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Scalability of Adaptation strategies to drought stress: the case of drought tolerant maize varieties in Kenya

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ABSTRACT

Droughts have devastating effects on agricultural productivity and livelihoods, which triggers a quest for adaptation strategies such as the development and deployment of drought tolerant maize varieties (DTMVs). This study examines the scalability of DTMVs in Kenya using household survey data from eight counties. Results show that the 2018 DTMV adoption rate of 26% could be doubled to 52% as farmer knowledge constraints are alleviated, could potentially be further increased to 56% if seed access constraints are addressed, and even rise to 60% if seed affordability constraints are lifted. There is heterogeneity in scalability across counties attributable to differences in levels of scaling efforts. The use of electronic media appears to be a key success factor to create awareness about DTMVs but could exclude more marginalized households and communities, which highlights the need for multipronged awareness strategies. Scalability calls for public-private partnerships to foster a sustained supply of seed to the farming communities at competitive prices.

KEYWORDS

Drought tolerance; maize varieties; scalability; seed accessibility; affordability; Kenya

1. Introduction

Climate change predictions for sub-Saharan Africa (SSA) suggest rainfall reduction, increasingly variable/erratic rainfall distribution patterns, and higher frequency of droughts (Hadebe et al., 2016). In SSA, where maize production is primarily rainfed, climate change poses significant risks to productivity (Cairns et al., 2012; Heisey & Rubenstein, 2015). Climate change models predict maize yield losses of 5–33% by 2050, depending on the severity of climate change (Jones & Thornton, 2003; Nelson et al., 2010). Maize losses are expected to affect downstream sectors such as the food-processing, animal feed and poultry sectors (Gbegbelegbe et al., 2014; Pauw et al., 2010), as well as cause a sharp increase in maize prices (Ignaciuk & Mason-D'Croz, 2014). Hence, adaptation strategies that buffer the effects of climate change are important.

In Kenya, maize is a major food crop, accounting for 40% of the crop area (2.1 million hectares) and for more than 51% of all staples grown, yet yield remains low (1622 kg/ha, CIMMYT, 2015). This low maize productivity is attributed to abiotic stresses such as poor soil-fertility and frequent droughts (Worku et al., 2020), as well as biotic stresses (Cairns & Prasanna, 2018; Keno et al., 2018). To enhance maize yields and to adapt to climate change, drought-tolerant maize varieties (DTMVs) have been developed and deployed by the International Maize and Wheat Improvement Center (CIMMYT) in partnership with the Kenya Agricultural and Livestock Research Organisation (KALRO) and seed companies. In addition to drought tolerance, the stress tolerant varieties have other key attributes/traits, such as resistance to major biotic stresses, responsiveness to inputs and good nitrogen use efficiency (Fisher et al., 2015).

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New stress tolerant maize varieties can out-yield commercial checks by 50% under on-farm testing conditions (Setimela et al., 2012, 2014). D this, DTMV adoption in Kenya is far from universal (CIMMYT, 2017). This calls for a facilitative approach for widespread adoption of improved technologies and practices at the population level, also known as scaling (USAID, 2015).[1]

In Kenya, the scaling of DTMVs involves a number of stakeholders including CIMMYT, public sector institutions such as KALRO, the private sector (seed companies and agro-dealers) as well as Non-Governmental Organizations (NGOs). The process involves developing germplasm, subjecting it to the National Performance Trials (NPTs), then releasing the variety, certifying seed production, and distributing them to farmers.

Previous studies aimed to understand the diffusion processes of DTMVs (Simtowe et al., 2019). Adoption rates indicate that there is scope for wide adoption of these varieties once information and seed access constraints are addressed.

This paper seeks answers to two related questions: (1) What is the potential for scaling DTMVs in Kenya? (2) What are the promising interventions to realize such scaling potential? Such analysis is critical to understand the current bottlenecks to DTMV adoption and for planning and partnership building for better scaling of them. We answer these questions by applying the average treatment effect (ATE) framework initially proposed by Diagne and Demont (2007) and applied by others (Dontsop et al., 2013; Kabunga et al., 2012) but follow Simtowe et al. (2019) to extend the framework by considering the physical availability and the price affordability of seed. We proceed in Section 2 by discussing the scaling strategy being deployed, while Section 3 presents the analytical framework, and Section 4 provides data sources and descriptive statistics. Section 5 presents the results and discussions, and section 6 concludes.

2. Scaling of DTMVs

CIMMYT has been implementing a product-oriented breeding programme targeted at improving maize for the drought stress prone mid-altitudes of Eastern and Southern Africa. As depicted in Figure 1, the scaling of DTMV products involves several players, including farmers, public and private entities as well as NGOs. For Kenya, CIMMYT develops hybrid seed with KALRO and/or seed companies. New DTMVs can be tested in the NPT in which performance of the new hybrids is compared to commercial checks under a wide range of environments representative of the target agroecology. Following results from NPT testing over two years, the hybrid may be recommended for release if the performance of the new hybrid yields 10% above the mean of the commercial check, and it has the key attributes like foliar disease resistance. The next stage involves performance evaluation of the hybrid and its parents in the distinct, uniform and stability (DUS) test after which the hybrid is recommended to the NPT committee for release and gazette by the government. After release, the process of commercialization is initiated with production of basic/foundation seed from breeder seed; and production of certified seed from basic/foundation seed. Certified seed of the hybrid may be sold to farmers through various distribution channels including through the seed company's own outlets, agro-dealers and stockists.

A major seed scalability factor relates to the capacity of the seed companies and the National Agricultural Research Systems (NARS) to produce foundation seed. Foundation seed has been found to be one of the bottlenecks in the seed industry (Langyintuo et al., 2008). CIMMYT partners with both small and medium sized seed companies to scale DTMVs. Some of these seed companies may lack capacity to maintain the genetic purity of breeder seed, leading to challenges with foundation seed production. Thus, some seed companies rely on partners such as CIMMYT to supply breeder seed in order to produce foundation seed.

CIMMYT strengthens capacities of different actors along the seed value chain to help address breeder and foundation seed constraints. It provides training to breeders and technicians from NARS and seed companies on maintenance of parental inbred lines, basics of breeder and foundation seed production, and development and use of seed roadmaps to plan for future demands of all classes of seed. Seed companies are also trained in marketing strategies. A company called QualiBasic Ltd. has been established to produce and supply quality foundation seed (basic seed) to seed companies in Eastern and Southern Africa. Many seed companies lack capacity to produce large volumes of certified seed and need support to sustain seed production activities.

In collaboration with partners, CIMMYT also trains agro-dealers in business management, seed storage and marketing. Such partnerships between seed

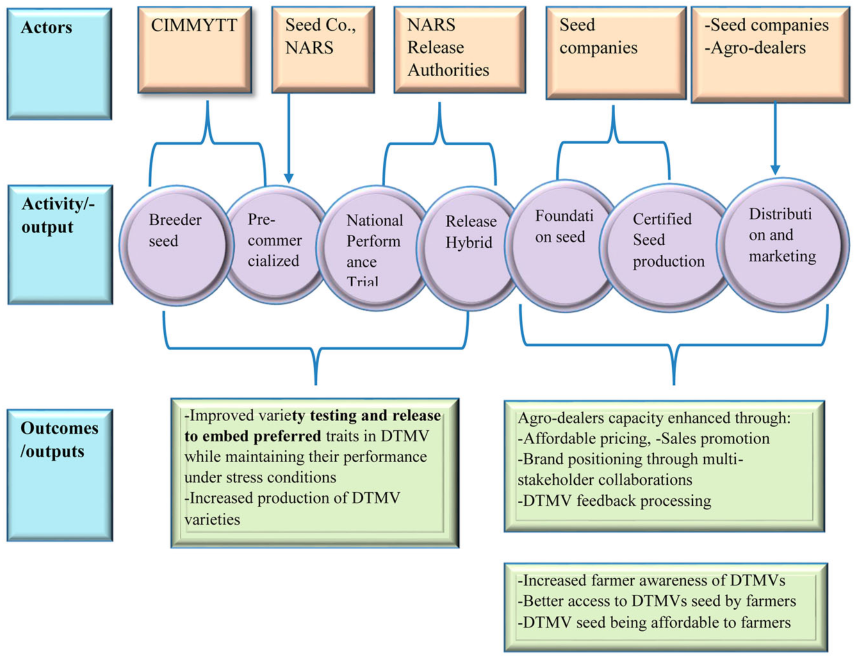

Figure 1. Flow chart showing scaling strategy for drought tolerant maize varieties.

companies, the Ministry of Agriculture and other national research institutions, agro-dealers and NGO-based extension agents have led to a rapid scale-out of certified seed production and distribution. The demand for DTMVs is a key driver of the DTMV seed value chain. Demand is generated through partnerships with extension providers who create awareness about the DTMVs through several channels including demonstration plots, radio, and face to face field visits in farmers' fields by extension agents. Despite such efforts, there is often a gap in understanding the potential demand and adoption rates for DTMVs and the extent to which such efforts can lead to sustained wide adoption among farming communities in Kenya.

2. Analytical framework

The analytical framework for understanding adoption decisions is based on Simtowe et al. (2019). To better understand adoption decisions, one needs to understand whether a potential adopter is informed about the existence of the technology, has access to the technology, and at a price that is affordable. Many factors influence adoption, but one cannot adopt a technology if it is not affordable, even if one is aware of it and it is physically available. The framework is thus quite relevant to understanding the adoption potential for DTMVs in Kenya.

In Figure 2 we show that awareness of and access to DTMV seeds are both necessary conditions for adoption. Indeed, while it is possible to observe farmers that are aware of improved varieties without getting access to the seeds, it is not possible to observe the access to seed status among farmers that are not aware of the existence of DTMVs (Figure 2). By extension, the farmers can be aware of DTMVs without having access to the seeds 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 of DTMVs and among those that have no physical access to seed. Similar to Dontsop et al. (2013), we use the term 'access' here to imply physical availability of the seed in the farmer's environment and not the acquisition availability (affordability).

We follow Simtowe et al. (2019) to identify the status of each of the sampled households in terms of their awareness of DTMVs, their physical access to DTMV seed and their ability to purchase seed at market prices. As depicted in Figure 2, in the first stage, all farmers were asked whether they knew

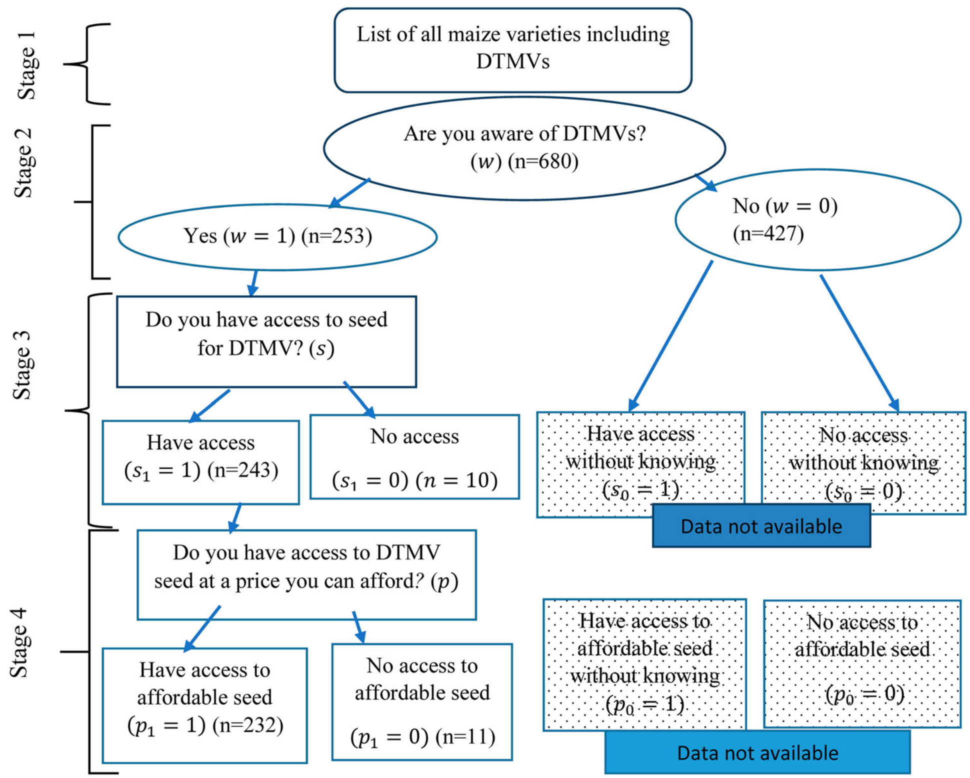

Figure 2. Flowchart linking DTMV awareness, seed access and affordability variables.

specific DTMVs. In the second stage, those who reported having knowledge (denoted by 'w') of DTMVs ($w = 1$), were asked: 'If you want to plant this variety, do you have access to seed of this variety?' If a farmer responded (s)he had physical access to the seed of that variety of DTMV, (s)he was asked: 'If you want to purchase seed for this variety, can you afford it?' Based on these questions, we identified the status of each household in terms of DTMV awareness, physical access to DTMV seed and affordability of DTMV seed. We denote 's' to stand for the (physical) access to seed 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 DTMVs (that is $w = 0$), they were not asked the questions related to access to seed. As expressed by Dontsop et al. (2013), this implies that we do not have information on access to DTMV seeds for 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 without their knowledge of it. Dontsop et al. (2013) note that 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 acquisition affordability seed 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 questions related to seed affordability. As in the case of the availability of seed, this also means that we do not have information on access to the 'affordable' seed for the farmers who were not aware of DTMVs. Indeed, some farmers who were not aware of DTMVs may have been able to afford DTMV seed even though they were not aware of their existence.

Based on the earlier explanation, the physical access to seed 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

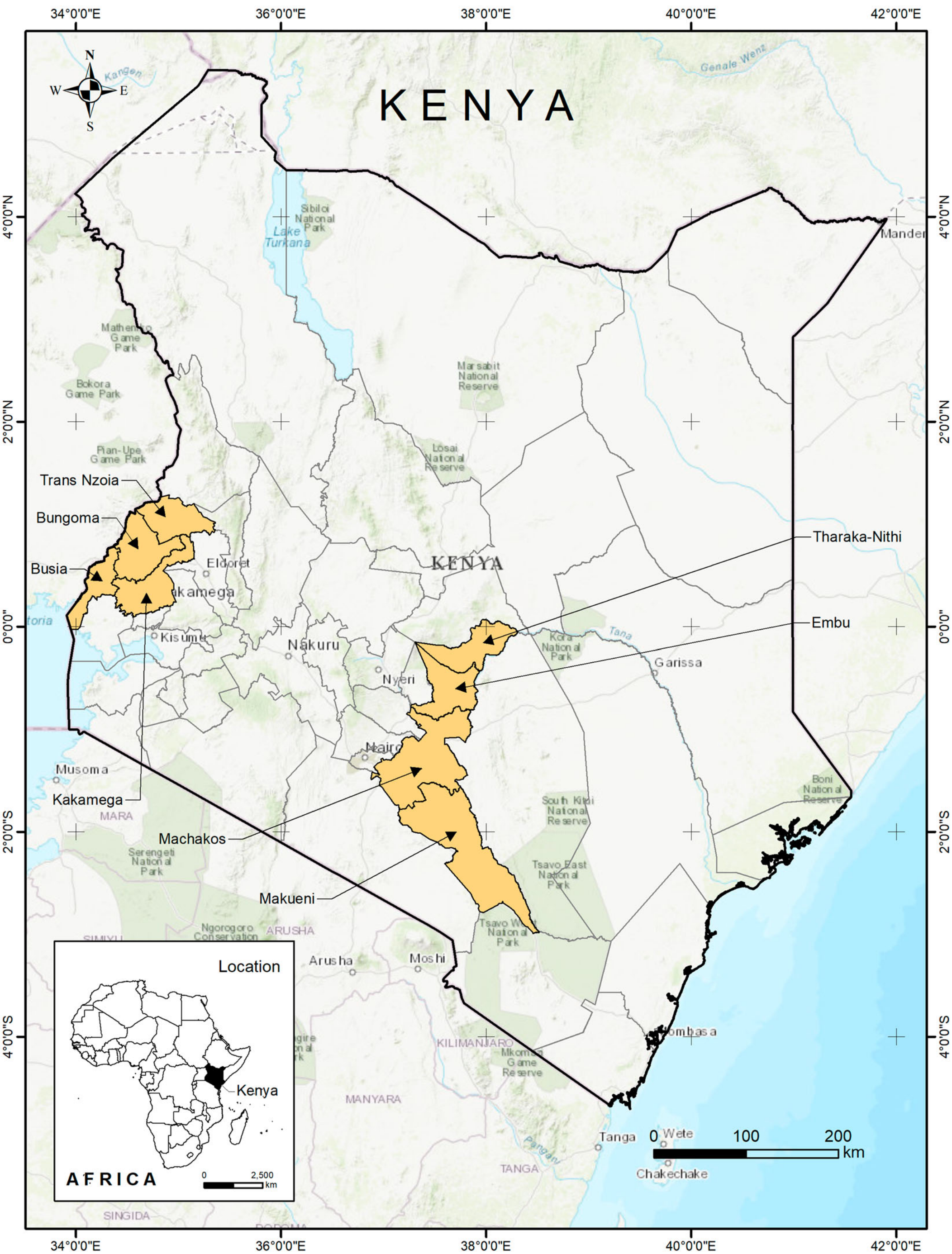

Figure 3. Map showing survey sites in Kenya.

potential adoption rate is always greater than or equal to the awareness- and physical access–unrestricted potential adoption rate. We follow Simtowe et al. (2019) 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 population scalability rates. A detailed discussion of

Table 1. Distribution of Sample households.

Makueni	Machakos	Embu	Thara Nithi	Kakamenga	Busia	Bungoma	Trans-Nzoia	Total
90	90	90	90	125	90	60	45	680

the framework and its empirical estimation strategy are discussed in Simtowe et al. (2019) and in the Appendix.

4. Data and descriptive statistics

4.1. Empirical data

For empirical data, we use a 2018 survey of households in eight counties in Kenya (Makueni, Machakos, Embu, Tharakanithi, Kakamega, Busia, Bungoma and Tranzoia) (Figure 3). A multistage, random sampling technique was employed in the selection of households. The first stage involved the selection of counties under the Feed the Future zones of influence and where maize is grown, which led to the selection of 8 counties. The second stage involved the selection of three major maize growing villages including one in which field demonstrations for maize were held, a neighboring village and a village far from the two villages.

Finally, at least thirty (30) households were randomly selected from each of the selected villages leading to the selection of 90 households per county. However, few households were sampled in Trans-Zoia (45), leading to a total sample size of 680 households (Table 1) for the survey.[2]

From each of the selected households, detailed information was collected that included household demographic and socioeconomic characteristics, crop production, awareness, scalability of improved maize varieties including DTMVs production conditions and utilization of maize, social capital risk attitudes, food security, and housing conditions.

4.2. Definition of dependent variables

Households that reported planting at least one DTMV in one of their maize plots are defined as adopters. There are several drivers to adoption, but in seed-related technologies there are two key variables. First, a household cannot accept DTMVs if they are not exposed or aware of their existence. Hence, the decision to use DTMVs is only relevant to a non-random subsample of households that are aware of their existence. 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 whether the household planted the DTMV in the 2018 growing season. The two subsequent questions to this were (i) whether a household had physical access to DTMV seeds during the planting time, and then (ii) whether a household could afford to purchase the seed at the prevailing market price. Based on these questions, we were able to identify three categories of households: (i) households that were aware of DTMVs (ii) households that were aware of DTMVs and that had physical access to seed whenever they wanted to purchase, and (iii) households that were aware of the existence of DTMVs and had affordable access to seed. The difference between the three groups is that the former focuses on the supply side of information and seed, thus making information and 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. The three categories of households are unique in that they represent three separate constraints to the scaling of seed.[3] This paper seeks to find out the extent of scalability of DTMVs once the three constraints are addressed. Out of 680 farmers in the sample, 253 were aware of DTMVs, 243 had access to seed (regardless of affordability), while 232 had access to seed at a price they could afford.

4.3. Independent variables and descriptive statistics

Table 2 presents descriptive statistics for some of the explanatory variables used in the analysis disaggregated by DTMV use and adoption status of households. The average land holding size was about 1 ha. About 69% of the households were male-headed. The average household size was 5.4 persons per household, with adopting households reporting significantly (at 5% level) larger households (6.1 persons) than the non-adopters (5.1 persons).

Table 2. Descriptive statistics by the adoption status of DTMVs.

Variables	Full Sample ($n = 680$)	Adopters ($n = 175$)	Non-adopters ($n = 505$)	Mean difference
Household size (No.)	5.35	6.05	5.12	−0.925***
Gender (1 male, 0 female)	0.69	0.74	0.68	−0.061
Age (years)	53.16	48.80	54.67	5.87***
Years of education	7.66	7.87	7.59	−0.28
Farm size (ha)	0.98	0.97	0.98	0.01
Received information on new varieties (%)	40.1	49.7	36.8	−12.9***
Sources of information (%)				
- Government	6.0	6.9	5.7	1.1
- Private extension	1.5	1.1	1.6	0.5
- NGO	6	10.9	4.4	6.5***
- Demos and field days	9	15	7	8**
- Input suppliers	9.9	13.7	8.5	5.2**
- Other farmers	21.5	28	19.2	8.8***
- Electronic Media	19.9	17.7	20.6	2.9*
Income Status				
- Able to build savings	2.4	2.9	2.2	0.7
- Able to save little	16	15	16	0
- Income equal expenses	32.1	29.1	33.1	4
- Draws from savings	34.3	41.1	31.9	−10
- Borrows to meet expenses	15.2	10.9	16.7	5.8
Membership in group (%) (1 = yes, 0 = otherwise)	78	73	80	7*
Distance to the market (km)	3.66	3.97	3.55	−0.41
Had dry spells in 2018 (%) (1 = yes, 0 = otherwise)	3.3	3.6	3.2	−0.29
Households that own livestock (%)	92.4	93.7	91.9	−1.9
Households are aware DTMVs (%)	37	100	15	−85***
Households have access to seed (%)	36	85	12	−73***
Households have access to affordable seed (%)	34	75	10	−65***

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

To capture access to information, farmers were asked whether they received information about new varieties. Farmers were then asked about their main sources of such information. About 40% of the households reported receiving information about new maize varieties in 2018. A significantly higher proportion of adopters (50%) reported receiving information about new maize varieties than non-adopters (37%), suggesting that 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 greater access than non-adopters. Other farmers (22%), electronic media (20%), input suppliers (10%), field days and demonstrations (9%), and government extension agents (6%) were the most widely reported sources of information about new varieties. Adopters tended to receive information from these sources suggesting that non-adopters were more information constrained.

There are significant variations in the awareness, access to seed and adoption of DTMVs across study counties (Figure 4). Overall, 37% of the households expressed DTMVs awareness, with the highest levels of awareness reported in Busia (89%), Trans-Nzoia (64%), Bungoma (62%) and Kakamega (51%). The other counties are largely in the Eastern region and reported low levels of DTMV awareness. Similar trends were observed in adoption rates with Busia (78%), Trans-Nzoia (49%), Bungoma (37%) and Kakamega (33%) registering higher adoption rates. This may in part reflect the presence of private seed companies directly involved in the promotion and marketing of DTMV seed, e.g. in Busia where Western Seed Company Ltd operates.

5. Results and discussions

5.1. Determinants of DTMV exposure and seed access

DTMV adoption amounted to 26% of our sample. Overall awareness of DTMVs was reported by 37% of the households, while 36% reported having physical access to the seeds and 34% had access to affordable seed. Based on this categorization, we estimate three probit regressions (Table 3) of factors that affect the propensity of exposure to DTMVs (model 1), the probability of the physical availability of DTMV seed in addition to awareness (Model 2), and the probability of access to affordable DTMV seed in addition to awareness and availability (Model 3).

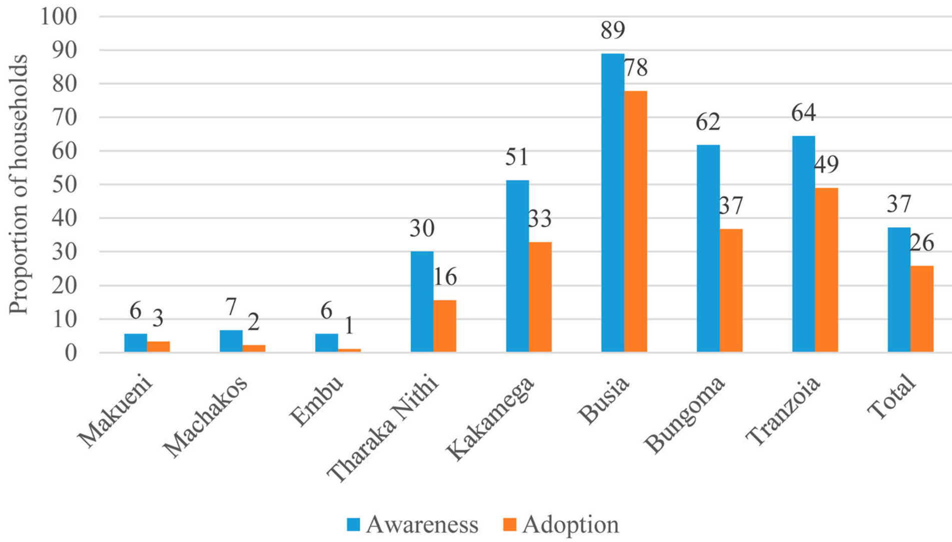

Figure 4. DTMV awareness and adoption by county, Kenya in 2018.

5.1.1. Determinants of DTMV awareness

For the awareness model (column 2), the age of the head of the household returned a negative and significant coefficient (at 1%), suggesting that the probability of being informed about DTMVs decreases with the age of the farmer. This finding is consistent with the fact that most farmers in this study received information through electronic media, which is a popular information source for youth. This finding also suggests that being a young farmer has implications for information search behaviours related to costs and effort. Years of education returned a positive and significant coefficient suggesting that education increases the propensity to access information about DTMVs. Unlike other studies (e.g. Simtowe et al., 2019), electronic media is the only information source with a positive and significant effect on DTMV awareness. The fact that other information sources and extension services such as government and non-governmental extension workers, were not significant in awareness creation suggests the need to revisit the extension systems' diffusion of information about new technologies in Kenya. These findings align with the reduced funding for extension and advisory service provision by the Government of Kenya, which has made traditional extension provision through farmer-extension contacts ineffective. Most of the income status variables (compared to the lowest base of needing to borrow) returned positive coefficients, suggesting that wealthier household had more privileged access to DTMV information, a factor that could be attributed to the wide use of electronic media in technology dissemination. Indeed, while this study and others (e.g. Mazher et al., 2003) emphasize the positive impact of electronic media as a source of agricultural information, it is important to ensure that such information sources are not exclusionary. Farmers in developing countries in particular, constitute economically and geographically marginalized groups which are at risk of digital exclusion and thereby social exclusion (Thakur & Chander 2018). Several information communication technology initiatives face challenges such as affordability, simplicity, accessibility, and scalability, which underscores the need for multi-pronged approaches to extension and advisory services to farming communities.

5.1.2. Determinants of DTMV seed availability in addition to awareness

Model 2 (column 3) presents marginal effects of the probability of households reporting physical DTMV seed access. The results are consistent with those in the awareness model, showing that age reduces the propensity to access seed while education has a positive impact, although the importance of age declines and is only significant at 10%. This suggests that while being young is critical to information access, youth has less effect on the physical access to seed. The reliance on electronic media also affects physical access to seed in addition to awareness, but may be again linked to the income status of the household, with wealthier

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

Variable	Model 1 (exposure)	Model 2 (exposure-access to seed)	Model 3 (exposure-access to seed at affordable price)
Household size (No.)	0.008	0.010	0.01
Gender (1 = Male; 0 = Female)	0.012	0.009	0.01
Age of head of household (Years)	−0.004**	−0.004*	0.00
Years of education	0.018**	0.017**	0.016**
Distance to Market (km)	0.036	0.037	0.02
Farm size (ha)	0.018	0.014	0.01
Farm demonstration in the household village	0.072	0.062	0.09
Information sources (Reference group: no information received)			
- Government extension	0.095	0.113	0.03
- Non-government extension	0.063	0.070	0.08
- Input suppliers	0.058	0.071	0.08
- Other farmers	−0.01	0.02	0.02
- Electronic Media	0.181**	0.181**	0.151*
Income status (Reference group; insufficient income need borrowing)			
- Able to build savings	0.121	0.2	0.28
- Able to save a little	0.237*	0.316**	0.366***
- Expenses equal savings	0.245**	0.278***	0.319***
- Draws from savings	0.184*	0.236**	0.291***
Busia	0.837***	0.850***	0.855***
Machakos	0.067	0.034	0.00
Embu	0.092	0.089	0.03
Tharaka Nithi	0.484***	0.447***	0.431***
Kakamega	0.674***	0.653***	0.617***
Bungoma	0.694***	0.692***	0.663***
Trans Nzoia	0.706***	0.721***	0.732***
N	679		
Aic	585.935		

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

households having a higher propensity to report physical seed access in addition to awareness of DTMV. Moreover, the importance of the income status variables was more pronounced in the physical access model compared to the awareness model. Several location dummies returned significant coefficients.

5.1.3. 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.

Unlike in the awareness and physical access model, age does not influence the probability of having access to DTMV seed at an affordable price, whereas education is still important. The effect of income status on access to seed at an affordable price positive is even more profound.

5.2. Scalability of DTMVs based on predicted potential adoption rates

DTMV scalability is assessed by predicting potential adoption rates with and without ATE correction for different levels of DTMV awareness, physical seed access and access to affordable seed. The results, including those of population selection biases and adoption gaps, are presented in Table 4. The sample awareness of DTMVs was estimated to be 37.1%, whereas the estimated physical access to seed and access to affordable seed was 35.6% and 34%, respectively. These results suggest asymmetric awareness and access to DTMV seed by farmers in the study area. The observed sample adoption rate for DTMVs was 26%, which is consistent with the joint treatment and adoption rates[4] for all three ATE corrected models. However, results show a huge potential for DTMV scaling. DTMVs could be scaled up to 52% if the farming community is made fully aware of the existence and benefits of DTMVs. The findings suggest that if the entire population of maize farmers was aware of DTMVs in 2018, the effective demand for DTMV seed could have doubled, resulting in an adoption gap, due to the lack of DTMV exposure, of 26%.

DTMVs are scalable to 56% of the farming community if the full population were to be made aware of and had access to DTMV seed. Awareness appears to be a greater bottleneck than seed availability, as availability of seed only increases scaling potential by 4% once farmers are aware. The cost of seed can further hamper scaling efforts. However, in this study making DTMV seed universally affordable only improves the scalability to 60% of the farming community. 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. Our results suggest that scaling DTMVs in Kenya will largely rely on efforts of disseminating information about DTMVs.

The scalability among the subpopulations that were only exposed to DTMVs (ATT_w), was 69%, which is slightly higher than that of a full population (ATE_w) of 52%, indicating a positive population selection bias

Table 4. Scalability of DTMVs based on predicted potential 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)	0.522*	0.050	10.50	0.564*	0.053	10.59	0.597*	0.059	9.9
Predicted adoption rate in treated subpopulation (ATT)	0.690*	0.026	26.32	0.718*	0.026	27.73	0.754*	0.025	29.12
Predicted adoption rate in untreated sub-population (ATU)	0.424*	0.072	5.90	0.480*	0.076	6.300	0.518*	0.048	6.07
Joint treatment and adoption rate (JTA)	0.256*	0.010	26.32	0.256*	0.009	27.73	0.256*	0.008	29.12
Population adoption gap (GAP)	−0.266*	0.045	−5.900	−0.309*	0.049	−6.30	−0.335*	0.055	−6.07
Population selection bias (PSB)	0.167*	0.042	4.020	0.153*	0.045	3.390	0.155*	0.05	3.183
Observed sample estimates									
Rate of treated (N_e/N)	0.371*	0.018	20.00	0.356*	0.018	19.38	0.340*	0.018	18.70
Adoption rate (N_a/N)	0.256*	0.016	15.28	0.256*	0.016	15.28	0.256*	0.016	15.28
Adoption rate among the treated subsample	0.690*	0.045	15.28	0.719*	0.047	15.28	0.743*	0.049	15.28

*Denote statistical significance at 5% level.

(PSB). Similarly, the scalability among subpopulations aware of DTMV and with physical accessibility to seed (ATT_{ws}) was higher (72%) than the scalability in the full population (ATE_{ws}) estimated at 56%. The same can be said for the scalability among a sub-population with full access to affordable seed (ATT_{wsp}) which was higher (75%) than the scalability in the full population (ATE_{wsp}) estimated at 60%. The population selection biases were positive and were estimated to be 17% for exposure, 15%, for joint exposure-seed availability, and 16% for joint exposure-seed availability-seed affordability. The positive PSBs are consistent with expectation because the promotion of DTMVs and the supply of seed is not done randomly, in that seed companies perform these activities in counties most suited for the cultivation of DTMVs and hence it is not a surprise to see the higher scalability among farmers with exposure to DTMVs and with access to seed than among the general population. This also reiterates that DTMV scaling efforts are targeted in counties with greater adoption potential in Kenya.

The scalability within the awareness-unconstrained subpopulation (ATT_w) of 69% was smaller than the scalability of 72% among the subpopulation with awareness-access-unconstrained (ATT_{ws}). The gap of 3% between the two rates of scalability 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 scalability 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 75%. The scalability was 42% among the subpopulations of farmers that were not exposed (ATU_w), 48% for those that were not exposed and had no access to seed (ATU_{ws}) and 52% for those that were not exposed, had no physical access to seed and at affordable prices (ATU_{wsp}).

5.3. Determinants of DTMV scalability under information and seed access constraints

Results of the determinants of DTMVs of the ATE probit model are presented in Table 5 in the form of marginal effects based on three models. Results present determinants of adoption conditional on exposure to the DTMVs (Model 1), conditional on physical access (Model 2) and conditional on seed affordability (Model 3). Being a male farmer increases the propensity to adopt DTMVs by 15.9%, 18.7% and 19.3% conditional on exposure, physical access to seed, and exposure and access to affordable seed, respectively. Belonging to a larger household is only significant and positive in Model 3, suggesting that conditional on seed affordability, an additional member to the households increases the propensity to cultivate DTMVs by 3.4%. Similarly, the education level of the head of the household is only significant and positive in Model 3, suggesting that conditional on making seed affordable, an additional year of education for the head of the household increases the propensity to cultivate DTMVs by 0.6%.

The only other important determinant of adoption is the location dummy for Busia county. The finding suggests that living in Busia county increases the

Table 5. ATE corrected marginal effects of the determinants of adoption of DTMVs under heterogeneous seed access and information exposure.[a]

Variable	Model 1 (exposure)	Model 2 (exposure-access to seed)	Model 3 (exposure-access to seed at affordable price)
Household size (No.)	−0.020	−0.026	0.034*
Gender (1 = Male; 0 = Female)	0.1597*	0.187*	0.193*
Age of head of household (Years)	−0.004	−0.004	−0.006*
Years of education	0.003	0.001	0.002
Distance to Market (km)	0.033	0.041	0.076
Farm size (ha)	−0.045	0.056	0.045
Farm demonstration in the household village	−0.015	−0.029	−0.051
Information sources (Reference group: no information received)			
- Government extension	−0.024	−0.050	0.020
- Non-Governmental extension	−0.015	−0.02157	−0.044
- Input supply	0.073	0.0566	0.061
- Other farmers	−0.015	−0.0721	−0.126
- Electronic media	−0.142	−0.017117	−0.192
Income status (Reference group; insufficient income, need to borrow)			
- Build savings	0.287	0.1860	0.035
- Save little	0.024	−0.1090	−0.278
- Expenses equal savings	0.145	0.0785	−0.076
- Draw from savings	0.212	0.1138	−0.040
Busia	0.426***	0.400***	0.411***
Machakos	−0.203	−0.147	−0.076
Embu	−0.343	−0.371	−0.293
Tharaka Nithi	−0.001	0.028	0.057
Kakamega	0.174	0.212	0.254
Bungoma	0.159	0.178	0.232
Trans Nzoia	0.2622	0.240	0.227
N	679	231	679
Aic	655.83	262.37	575.39

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.
[a]We only present results of the ATE-corrected adoption models for exposure, seed availability and access to seed at affordable prices.

propensity to cultivate DTMV by 43%, 40% and 41% conditional on exposure, physical access to seed in addition to exposure and access to affordable seed, respectively. The success in the scaling of DTMVs in Busia county can be attributed to the strong partnership between CIMMYT and the private seed company. The presence of Western Seed Company Ltd which provides improved varieties at competitive prices to farmers has been instrumental in creating the awareness of DTMVs such as WH403 and WH505 among farming communities, as well as in making seed for these varieties available to the farmers at competitive prices. The company uses several techniques to create awareness, including partnering with progressive farmers to plant demonstration farms to showcase the performance of varieties. The regular use of electronic media such as the radio is another popular means through which the company promotes its varieties. Western Seed Company Ltd also works with large distributors and village-level agro-dealers, and routinely discusses with them the need to understand farmers' preferences and prevailing challenges. In order to build the capacity of seed stockists, the company also provides after-sales training and capacity building to seed stockists on how best to reach farmers. Moreover, Western Seed Company has partnered with the Agricultural Development Corporation (ADC) in seed production and with One Acre Fund as a retail partner, while the African Enterprise Challenge Fund is a development partner.

6. Conclusions

The widespread adoption of improved technologies at the population level is critical in order to achieve sustained and substantial benefits from technology development. Yet often, agricultural technologies may not go beyond the pilot stage of the project and fail to scale. This paper examined the scalability of DTMVs in Kenya under three scenarios; (1) conditional on knowledge of DTMV; (ii) conditional on (physical) seed availability in addition to awareness; and (iii) conditional seed affordability in addition to awareness and physical availability. We find that the DTMVs in Kenya could be scaled up to 52% of the farming population if the whole population was exposed to them – double the observed adoption rate of 26% in our sample population. Conditional on awareness and physical seed availability, DTMVs are scalable to 56% of the farming community, and to 60% if in addition to awareness and seed availability, the seed were also made available at an affordable price. The study corroborates earlier empirical evidence that suggests a huge potential for the scaling of DTMV, however, this will have to come with substantial investment in the extension systems that sustain awareness creation of DTMVs among farmers. The use of electronic media appears to have a positive impact on DTMV awareness, however, over-reliance on such media may exclude more marginalized groups and thereby exacerbate social exclusion. Electronic media may not be accessible by the poor which makes it difficult to rely on it for scaling of DTMVs. This suggests that wide awareness and adoption of DTMVs will require a multipronged approach to extension and advisory services to diverse groups of farming communities.

The heterogeneous exposure and adoption of DTMV varieties across counties in Kenya provides important lessons for successful DTMV scaling. For example, the low awareness and adoption in Embu county is consistent with expectation as DTMV exposure should be higher among mid-altitude regions that are conducive for the growth of such varieties while Embu is a high-altitude region. Aside from the appropriateness of the DTMV for mid-altitude regions, the success in their scaling in Busia, Bungoma and Kakamega counties is in part, attributable to the strong public-private partnerships creating DTMV awareness and DTMV seed availability to the farming communities at competitive prices. The findings underscore the need for deploying both market and non-market-based approaches in DTMV scaling in Kenya. Market-based approaches could support in-country partnerships that enhance seed supply by seed companies while non-market-based approaches could further extend and target vulnerable groups that are less able to purchase seed. In a country such as Kenya with a relatively well-developed seed sector, DTMV awareness appears to be the critical bottleneck to increased scaling, however the appropriateness of the DTMV in relation to the agroecology is a critical factor for consideration in the scaling of DTMVs.

Notes

1. The scaling of proven technologies/practices is defined as the process of sustainably increasing the adoption of a credible technology/practice, or a package of technologies/practices, with quality to improve upon the demonstrated positive impact of the technology and achieve widespread use by stakeholders (USAID, 2015).
2. The Analysis is based on households that grew maize in the major growing season of 2018
3. (i) exposure to information about DTMV, (ii) physical access to seed and (iii) affordable seed price
4. Other authors, for example Diagne and Demont (2007), Kabunga et al. (2012) call this the joint exposure and adoption (JEA) because exposure is their major treatment of interest.
5. See Simtowe et.al. (2019) for a detailed discussion on the eight potential adoption outcomes.

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No potential conflict of interest was reported by the author(s). The authors declare that the manuscript is not under any competing interests.

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Appendix

We follow Simtowe et al. (2019) 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 scalability rates. According to this framework, every farmer in the population *theoretically* has eight potential adoption outcomes which can be expressed as[5]

$$\begin{aligned} y = & wspy_{111} + ws(1-p)y_{110} + w(1-s)py_{101} + w(1-s)(1-p)y_{100} \\ & + (1-w)spy_{011} + (1-w)\, s\,(1-p)y_{010} \\ & + (1-w)(1-s)y_{001} + (1-w)(1-s)(1-p)y_{000} \end{aligned} \tag{A1}$$

considering that 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, Equation (A1) is reduced to:

$$y = wspy_{111} \tag{A2}$$

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 to it 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, 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 Equation (A2) by setting $w = 1$ and expressed as follows:

$$y_1^{*} = spy_{111} \tag{A3}$$

Similarly, by setting $s = 1$, the physical seed access-unrestricted potential adoption outcomey_1^{**} is defined as

$$y_1^{**} = wpy_{111} \tag{A4}$$

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

$$y_1^{***} = wsy_{111} \tag{A5}$$

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

$$y_{11}^{*} = py_{111} \tag{A6}$$

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

$$y_{11}^{**} = sy_{111} \tag{A7}$$

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

$$y_{11}^{***} = wy_{111} \tag{A8}$$

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 (Equations A6–A8) 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, $E(y_{11}^{*})$, $E(y_{11}^{**})$ $E(y_{11}^{***})$ 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.

The empirical estimation of this model is restricted to only 3 out of the 7 potential population adopt rates: $ATE_w = E(y_1^{*})$, $ATE_{ws} = E(y_{11}^{*})$, 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 sub-sample (i.e. for $w = 1$) which makes it difficult to estimate them without further assumptions (Simtowe et al., 2019). 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 and -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 farmers' adoption of DTMVs.

The observed population adoption rate parameter n 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) and Simtowe et al. (2016). Hence, in what follows, we follow Simtowe et al. (2019) to use the notation JEAAA (joint awareness-access-affordability and adoption) for the observed population parameters ($E(y)$). 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 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 (Equation A9), lack of physical seed access (Equation A10) and lack of awareness (Equation A11) as follows:

$$GAP_{wsp} = E(y) - E(y_{111}) = JEAAA - ATE_{wsp} \tag{A9}$$

$$GAP_{ws} = E(y) - E(y_{11}^*) = JEAA - ATE_{ws} \tag{A10}$$

$$GAP_{w} = E(y) - E(y_1^*) = JEA - ATE_{w} \tag{A11}$$

where $ATE_{wsp}$is the average treatment effect parameter when joint awareness, physical seed access and seed at affordable prices is the treatment variable. $ATE_{ws}$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,$E\ (y_1^*\ |X\ = x)$, $E\ (y_{11}^*\ |X\ = x)$, and $E\ (y_{111}|X\ = x)$; 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:

$$ATT_w \ = E(y_1^*|w = 1) \tag{A12}$$

$$ATT_{ws} \ = E(y_{11}|w = 1,\ s = 1) \tag{A13}$$

$$ATT_{wsp} \ = E(y_{111}|w = 1,\ s = 1,\ p = 1) \tag{A14}$$

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

$$ATU_w \ = E(y_1^*|w = 0) \tag{A15}$$

$$ATU_{ws} \ = E(y_{11}^*|w = 0,\ s = 0) \tag{A16}$$

$$ATU_{wsp} \ = E(y_{111}|w = 0,\ s = 0,\ p = 0) \tag{A17}$$

Furthermore, as in Diagne (2006, 2010) and Diagne and Demont (2007), we define 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

$$PSB_w = ATT_w - ATE_w = E(y_1^*|w = 1) - E(y_1^*) \tag{A18}$$

$$\begin{aligned} PSB_{ws} &= ATT_{ws} - ATE_{ws} \\ &= E(y_{11}^*|w = 1,\ s = s_1 = 1) - E(\ y_{11}^*) \end{aligned} \tag{A19}$$

$$\begin{aligned} PSB_{wsp} &= ATT_{wsp} - ATE_{wsp} \\ &= E(y_{111}|w = 1,\ s = s_1 = 1,\ p = p_1 = 1) \\ &\quad - E(\ y_{111}) \end{aligned} \tag{A20}$$

This is empirically estimated by applying 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 Figure 2, 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 shown above. It is assumed that the conditional independence assumption holds in all cases. As expressed in Dontsop 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 outcomesy_1^*, y_{11}^* and y_{111}, conditional on a vector of covariates x. That is, using the standard notation for conditional independence (A1): $w \perp y_1|x$, $w, s \perp y_{11}|x$ and $w, s,\ p \perp y_{111}|x$. By the propriety of conditional independence, assumption (A1) also implies that $w \perp y_1^*|x$ (Dontsop et al., 2013). Therefore, we can use the same identification results and estimation procedures as in Diagne and Demont (2007) to identify and estimate parameters related to the three treatments.