 report high seed price as a commonly mentioned constraint to adopt improved seed varieties. However, high seed price alone is insufficient to explain the low adoption rates of improved seed varieties, despite the favourable seed policies established since the nineties.

[25] The Drought Tolerant Maize for Africa (DTMA) project, funded by the Bill & Melinda Gates Foundation, has contributed significantly to release seven of these varieties in the Ugandan Market, in the period 2007-2013. These included six hybrids and one OPV. A detailed description of these varieties is presented in Appendix 2.

[26] Mount Elgon is an important water catchment for the Nzoia River, flowing on Lake Victoria and the Suam River, which flows into Lake Turkanaand Obongi.

[27] There were 56 legally recognized ethnic groups in Uganda at the time of the 2002 population census (UBOS, 2002), most broadly distinguished by language. The Bagisu occupy the well-watered western slopes of Mount Elgon. This area has the highest population density in the nation, which can reach 250 people per sq. km. As a result, nearly all land is cultivated and land pressure has led to population migration and social conflicts.

[28] Of the 48 ethnic groups represented in the Uganda National Panel Survey, only 19 groups have at least one member who planted improved seed varieties for 2 or 3 years in the period under analysis. More details on socio demographic differences between *innovators* and traditional farmers are provided in Section 3.3.

[29] There are seven primary school years in Uganda. With normal annual progression this means primary school should last seven years.

[30] The results are consistent when looking at each crop separately. The only exception is cassava. The major source of cassava seed for both traditionalists and innovators are their fellow farmers. The reader can refer to Appendix A3 for the detailed breakdown by farmer type of the sources of seed for maize and cassava.

[31] Our plot area data leverages GPS positioning data where possible, and farmers self-reported plot area where GPS data is not available. It has been documented that farmers tend to under-estimate plot area except when the plot is very large (Calogero et al., 2013).

[32] This analysis supports the pursuit of further research on this important topic. We hope to extend the analysis in this paper once more data becomes available for the country, by including at least one more round of data collection in the UNPS panel dataset we use, once it will be made available by the World Bank Integrated Surveys on Agriculture project. Although our theoretical model and empirical analysis provides information on what are the key regressors to include in an analysis of adoption patterns by Ugandan farmers, linear probability models (such as logit and probit models) will allow us to estimate coefficients identifying whether adoption decisions are correlated within social networks, and also to estimate in a more formal setting the determinants of (early) adoption of new technology as well as the determinant of agricultural yields improvements.

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