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Heterogeneous seed access and information exposure: implications for the adoption of drought-tolerant maize varieties in Uganda

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Abstract

Frequent droughts in sub-Saharan Africa imply water stress for rainfed agriculture and, ultimately, food insecurity, underlining the region's vulnerability to climate change. Yet, in the maize-growing areas, farmers have been given new drought-coping options following the release and availability of drought-tolerant maize varieties (DTMVs). These varieties are being disseminated through the National Agricultural Research and Extension Systems in collaboration with seed companies; however, their adoption still appears somewhat modest, and empirical studies on their adoption potential and associated drivers are scarce. We use empirical data from Uganda to estimate the actual and potential adoption rates and the adoption determinants of DTMVs under information and seed access constraints. Adoption rates for DTMVs could have been up to 22% in 2015 instead of the observed sample adoption rate of 14% if the whole population had been exposed to them. The adoption rate could increase to 30% if seed were availed to the farming population and to 47% if seed were sold at a more affordable price to farmers. The observed adoption rate of 14% implies gaps in the potential adoption rates of 8%, 16%, and 33% because of a lack of awareness, a lack of seed access, and high seed prices, respectively. The findings underscore the role of both market and non-market-based approaches and the potential to further scale the cultivation of DTMVs in Uganda.

Keywords: Drought tolerance, Improved varieties, Adoption, Exposure, Seed access, Seed price

Introduction

Agricultural production in Sub-Saharan Africa is weather sensitive and vulnerable to climate change (Mendelsohn 2008), with frequent droughts and floods contributing to food insecurity, water scarcity, and famine (Ngingi 2009). African maize farmers are adapting to this weather variability in multiple ways (Fisher et al., 2015), including the use of drought-tolerant maize varieties (DTMVs). These varieties have been bred using modern conventional methods, without genetic modification, following efforts by the International Maize and Wheat Improvement Center (CIMMYT) in partnership with the National Agricultural Research Institutions in different African countries. In addition to drought tolerance, the varieties often have other attractive traits, such as resistance to major biotic stresses, responsiveness to inputs and good nitrogen use efficiency (Fisher et al. 2015).

The DTMVs underwent extensive multi-location on-farm testing using participatory variety selection approaches with farmers across Eastern and Southern Africa, with DTMVs out-yielding popular commercial checks (Fisher et al. 2015; Setimela et al. 2017). In addition, there is evidence that DTMVs adoption positively impacts productivity, risk exposure, and welfare of smallholder farming households in Africa (Wossen et al. 2017; Awotide et al. 2016; Kostandini et al. 2013). By early 2016, over 200 DTMVs had been released in 13 countries of sub-Saharan Africa. The seed dissemination and delivery has been the responsibility of the national agricultural research and extension systems and public and private seed companies. Yet the DTMV adoption rates remain somewhat modest, and the drivers of adoption are not fully understood.

Earlier literature on technology adoption in Sub-Saharan Africa had a farmer orientation. Adoption was affected by risk and uncertainty, farmer learning processes, the rationing of complementary inputs such as fertilizer or water and farm characteristics, such as farm size (Minot et al. 2007). Some explanations invoked the more complex decision-making environment of semi-commercialized farmers. The household framework emerged as an analytical paradigm for predicting adoption, highlighting the importance of incomplete markets and transaction costs (Benjamin, 1992; Vakis et al. 2004). This framework emphasizes that when markets are imperfect, household consumption decisions cannot be separated from farm production decisions. Hence, household characteristics, as well as farm physical characteristics and relative prices, determine whether households will choose to grow a variety or not (Minot et al. 2007). Adoption scholars have also acknowledged the role of intra-household decision-making processes and the role of gender in variety choice (Doss and Morris 2000; Doss 2013; Colfer et al. 2015; Anderson et al. 2017). Finally, a thread that runs throughout the literature is the importance of farmer perceptions (Adesina and Forson 1995), variety traits, and farm household preferences for both agronomic and consumption-related traits (Wale and Yalew 2007; Asrat et al. 2010).

A more recent strand of literature (Diagne 2006, 2010; Diagne and Demont 2007; Simtowe et al. 2016; Kabunga et al. 2012) has emphasized the role of heterogeneous information exposure on technology adoption. Such studies show how estimating adoption rates for a new technology not well known to the population can yield inconsistent and biased estimates. However, as pointed out by Diagne (2010), the potential adoption rate based on awareness alone, and by extension, knowledge (Kabunga et al. 2012), still underestimates the true potential adoption rate of a new technology, because being aware and having knowledge of the technology is not enough for adoption. Indeed, as expressed by Donstop et al. (2013), one may be aware but have no access to the innovation, as may be the case with seed access of new DTMVs. Seed access of a new variety thereby potentially becomes an important factor for its adoption. Donstop et al. (2013) and Dibba et al. (2015) thereby extend the estimation of potential adoption rates by considering both the lack of awareness and technology access as constraints to adoption. In this paper, we further extend the estimation and provide a micro-perspective of DTMV adoption rates and their determinants in Uganda under heterogeneous seed price affordability, seed availability/access, and information exposure. We apply the average treatment effect (ATE) framework proposed by Diagne and Demont

(2007) but go a step further to also consider the availability and price affordability of seed. Our extension from these studies is premised on the fact that beyond the awareness of the new variety and physical availability/accessibility of seed, the affordability of that seed is a critical factor affecting the adoption of improved varieties. We thus consider households' exposure to DTMVs, access to seed, and access to seed at an affordable price to be heterogeneous. Indeed, households for whom the seed is not affordable are unlikely to adopt the variety of their choice even if they know it and the seed may be physically available in their locality.

An analysis of the adoption rates under seed access constraints is critical for understanding the current bottlenecks in maize value chains and for expediting DTMV scaling through more concerted private and public sector efforts. The study is expected to contribute to understanding the potential demand for DTMV seed and the seed sector support needed to scale DTMVs in Uganda. The rest of the paper is organized as follows: Section 2 discusses analytical methods while data sources and descriptive statistics are presented in Section 3. The results and discussions of adoption rates and determinants are presented in Section 4, and Section 5 concludes.

Analytical framework

In analyzing DTMV adoption decisions, we need to address whether a potential adopter is informed about its existence and has physical access to seed and at a price that is affordable. Once the DTMVs are released, information about their existence is disseminated through multiple channels that include (i) on-farm trials, (ii) demonstration plots controlled by agricultural extension agents, (iii) field days for farmers, (iv) agricultural shows to which farmers are invited and farmer-to-farmer exchange of information occurs, and (v) varietal promotion. The seed is usually produced by private seed companies and can be distributed by government, public sector agencies, cooperatives, and the private sector—agro-dealers or, as is often the case, by a combination of all of these.

As the DTMVs are new and the target population is not universally exposed to them, observed sample adoption rates do not consistently represent the true population adoption parameters, even when based on a randomly selected sample. The reason is that researchers and extension workers have a tendency to target progressive farmers first, while farmers self-select into exposure (Diagne 2006). To account for selection bias, Diagne and Demont (2007) use the counterfactual average treatment effect (ATE) framework, which allows for both nonparametric and parametric methods to derive consistent estimates. The ATE parameter measures the effect, or impact, of a "treatment" on a person randomly selected in the population (Rubin, 1974; Wooldridge 2002). But as expressed by Donstop et al. (2013), apart from a lack of awareness, there are is another constraint, which is the lack of access to seed. The farmer can be aware of DTMV but cannot become an adopter if (s)he does not have access to them. DTMV awareness and seed access are, therefore, both necessary conditions for adoption. Donstop et al. (2013) also show that while it is possible to observe farmers can be aware of improved varieties without getting access to their seed, it is not possible to observe the seed access status among farmers that are not aware of the existence of DTMVs (Fig. 1). By extension, the farmers can be aware of DTMVs without having access to their seed at an affordable price, but we do not know the status in terms of accessibility to affordable DTMV seed among farmers that are unaware of the existence

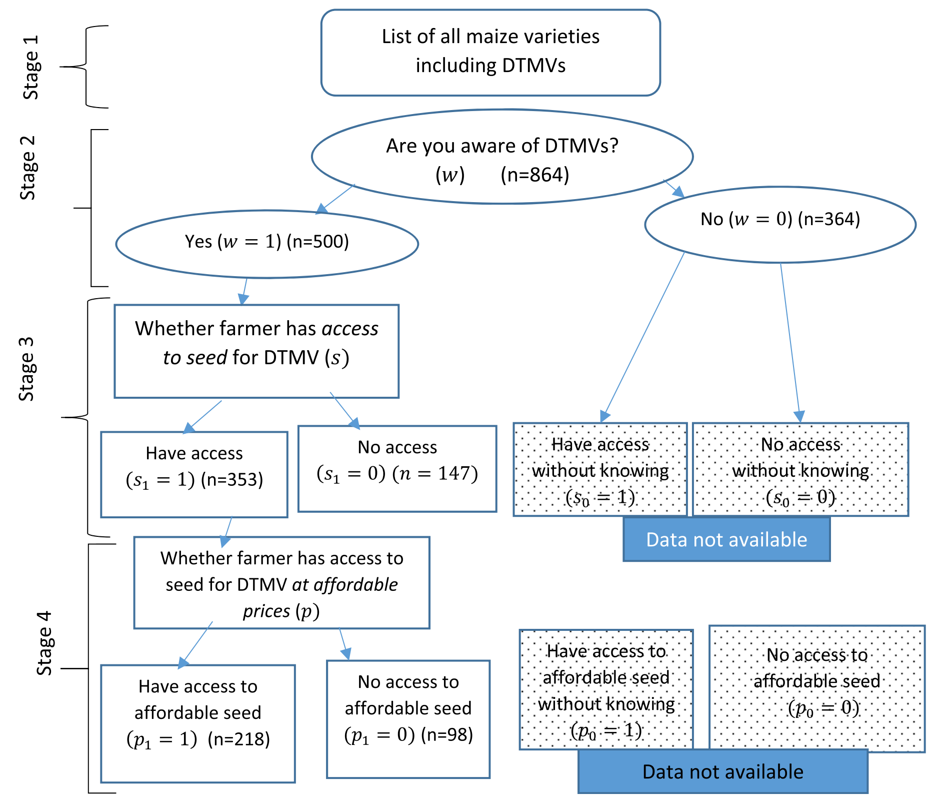

Fig. 1 Flowchart linking awareness, seed access and affordability variables

of DTMVs and among those that have no physical access to seed. As in the case of Donstop et al. (2013), in this paper, we use the term "access" to imply physical availability of the seed in the farmer's environment and not the acquisition availability (affordability). Our extension in this study is that we also explore how the acquisition (price) affordability of DTMV seed affects adoption rates.

To obtain the access and affordability variables, we collected information on all possible reasons for not adopting the DTMVs through individual interviews among households that were aware of DTMVs but did not adopt them (Fig. 1). At the first stage, all farmers were asked whether they knew specific DTMVs. At the second stage, for those who reported having knowledge (denoted by w) of DTMVs ($w = 1$), the following specific question was asked: "Did you grow any of the DTMVs in the 2015 planting season?" When a farmer responded that (s)he did not grow any DTMV, (s)he was asked to provide reasons for not growing them. A wide range of responses were recorded; however, of interest were responses related to seed accessibility and seed affordability. We denote s to stand for the (physical) access to seed status of a farmer, with $s = 1$ for farmers who had access to seed and $s = 0$ for farmers who had no access to seed. For farmers who did not know about DTMV (that is $w = 0$), they were not asked about seed access. As expressed by Donstop et al. (2013), this implies that we do not have information on seed access status of the farmers who were not aware of DTMVs. Indeed, some of the farmers who are not aware of DTMVs may actually have access to DTMV seed even though they are not aware of its existence. As expressed by Donstop et al. (2013), this could be the case, for example, when the variety is present in the village, but the farmer is not aware of the variety. We denote p to stand for the seed acquisition affordability status of a farmer, with $p = 1$ for farmers that had access to seed at an affordable price and $p = 0$ for farmers who had no access to affordable seed. For farmers who did not know about DTMV (that is $w = 0$), they were not asked about seed affordability. As in the case of seed availability, this implies that we do not have information on access to the "affordable" seed status of the farmers who were not aware of DTMVs. Indeed, some of the farmers who are not aware of DTMVs may actually be able to afford DTMV seed.

Based on the earlier explanation, the physical seed access status variable is either 0 or 1 and it is only observed among individuals that are aware of DTMVs. Hence, the awareness and the physical access–unrestricted potential adoption rate is always greater than or equal to the awareness–unrestricted one. Similarly, the awareness–, physical access–, and acquisition affordability–unrestricted potential adoption rate is always greater than or equal to awareness– and physical access–unrestricted potential adoption rate.

In what follows, we extend the ATE adoption framework proposed by Diagne and Demont (2007) to estimate three types of potential adoption rates; (i) the awareness–unrestricted; (ii) the awareness–access–unrestricted; and (iii) the awareness–access–affordability–unrestricted DTMV potential adoption rates and the associated adoption gaps in Uganda, as well as the determinants of DTMV awareness, access , affordability, and adoption.

We adopted the potential outcome framework of Rubin (1974), in which every farmer in the population has *theoretically* eight potential adoption outcomes:

(i) An outcome with awareness and access to seed at an affordable price, say y_{111} (that is, y_{111} is the outcome when $w = 1$, *and* $s = 1$ *and* $p = 1$)
(ii) An outcome when is aware and has access to seed but when seed is sold at a price farmers cannot afford, say y_{110} (that is, y_{110} is the outcome when $w = 1$, $s = 1$ and $p = 0$)
(iii) An outcome with awareness, with affordable seed price, but farmers do not have access to seed, say y_{101} (that is, y_{101} is the outcome when $w = 1$, $s = 0$, and $p = 1$)
(iv) An outcome with awareness of DTMV, but one does not have access to seed and the seed price is not affordable, say y_{100} (that is, y_{100} is the outcome when $w = 1$, $s = 0$, and $p = 0$)
(v) An outcome without awareness of DTMV, but having access to seed and at a price that is affordable, say y_{011} (that is, y_{011} is the outcome when $w = 0$, $s = 1$, and $p = 1$)
(vi) An outcome without awareness of DTMV and with access to seed but the seed price is not affordable, say y_{010} (that is, $y_{010}$is the outcome when $w = 0$, $s = 1$, and $p = 0$)
(vii) An outcome without awareness of DTMV and with no access to seed but the seed price is affordable say y_{001} (that is, $y_{001}$is the outcome when $w = 0$, $s = 0$, and $p = 1$)

(viii)An outcome without awareness of DTMV and without access to seed and when the seed price is not affordable say y_{000} (that is, $y_{000}$is the outcome when $w = 0$, $s = 0$, and $p = 0$).

Hence, the observed adoption outcome y can be expressed relative to the eight potential adoption outcomes as:

$$y = wspy_{111} + ws(1-p)y_{110} + w(1-s)py_{101} + w(1-s)(1-p)y_{100} + (1-w)spy_{011} + (1-w)\, s\, (1-p)y_{010} + (1-w)(1-s)y_{001} + (1-w)(1-s)(1-p)y_{000} \quad (1)$$

Since awareness, physical seed access, and seed price affordability are necessary conditions for adoption in that order, we have $y_{101} = y_{100} = y_{001} = y_{010} = y_{001} = y_{011} = y_{000} = 0$. Hence, Eq. (1) is reduced to:

$$y = wspy_{111} \quad (2)$$

The potential outcome is always 0 when the farmer is not aware, and/or does not have access to seed and/or not have access at an affordable price. It follows that y_{111}, which is the potential outcome, is also the treatment effect of a given farmer when the farmer is aware and has physical seed access and seed access at an affordable price. The average treatment effect of awareness and physical access to seed at an affordable price is expressed as the expected value $E(y_{111})$.

If we consider awareness as a treatment, the awareness–unrestricted potential adoption outcome can be derived from Eq. (2) by setting $w = 1$ and expressed as follows:

$$y_1^* = spy_{111} \quad (3)$$

Similarly, by setting $s = 1$, the physical seed access–unrestricted potential adoption outcome y_1^{**} is defined as:

$$y_1^{**} = wpy_{111} \quad (4)$$

After setting $p = 1$, the seed acquisition affordability–unrestricted potential adoption outcome can also be expressed as:

$$y_1^{***} = wsy_{111} \quad (5)$$

Similarly, the awareness and physical seed access–unrestricted potential adoption outcome is by setting $(w, s) = (1, 1)$ expressed as:

$$y_{11}^* = py_{111} \quad (6)$$

The awareness and acquisition affordability–unrestricted potential adoption outcome is by setting $(w, p) = (1, 1)$ expressed as:

$$y_{11}^{**} = sy_{111} \quad (7)$$

The physical seed access and acquisition affordability–unrestricted potential adoption outcome is by setting $(s, p) = (1, 1)$ expressed as:

$$y_{11}^{***} = wy_{111} \quad (8)$$

The average treatment effect (ATE) of awareness, physical seed access, and acquisition affordability as measured by the expected value $E(y_{111})$ is the potential adoption rate when the full population is aware of DTMVs and has physical access to the seed for DTMVs at a price affordable by the full population. This is different from the potential adoption rate when the full population is only aware of DTMVs $E(y_1^*)$, and it is also different from the potential adoption rate when the full population only has physical access to DTMV seed $E(y_1^{**})$. It is also different from the population potential adoption rate when the full population has access to seed at an affordable price (with some not necessarily being aware), which is measured by the parameter $E(y_1^{***})$. Three more joint bivariate potential adoption rates (Eqs. 6–8) correspond to awareness and physical access to seed (y_{11}^*),awareness and acquisition affordability of seed (y_{11}^{**}), and physical seed access and acquisition affordability of seed (y_{11}^{***}).

To distinguish the seven population potential adoption rates, we call parameter $E(y_{111})$ the awareness–physical seed access at affordable prices unconstrained potential adoption rate (ATE_{wsp}), whereas $E(y_1^*)$, $E(y_1^{**})$ and $E(y_1^{***})$ are called awareness unconstrained (ATE_w), access unconstrained (ATE_s), and affordability–unconstrained (ATE_p) population potential adoption rates, respectively. $E(y_{11}^*)$, $E(y_{11}^{**})$, and $E(y_{11}^{***})$ are called the joint bivariate potential adoption rates corresponding to awareness and physical seed access (ATE_{ws}), awareness and seed affordability (ATE_{wp}), and physical seed access and seed affordability ATE_{sp}), respectively.

Among the seven population potential adoption rates defined above, we restrict our empirical estimation to only three: ATE_w=E(y_1^*), ATE_{ws} =E(y_{11}^*), and ATE_{wsp}=E(y_{111}). The exclusion of the two marginal potential adoption rates (related to physical seed access (ATE_s) and acquisition affordability (ATE_p)) from the empirical analysis is justified by the fact that the two variables (i.e., *s and p*) are observed only for the aware subsample (i.e., for $w = 1$) which makes it difficult to estimate them without further assumptions. The same is true for the excluded joint bivariate potential adoption rate related to physical seed access and acquisition affordability ($ATE_{sp} = E(y_{11}^{***})$). The exclusion of the joint bivariate potential adoption rate related to awareness and acquisition affordability ($ATE_{wp} = E(y_{11}^{***})$) from the empirical analysis is justified by the fact that it measures the same quantity as the potential adoption rate under unrestricted joint awareness–physical access–acquisition affordability ($ATE_{wsp} = E(y_{111})$) since it is measured only for those with physical access to seed ($s = 1$). The choice of three potential adoption rates ATE_w=E(y_1^*), ATE_{ws}=E(y_{11}^*), and ATE_{wsp}=E(y_{111}) for the empirical analysis is justified by their policy relevance in two ways. First, understanding the marginal adoption changes resulting from awareness creation should inform policy on the level of investment required for improving the adoption of DTMVs through activities that enhance the awareness about DTMVs among the farming population. Second, understanding the marginal increase in adoption rates resulting from increased seed availability and affordability should be useful to seed suppliers in forecasting the potential demand for DTMV seed at given market prices and should also inform public policy regarding the magnitude of price support required to enhance farmer's adoption of DTMVs.

The major contribution of this paper is that this is the first attempt to estimate the joint average treatment effect of joint awareness, physical seed access, and acquisition affordability measured by the expected value E(y_{111}). This differs from the marginal adoption rate corresponding to awareness E(y_1^*), defined in Diagne and Demont (2007) and also differs from the joint bivariate potential adoption rate corresponding to awareness and physical access E(y_{11}^*) defined by Dontsop et al. (2013).

In this paper, the observed population adoption rate parameter (which is consistently estimated by the sample adoption rate computed from a random sample) is a measure of the population joint awareness–physical access–acquisition affordability and adoption rate which is the same as the population joint awareness, seed access, at affordable prices, and adoption rate as $E(y) = E(wspy_{111})$ and not a measure of the population joint awareness and adoption $E(wy_{11})$ rate as argued in Diagne and Demont (2007). Hence, in what follows, we use the notation JEAAA (joint awareness–access–affordability and adoption) for the observed population parameters ($E(y)$). It is also clear from the above that $E(y) \leq E(y_1^*) = E(spy_{111}) \leq E(y_{111})$ and $E(y) \leq E(y_{11}^*) = E(py_{111}) \leq E(y_{111})$ (since w, s, *and* p are binary), meaning that the awareness–unconstrained and awareness–physical access–unconstrained, potential adoption rates are both greater than the observed actual adoption rate but always lower than the awareness–physical seed access–acquisition affordability unconstrained potential adoption rate.

We can then define three adoption gaps with one attributable to lack of seed access at affordable prices (Eq. 9), lack of physical seed access (Eq. 10), and lack of awareness (Eq. 11) as follows:

$$GAP_{wsp} = E(y) - E(y_{111}) = JEAAA - ATE_{wsp} \tag{9}$$

$$GAP_{ws} = E(y) - E\left(y_{11}^*\right) = JEAA - ATE_{ws} \tag{10}$$

$$GAP_{w} = E(y) - E\left(y_{1}^*\right) = JEA - ATE_{w} \tag{11}$$

where $ATE_{wsp}$is the average treatment effect parameter when joint awareness, physical seed access, and seed at affordable prices are the treatment variables. ATE_{ws} is the average treatment effect parameter when awareness and seed access, jointly, is the treatment variable and ATE_w is the average treatment effect parameter when awareness is the treatment variable.

According to the ATE framework, the awareness–unrestricted (ATE_w), the joint awareness–physical access–unrestricted (ATE_{ws}), and the joint awareness–physical access–affordability–unrestricted (ATE_{wsp}) potential adoption rates can be defined for various subpopulations by the values x in the support of some random variable X as the average treatment effects conditional on x, $E\ (y_1^* \mid X = x)$, $E\ (y_{11}^* \mid X = x)$, and $E\ (y_{111} \mid X = x)$; E respectively (the conditional ATE parameters). It follows that the potential adoption rates in the subpopulation aware of DTMVs, in the subpopulation aware and with physical seed access, and in the subpopulation aware and with physical seed access at affordable prices, correspond to the average treatment effect on the treated (ATT) parameters and expressed as follows:

$$ATT_w = E(y_1^* | w = 1) \tag{12}$$

$$ATT_{ws} = E(y_{11} | w = 1, s = 1) \tag{13}$$

$$ATT_{wsp} = E(y_{111} | w = 1, s = 1, p = 1) \tag{14}$$

The potential adoption rates in the untreated subpopulations are given by the respective ATE on the untreated (ATU) as follows:

$$ATU_w = E(y_1^* | w = 0) \tag{15}$$

$$ATU_{ws} = E\left(y_{11}^* | w = 0, s = 0\right) \tag{16}$$

$$ATU_{wsp} = E(y_{111}|w = 0, s = 0, p = 0) \quad (17)$$

Furthermore, as in Diagne (2006, 2010) and Diagne and Demont (2007), we will define the awareness, awareness–physical seed access, and awareness–physical access–acquisition affordability population selection bias (PSB) parameters that measure the extent to which the three treatment status variables are not randomly distributed in the population, respectively, as:

$$PSB_w = ATT_w - ATE_w = E\left(y_1^*|w = 1\right) - E\left(y_1^*\right) \quad (18)$$

$$PSB_{ws} = ATT_{ws} - ATE_{ws} = E\left(y_{11}^*|w = 1, s = s_1 = 1\right) - E\left(\ y_{11}^*\right) \quad (19)$$

$$PSB_{wsp} = ATT_{wsp} - ATE_{wsp} = E(y_{111}|w = 1, s = s_1 = 1, p = p_1 = 1) - E(\ y_{111}) \quad (20)$$

The empirical estimation involves the application of the ATE framework to provide consistent estimates of $E(y_1^*),\ E(y_{11}^*),\ and\ E(y_{111})$. In fact, the parameters for y_1^* are identified and estimated exactly the same way as in Diagne and Demont (2007) using the w (awareness) variable while for the case of y_{11}^* and y_{111}, we use the ws and wsp variables, respectively. As shown in Fig. 1, all three variables are only observed for the farmers that are aware of DTMVs (that is, for farmers with $w = 1$) but the products *ws and wsp* are known for all farmers, as also shown above. It is assumed that the conditional independence assumption holds in all cases. As expressed in Donstop et al. (2013), it is assumed that the distributions of the treatment status variables w, ws, *and wsp*, are independent of the distribution of the potential outcomes y_1^*, y_{11}^*, and y_{111}, conditional on a vector of covariates x. That is, using the standard notation for conditional independence (A1): $w \perp y_1 \mid x$, $w,\ s \perp y_{11} \mid x$, and $w,\ s,\ p \perp y_{111} \mid x$. By the propriety of conditional independence, assumption (A1) also implies that $w \perp y_1^* \mid x$ (Donstop et al. 2013). Therefore, we can use the same identification results and estimation procedures as in Diagne and Demont (2007) and Diagne (2012) to identify and estimate parameters related to the three treatments. The Additional file 1 elaborates on the parametric estimation of ATE.

Data and descriptive statistics

Survey design

The data draws from a survey of households conducted by CIMMYT in collaboration with Makerere University in Uganda from four regions in Uganda (East, West, Central, and North) in October 2015. A multistage, random sampling technique was employed in the selection of households for the survey. The first stage involved the selection of regions under the Feed the Future (FtF) zones of influence and where maize is largely grown. The second stage involved the selection of major maize-growing districts from the four regions which led to the selection of 14 districts. From each district, 42 village were selected using a sampling design that makes explicit use of the population measure, "the probability proportional to size" sample design. Finally, 20 farming households were randomly selected from each of the selected villages leading to the selection of 1000 households for the survey[1]. More households were sampled in the Eastern and Northern regions, because they are the largest maize-producing regions in Uganda (Abate 2013). From each of the selected households, detailed information was collected that included household demographic and socioeconomic characteristics, crop production, awareness, adoption dis-adoption of improved maize varieties including DTMVs, production conditions and utilization of maize, social capital risk attitudes, food security, and housing conditions.

Definition of dependent variables

We define adopters as households that reported planting at least one DTMV. In our sample, 14% of the households reported having planted at least one DTMV in one of their maize plots. There are several drivers to adoption, but clearly, in seed-related technologies, as is the case in this study, two key variables are of consideration. First, a household cannot adopt DTMVs if they are not exposed or aware of their existence. Hence, the decision on whether to adopt DTMVs is only relevant to a non-random subsample of households that are aware of the existence of DTMVs. We assessed the awareness of DTMVs by asking respondents whether they had heard of at least one of the DTMVs listed in the questionnaire. We measured the awareness of at least one DTMV as a dummy variable, taking the value of one if the respondent acknowledged being aware of DTMV and zero otherwise. A follow-up question to this was a question of whether the household planted the DTMV in the 2015 growing season. Other important variables in the adoption of seed-related technologies relate to the availability and affordability of the seed itself. We constructed a dummy variable for seed availability by asking respondents that were aware of the existence of DTMVs but did not adopt them to give reasons for no adoption. Based on this question, we were able to identify two extra categories of households: (i) households that were aware of DTMVs and that had physical seed access if they wanted to purchase and (ii) households that were aware of the existence of DTMVs and had affordable access to seed. The difference between the two groups is that the former focuses on the supply side of seed, thus making seed available to the farmer while the latter is confounded by both the supply and demand side, as farmers may fail to purchase seed even when it is availed to them at a price higher than they can afford. Out of 864 farmers in the sample, 57% were aware of DTMVs, 40% had seed access (regardless of affordability), while 25% had seed access at a price they could afford.

Independent variables and descriptive statistics

Table 1 presents descriptive statistics for some of the explanatory variables used in the analysis disaggregated by the adoption status of the households. About 86% of the households were male-headed, and there was no difference in the proportion of male-headed households between adopters and non-adopters. The average household size was 6.4 persons per household, with adopting households reporting significantly (at 5% level) larger households (6.9 persons) than the non-adopters (6.3 persons). The average land holding size was 1.8 ha and adopting households had significantly larger landholdings (2.2 ha) than the non-adopters (1.7 ha). Land allocated to maize (0.88 ha) accounted for 50% of the total land with adopting households allocating a larger size of land (1.2 ha) compared to non-adopters (0.83 ha). This observation is suggestive of the fact that adopters of DTMVs also tend to be better endowed and produce more maize by allocating a larger portion of their land to maize cultivation.

To capture access to information, farmers were asked whether they received information about new varieties. Following this, farmers were asked to mention their main

Table 1 Descriptive statistics by the adoption status of DTMVs

	Full Sample (n = 864)	Adopters (n = 120)	Non-adopters (n = 744)	Mean difference
Household size	6.4	6.9	6.3	0.6**
Gender (1 male, 0 female)	0.86	0.86	0.86	0
Age (yrs)	42	42.6	41.8	0.79
Years of education	6.46	6.69	6.42	0.26
Farm size (ha)	1.78	2.2	1.7	0.5*
Maize area (ha)	0.88	1.17	0.83	0.34***
Received free seed (1 = yes, 0 = otherwise)	0.03	0.12	0.02	– 0.10***
Social capital and access to information				
Received Information on new varieties (%)	39	54	36	18***
Sources of information (%)				
Other farmers	16	17	15	1
Electronic Media	12	11	13	2
Government	4	12	2	9**
Input suppliers	3	5	2	3
Field days	2	4	1	3**
Membership in group(1 = yes, 0 = otherwise)	77	81	76	5
Distance to the market (km)	11.71	12.63	11.56	1.06
Households with incomes enough to save (%)	10	17	9	8**
Had dry spells in 2015 (1 = yes, 0 = otherwise)	0.76	0.76	0.75	0.01
Total livestock units owned	1.07	1.34	1.03	0.32**
Households are aware DTMVs (%)	57.9	100	51.0	48.9***
Household have access to seed (%)	40.7	100	31.1	68.8***
Households have access to affordable seed (%)	25.2	100	13.1	86.8***

*, **, and *** imply that difference between adopters and non-adopters is statistically significant at 90%, 95% and 99% level (t-tests are used for differences in means)

sources of such information. About 39% of the sampled households reported receiving information about new maize varieties in 2015. A significantly higher proportion of adopters (54%) reported receiving information about new maize varieties than the non-adopters (36%), suggesting that the access to information on new maize varieties affected the likelihood of cultivating at least one DTMV. This also suggests differences in access to extension services between the two groups, with adopters having higher access than non-adopters. Other farmers, electronic media, and government extension were the most widely reported sources of information about new varieties. Underscoring the significance of government extension services in promoting DTMV adoption, more adopters (12%) than non-adopters (2%) reported receiving variety information from the government. The findings suggest that non-adopters are more information-constrained than adopters. Membership in social groupings such as cooperatives, farmer groups, and in faith-based organizations can have a significant impact on adoption (Bandiera and Rasul 2006). In our survey, membership in farmer groups was quite prevalent and reported by 77% of the respondents, but there was no difference in membership rates between adopters and non-adopters.

The government of Uganda has been implementing an input subsidy program for some time. Only 3% of the sampled household reported receiving free seed with a significantly higher proportion of adopters (12%) than non-adopters (2%) receiving free seed. Respondents were asked to provide information on the household levels of income. About 10% expressed that their income levels allowed them to make enough savings. A higher proportion of DTMV adopters (17%) than non-adopters (9%) reported belonging to a higher income category.

Results and discussions

Drought-tolerant maize diffusion and adoption: a descriptive analysis

We use the concept "diffusion" to imply awareness or knowledge of the DTMVs by the farmers. In the adoption literature, however, the terms "diffusion" and "adoption" are mostly used interchangeably (Rogers 1976; Sunding and Zilberman 2001). Feder et al. (1985) describes technology adoption as a multistage process the decision-maker undergoes from the time they get exposed to the technology through to the time they decide to start using the DTMVs. Central to the adoption decisions is the role of information about the technology. A lesser discussed issue in adoption literature is the role of the physical seed availability and accessibility at affordable prices and how they affect adoption. As depicted in Fig. 2, the adoption process starts with the potential adopter becoming aware of the existence of DTMVs. The second stage involves information acquisition, through which the potential adopter gets to know DTMV attributes and builds perceptions (Adesina and Forson 1995). While this phase determines whether the producer has heard about the DTMVs, it is also a learning phase during which the potential adopter gets to further understand the attributes of a technology. Consistent with this notion, Klotz et al. (1995) posit that a producer's optimal information level is the solution to an underlying utility-maximization problem characterized by an income-leisure trade-off and that conditional upon the producer being aware of a new technology, the decision of whether to adopt the new technology is made. Most adoption literature (Diagne and Demont 2007; Simtowe et al. 2016; Kabunga et al. 2012) assumes that conditional on awareness, seed should be available and accessible; hence, farmers are expected to immediately move in to the trial and experimentation stage. However, experimentation and trial only occur on two conditions: (1) that seed is physically available; thus, seed is produced by the seed supplier and locally available and (2) that seed is affordable to the farmer, thus availed at prices

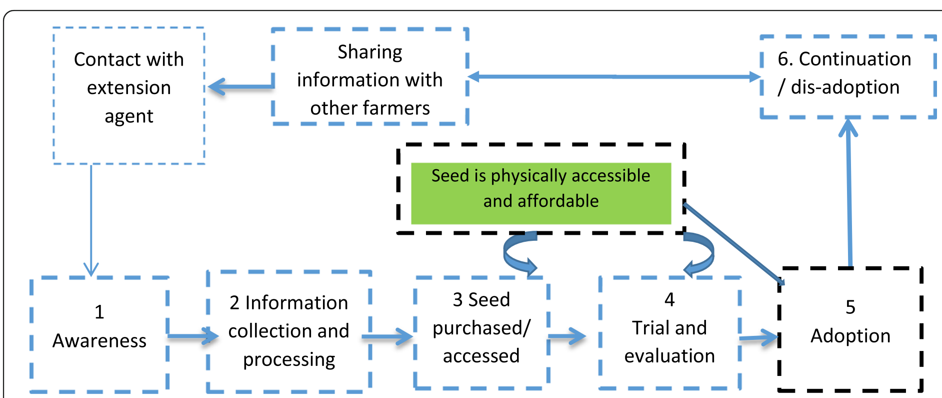

Fig. 2 Stages of the adoption process for improved seeds

commensurate with farmer's incomes. Thus, we include in between the third and fourth stages an assumption of seed availability and accessibility. The fourth stage then involves trial or experimentation by the potential adopter on a small portion of land before adoption. The individual then goes through the fifth stage, which involves the actual DTMV adoption, which is again conditioned on the availability of and accessibility to the seed. After adoption, a farmer may decide to continue or discontinue using it depending on the experience and benefits. We follow the definition of Feder et al. (1985) of adoption as the decision to use an innovation in long-run equilibrium given full information about its potential. We thus confine the definition of adoption to the growing of one or more of the drought-tolerant maize varieties by a farmer.

Table 2 depicts results of DTMV diffusion and adoption[2]. About 57% of the respondents expressed awareness of at least one DTMV. Knowledge of DTMVs was more prevalent in the Northern (82%) and Eastern regions (67%). However, only 18% expressed ever growing one of the DTMVs and only 14% grew one of the DTMVs in 2015.

These sample adoption rates are likely to be biased downwards because they include farmers who were not yet exposed to the varieties as well as those who had no access to seed, and therefore, they cannot adopt unless exposed and given access to seed. There are significant differences in adoption rates for DTMVs between the sample adoption rate and the adoption rate within the exposed subsample and the subsample with access to seed. The overall adoption rate among the subsample of exposed farmers in 2015 season was 24% compared to a lower adoption rate of 14% for the whole sample, while the adoption rates among those with access to seed was about 54%. However, the adoption rates among the subsamples that are exposed and those that have access to seed are likely to significantly overestimate the population adoption rate due to the positive selection bias by which the population most likely to adopt gets exposed first and gets access to seed. Diagne (2006) points out that the positive selection bias arises from two sources. The first source is the farmer's self-selection into exposure. The second source of selection bias is the fact that researchers and extension workers target their technologies at farmers who are more likely to adopt. For this study, a third source of selection bias in the context of access to seed is that by which seed traders and distributors sell seed in regions where they expect higher profits due to a combined effect of lower transaction costs, better prices, and higher volumes to be sold, making seed availability a non-random variable.

Table 2 Diffusion and adoption of DTMVs

Characteristic	Total (n = 864)	East (n = 438)	West (n = 45)	North (n = 322)	Central (n = 58)
Know at least one DT variety	57.9	67.8	82.2	44.7	36.2
Ever planted at least one DT variety	17.8	24.4	35.6	8.7	5.2
Planted at least one DT variety in 2015	13.8	19.6	28.9	5.6	3.4
Planted at least one DT variety in 2015 among those aware	23.8	29	35.1	12.5	9.5
Planted at least one improved variety (OPV or hybrid) in 2015	72.9	71.1	93.3	70.2	86.2
Planted at least one OPV variety	49	41.1	64.4	57.8	48.3
Planted at least one hybrid variety	27.7	32.3	31.1	13.7	37.9
Planted at least one local variety	26.9	29.5	6.7	28.9	12.1

Determinants of exposure to DTMV and of access to DTMV seed

About 40% of the farmers reported that DTMV seed was available to them, while 25% reported having access to seed at prices that they could afford. Based on this categorization, we estimate three probit regressions (Table 3) of factors that affect the propensity of exposure to DTMVs (model 1), the propensity of seed availability in addition to awareness (model 2), and the propensity of access to affordable seed in addition to awareness and seed availability (model 3). The results across the three models show that several variables show statistically significant coefficients.

Table 3 Probit estimates of the determinants of exposure, access and affordability of DTMV seed

	Model 1 (exposure)	Model 2 (exposure-seed access)	Model 3 (exposure-seed access at affordable price)
Gender of hh head (1 − m, 0 = f)	0.110	0.048	− 0.015
Years of education	0.000	0.003	0.010*
Age of head of household	− 0.093	− 0.028	− 0.015
Household size	0.015*	0.011	0.012*
Membership in association (1 = yes, 0 = otherwise)	0.056	0.074	0.013
Farm size	− 0.005	− 0.017	0.00
Distance to market	0.002	0.001	0.003
Information sources (reference group: no information received)			
Government	0.380***	0.450***	0.278**
NGOs	0.318***	0.268	0.214
Field days	0.372***	0.428***	0.203
Radio	0.006	0.055	− 0.03
Agro-dealers	0.379***	0.366***	0.167
Other farmer	0.365***	0.247***	0.036
Electronic media	0.409***	0.239***	0.120*
Income status (reference group; insufficient need borrowing)			
Allows to build savings	0.053	0.111	0.333***
Allows to save	0.057	0.105	0.194**
Income equal expenses	− 0.019	0.043	0.106
Draws from saving	0.047	0.077	0.154
Frequency of drought	− 0.009	− 0.012	− 0.015
Received subsidy (1 = yes, 0 = no)	0.131	0.271**	0.387***
Livestock units	0.033*	0.009	0.018
Eastern	0.296***	0.336***	0.250***
Western	0.360***	0.419***	0.413***
Northern	0.107	0.045	− 0.007
No. of observations	864	864	864
Log likelihood	− 436.97	− 480.80	− 411.13
LR chi-squared	288.46	197.05	153.24
Df	29	29	29
Pseudo R^2	0.25	0.17	0.20

$^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

Determinants of exposure

For the exposure model (model 1, column 2), the size of the household returned a positive and significant coefficient (at 10%), suggesting that larger households have a higher propensity to come across information that exposes them to DTMV. This finding suggests that the demographics of a household have implications for the information search behavior of a household related to the costs and effort. It is not surprising that most of the proxy variables for access to information and extension services were highly significant (at 1%) and returned the expected positive coefficient, underscoring the importance of farmers' extension systems in the diffusion of information about new technologies. All income status variables returned insignificant coefficients, suggesting that income did not affect the farmer's awareness of DTMVs since most information is usually disseminated for free by government, fellow farmers, and through other farmer gatherings.

Determinants of seed availability in addition to awareness

Model 2 (column 3) presents marginal effects of the probability of households reporting seed availability in addition to being aware of DTMVs without considering the seed price. The results show that reliance on government, field days, agro-dealers, other farmers, and electronic media for information on new varieties increased the likelihood of reporting that seed was available to the household. However, the magnitude of the effect of these variables is much lower than in the exposure model (model 1), suggesting that seed availability is also influenced by other factors such as free seed distribution by government, which also returned a positive and significant coefficient which underscores the potential role of public interventions in increasing seed accessibility by farmers.

Determinants of seed affordability in addition to awareness and availability

Model 3 (column 4) presents results of the likelihood of having access to DTMV seed at an affordable price in addition to being aware of DTMV. During the study year, the most cultivated DTMV (Longe 10H) was selling between UgS 4000 and 6000 per kilogram of seed[3] depending on the location. However, farmers were willing to pay an average price of UgS 2150 per kilogram, which is almost half of the market price. A key observation is that farmers in Uganda are used to purchasing open pollinated maize varieties at a lower price of about US$ 0.7–0.8 per kilogram. Hybrid varieties were introduced at a higher price of about US$1.3–2 per kilogram depending on the variety and company, and farmers have not come to terms with price differences between the OPV and hybrid. Such misunderstanding can be cleared with intensified promotion of the hybrids, including DTMVs and the reasons for price differences between hybrids and OPVs.

The results in Table 3 show that more years of education enhances the probability of having access to DTMV seed at an affordable price. The coefficient for household size was positive and significant (at 10%), suggesting that a percentage increase in the size of the household increases the probability of accessing seed at affordable prices by 12%.

Moreover, relying on government as a source of information also increased the probability of accessing affordable seed by 28%. Two of the wealth-related variables returned positive and significant coefficients. Households with incomes large enough to build savings and those whose incomes were just enough to allow them to make some savings were more likely to report access to affordable seed than low-income households. Furthermore, being a recipient of free seed from the government increased the probability of accessing DTMV seed at affordable prices by about 39%. In general, the findings on awareness underscore the need for intensified efforts to create awareness about the existence of DTMVs among farmers the need for interventions that enhance the availability and affordability of DTMV seed to farmers.

Predicted DTMV adoption rates

The results of the predicted adoption rates with and without ATE correction for different DTMV population awareness, seed availability and seed affordability, population selection biases, and adoption gaps are presented in Table 4. The sample awareness of DTMVs in the study area in Uganda was estimated to be 57.4%, whereas the estimated seed access and seed access at affordable prices was 40.4% and 25.3%, respectively, in 2015. These results indicate that not all maize farmers in Uganda knew about the existence of DTMVs and that only a quarter had seed access at affordable prices. The observed sample adoption rate for DTMVs was 14%. This is much lower than what is reported in Fisher et al. (2015) for Uganda, apparently due to differences in the classification of DTMVs[4]. The joint treatment and adoption rates[5] for all of the three ATE-corrected models are also around 14%. Diagne and Demont (2007) show why the observed sample adoption rates are expected to be the same as the ATE-corrected joint treatment and adoption rates. Indeed, in the absence of universal diffusion and access to DTMV seed among the maize farming population, the observed adoption rate estimates significantly understate the potential adoption rate (i.e., the adoption rate that would be obtained if the whole

Table 4 Predicted DTMVs adoption rates

	Parameter with awareness unconstrained			Parameter with awareness–access–unconstrained			Parameter with awareness–access–affordability–unconstrained		
	Est	S.E	*Z*	Est	S.E	*Z*	Est	S.E	*Z*
ATE-corrected population estimates									
Predicted adoption rate in full population (ATE)	0.219*	0.018	12.42	0.295*	0.025	11.69	0.466*	0.038	12.22
Predicted adoption rate in treated subpopulation (ATT)	0.241*	0.017	13.82	0.342*	0.023	14.8	0.542*	0.031	17.63
Predicted adoption rate in untreated subpopulation (ATU)	0.190*	0.022	8.69	0.263*	0.030	8.77	0.440*	0.043	10.21
Joint treatment and adoption rate (JTA)	0.138*	0.010	13.80	0.138*	0.009	14.8	0.137*	0.008	17.63
Population adoption gap (GAP)	− 0.081*	0.009	− 8.69	− 0.16*	0.018	− 8.7	− 0.329*	0.032	− 10.21
Population selection bias(PSB)	0.022*	0.007	3.11	0.047*	0.013	3.59	0.077*	0.023	3.41
Observed sample estimates									
Rate of treated (N_e/N)	0.574*	0.017	33.86	0.404*	0.017	24.12	0.253*	0.015	17.07
Adoption rate (N_a/N)	0.138*	0.012	11.70	0.138*	0.012	11.69	0.139*	0.012	11.8
Adoption rate among the treated subsample	0.241*	0.021	11.70	0.340*	0.029	11.69	0.550*	0.047	11.8

*Statistical significance at 5% level

population were exposed to the DTMVs or have seed access). The predicted adoption rate for the full population after correcting heterogeneity in the awareness of DTMV (ATE_w) was 22%. This is higher than the observed sample adoption rate because of the low levels of diffusion of DTMVs among the farming community. This indicates that if the entire population of maize farmers was aware of DTMVs in 2015, the effective demand for DTMV seed could have increased from 14% to 22%, resulting in an adoption gap due to the lack of DTMV exposure of 8%.

Correcting for heterogeneity in the joint awareness and physical seed availability, the predicted adoption rate for the full population (ATE_{ws}) was 30%. This means that if, in addition to being aware, all farmers had DTMV seed physically availed to them, the effective demand of DTMV seed would have been 30%. The corresponding estimate of the adoption gap of 16% resulting from non-availability of seed can therefore be interpreted as the seed access gap, which is the potential demand loss due to non-access to seed (Donstop et al. 2013), which also suggests that there is scope for scaling the cultivation of DTMVs in Uganda if seed companies can increase the supply of seed to the farming community.

The cost of seed can prevent potential adopters from adopting DTMVs. This is apparently the case in Uganda, where correcting for heterogeneity in joint awareness–seed availability–accessibility to affordable seed increases the predicted DTMV adoption rate for the full population (ATE_{wsp}) to 47%. The corresponding estimate of the adoption gap resulting from the joint lack of awareness, seed access, and seed at an affordable price is 32% and significant at 1% level. These adoption gap estimates imply that there is still potential for increasing DTMVs adoption rates significantly once awareness, and seed accessibility constraints are addressed. It should be emphasized that these estimated adoption gaps are solely due to the lack of awareness of the existence of DTMVs, lack of seed, and a lack of access to affordable seed. However, the magnitude of the adoption gaps depends on the same factors that determine the probability of treatment participation and population adoption rates. Hence, by appropriately changing the values of these determinants through some policy instruments, one can increase actual adoption through a simultaneous narrowing of the adoption gap and an increase in the population adoption rate (Diagne 2010).

The results suggest that scaling DTMVs in Uganda will not only rely on the dissemination of information about DTMVs, nor the increased supply of seed, but that it will also depend on the extent to which the set price of seed is commensurate with the purchasing power of farmers. In other words, awareness creation ought to be done simultaneously with seed supply. Moreover, the fact that making seed affordable could scale the cultivation of DTMV to almost half of the farmers should be of interest to the government of Uganda, which has been running an input subsidy program for more than a decade.

The predicted adoption rate among the subpopulations that were exposed to DTMVs (ATT_w) was 24%, which is slightly higher than that of a full population (ATE_w) of 22% indicating a positive population selection bias (PSB). Similarly, the predicted adoption rates among subpopulations aware of DTMV and with physical accessibility to seed (ATT_{ws}) were higher (34%) than those of the full population (ATE_{ws}) estimated at 29.5%. The population selection biases were positive and were estimated to be 2%, 5%, and 8% for exposure, joint exposure and seed availability, and seed affordability, respectively. The positive PSBs imply that the probability of adoption for a farmer with exposure to DTMVs and with access to seed is significantly higher than the propensity of adoption for any other farmer randomly selected in the general population, which suggests an association with successful targeting of the DTMV scaling efforts in Uganda.

The results show that the estimated adoption rate within the awareness unconstrained subpopulation (ATT_w) of 24% was smaller than the adoption rate of 34.2% among the subpopulation with awareness–access–unconstrained (ATT_{ws}). As expressed by Donstop et al. (2013), the gap of 10% between the two adoption rates can be explained by the fact that the subpopulation of farmers who were aware and had access to seed was included in the subpopulation of farmers who were aware of the variety. For the same reason, the estimated adoption rate within the awareness unconstrained subpopulation (ATT_w) and that among the subpopulation with awareness–access–unconstrained(ATT_{ws}) are both smaller than the adoption rate with a subpopulation with awareness–access–affordability unconstrained (ATT_{wsp}) of 54.2%. The potential adoption rates among the subpopulations of farmers who were not exposed (ATU_w), who were not exposed and had no access to seed (ATU_{ws}), and who were not exposed, had no physical access to seed and at affordable prices (ATU_{wsp}) were 19%, 26%, and 44%, respectively.

Determinants of DTMV adoption under information and seed access constraints

Results on the determinants of DTMVs of the ATE probit model are presented in Table 5. The results are presented in the form of marginal effects and are presented based on three models. Results in model 1 (column 2) present determinants of adoption conditional on exposure to the DTMVs. The reliance on fellow farmers as a source of information lowers the propensity to adopt DTMVs by 9%. Belonging to a higher income group of households that have enough savings increases the propensity to adopt DTMVs by 37% compared to households with low income and that require borrowing to participate in economic activities. Receiving free maize seed from government also increases the propensity to grow DTMVs maize by 62%, suggesting that there is scope for scaling out the cultivation of DTMVs through the scaling of input subsidy programs that enable low-income households to access seed which they would otherwise not access under prevailing market prices.

The results in model 2 (column 3) are consistent with those in model 1, with the wealth-related variable turning out as crucial determinants of adoption. However, in model 3, conditional on having access to affordable seed, the effect of wealth-related categories, though positive, fizzles out while access to free seed from government increases the propensity to adopt DTMVs by 47%. The findings largely underscore the significance of addressing both the supply side and demand side constraints in promoting the adoption of DTMVs.

Conclusions

We have provided estimates of actual and potential adoption rates and the determinants of adoption for DTMVs under three scenarios: (1) conditional on exposure, (ii) conditional on (physical) seed availability in addition to awareness, and (iii) conditional on seed affordability in addition to awareness and (physical) availability. We find that the DTMV adoption in Uganda could have been up to 22% in 2015 instead of the observed sample adoption rate of 14% if the whole population was exposed to them, suggesting that there is potential for increasing the adoption rate of DTMVs by 8 % if its

Table 5 ATE-corrected marginal effects of the determinants of adoption of DTMVs under heterogeneous seed access and information exposure

	Model 1 (ATE probit with exposure unconstrained)	Model 2 (ATE probit with exposure–access–unconstrained)	Model 3: (ATE probit with exposure–access–affordability–unconstrained)
Gender of hh head (1 = m, 0 = f)	− 0.076	− 0.082	− 0.047
Years of education	0.002	0.001	− 0.013
Age of head of household	− 0.079	− 0.117	− 0.197
Household size	0.007	0.009	0.007
Membership in association (1 = yes, 0 = otherwise)	− 0.009	− 0.037	− 0.006
Farm size	0.000	0.01	0.008
Distance to market	0.027	0.036	0.039
Information sources (reference group: no information received)			
Government	0.148	0.137	0.222
Field days	0.084	0.08	0.233
Radio	− 0.024	− 0.063	0.036
Agro-dealers	0.068	0.131	0.259
Other farmer	− 0.085*	− 0.102	− 0.054
Income status (reference group; insufficient income need borrowing)			
Allows to build savings	0.371**	0.420**	0.213
Allows to save	0.213*	0.260*	0.175
Income equal expenses	0.102	0.094	− 0.004
Draws from saving	0.286*	0.331*	0.359*
Frequency of drought	− 0.005	− 0.003	0.007
Received Subsidy (1 = yes, 0 = no)	0.619***	0.606***	0.467***
Livestock units	0.011	0.016	0.007
Eastern region	0.291**	0.342**	0.442**
Western region	0.379*	0.399*	0.375**
Northern region	0.082	0.147	0.24
No. of observations	489	345	214
Log likelihood	− 221.67	− 182.85	− 123.43
LR chi^2	86.0	73.10	48.48
Df	29	29	29
Pseudo R^2	0.78	0.17	0.16

We only present results of the ATE-corrected adoption models for exposure, seed availability and access to seed at affordable prices
*$p < 0.10$, **$p < 0.5$, ***$p < 0.01$

knowledge can be extended to the masses. Conditional on awareness and seed availability, the adoption rate could increase to 30%, and if in addition to awareness and seed availability, the seed were also made available at an affordable price, the adoption rate could increase to 47%. The findings suggest that unlocking the DTMV adoption puzzle will partially depend on relaxing the information constraint and making seed widely accessible and at affordable prices to farmers.

Exposure to DTMVs is largely influenced by the extent to which the household has access to information on new varieties through the extension support services, while seed accessibility is largely a function of wealth-related factors. Conditional on awareness of the DTMV, household relying on neighbors as sources of information have a lower propensity to adopt than those relying on other formal sources of information. Conditional on accessing seed, wealthier households and those with access to free seed provided by the government are more likely to grow DTMVs than those that do not have access to free seed. The findings underscore the need for deploying both market and non-market-based approaches in DTMV scaling in Uganda. Market-based approaches could support in-country partnerships that enhance seed supply by seed companies and linking farmers to finance institutions to access credit for seed and fertilizer, while non-market-based approaches could further extend and target the seed subsidy program.

The results further show that universal adoption of DTMVs is unlikely even after addressing both information and seed access constraints, which suggest that there are other constraints to DTMV adoption. Such constraints may include, but are not limited to, other (e.g., more humid) maize agro-ecologies, the existence of other competing (non-DTMV) maize varieties (e.g. other hybrid maize varieties available on the market), and variety attributes currently not present in the DTMV portfolio. Some of these constraints can be addressed through further breeding efforts that embed preferred traits into the DTMVs without compromising on their performance under drought conditions.

Endnotes

[1]The analysis is based on households that grew maize in the major growing season of 2015, hence the sample of 864.

[2]A full description of the actual varieties adopted is presented in the Appendix

[3]One US dollar is equivalent to 3700 Uganda shillings

[4]In this study, we excluded some varieties from the DTMV list because after discussions with breeders, they were found to be non-drought tolerant. The variety called Longe5, for example, is widely cultivated and was classified as drought tolerant, but after discussions it has been agreed that it is non-tolerant to drought, hence excluded from our list of DTMVs.

[5]Other authors, for example Diagne and Demont (2007) and Kabunga et al. (2012), call this the joint exposure and adoption (JEA) because exposure is their major treatment of interest.

Additional file

Additional file 1: Table S1. Diffusion and adoption of DTMVs in Uganda. (DOCX 38 kb)

Appendix

Parametric estimation of ATE

The consistent estimation of ATE and ATT requires controlling appropriately for the treatment status. One approach is based on the conditional independence assumption (Wooldridge 2002: Ch. 18; Imbens and Wooldridge 2009), which states that a set of observed covariates determining treatment status when controlled for renders the treatment status w independent of the potential outcomes y_1 and y_0 (Kabunga et al. 2012). The ATE parameters can be estimated based on the following equation that identifies

$ATE(x)$ and which holds under the conditional independence (CI) assumption (see Diagne and Demont 2007):

$$ATE\ (x) = E(\ \hat{y_i}|x) = E(y|x, d = 1) \quad (21)$$

where d is the treatment status and $\hat{y_i}$ is a generic variable that stands for the potential adoption outcomes ($y_1^*, y_{11}^*,\ \ or\ y_{111}$). Awareness is the treatment variable $d = w$ while when joint awareness and physical access to seeds is the treatment $d = ws$. Joint awareness–physical access to seed–acquisition affordability is the treatment variable, $d = wsp$ (Eq. 21). It follows that $(d, \hat{y_i}) = (w, y_1^*), (ws, y_{11}^*),$ and (wsp, y_{111}). The parametric estimation proceeds by first specifying a parametric model for the conditional expectation in the right-hand side of the second equality of Eq. (21), which involves the observed variables y, x, and d:

$$E(y|x, d = 1) = g(x, \beta) \quad (22)$$

Where g is a known (possibly nonlinear) function of the vector of covariates x and the unknown parameter vector β which is to be estimated using standard least squares (LS) or maximum likelihood estimation (MLE) procedures using the observations (y_i, x_i) from the subsample of exposed farmers, only with y as the dependent variable and x the vector of explanatory variables. With an estimated parameter $\hat{\beta}$, the predicted values $g(x_i, \hat{\beta})$ are computed for all the observations i in the sample (including the observations in the non-treated subsample) and ATE, ATET and ATU are estimated by taking the average of the predicted $g(x_i, \hat{\beta})$ $i = 1,..,n$ across the full sample (for ATE) and respective subsamples (for ATT and ATU) (Diagne and Demont 2007):

$$A\hat{T}E = \frac{1}{n}\sum_{i=1}^{n} g\left(x_i, \hat{\beta}\right) \quad (23)$$

$$ATT = \frac{1}{n_e}\sum_{i=1}^{n} w_i g\left(x_i, \hat{\beta}\right) \quad (24)$$

$$ATU = \frac{1}{n - n_e}\sum_{i=1}^{n} (1 - w_i) g\left(x_i, \hat{\beta}\right) \quad (25)$$

As also expressed by Diagne and Demont (2007), the effects of the determinants of adoption as measured by the K marginal effects of the K-dimensional vector of covariates x at a given point $\overline{x}$ are estimated as:

$$\frac{\partial E(y_1|\overline{x})}{\partial x_k} = \frac{\partial g\left(\overline{x}, \hat{\beta}\right)}{\partial x_k} \quad k = 1, .., K \quad (26)$$

where x_k is the kth component of x. The estimation is conducted in two stages, with the first stage explaining the determinants of being treated (w, ws, wsp), before estimating the adoption model in the second stage.

Abbreviations

ATE: Average treatment effect; ATT: Average treatment effect on the treated; ATU: Average treatment effect on the untreated; DTMV: Drought-tolerant maize varieties; FtF: Feed the Future; PSB: Population selection bias

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Authors' contributions
All authors in this paper variously contributed to the data collection, data analysis, and/or write-up of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The data used in this study are from the household survey conducted in Uganda in the year 2015 and are available on request

Competing interests
The manuscript is not under any competing interests and it is not being considered for publication elsewhere.

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