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RESEARCH

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Improved maize seeds and farm profitability in Tanzania: Evidence from the National Sample Census of Agriculture 2019/20

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Abstract

Background: Maize plays a critical role in ensuring food security and supporting rural livelihoods in Tanzania. However, smallholder maize farmers continue to face persistent profitability challenges driven by low productivity, high input costs, and market inefficiencies. Although the government has prioritized promoting improved seed varieties across various agricultural development initiatives, evidence of their actual economic benefits in smallholder farming conditions remains limited. Understanding how different seed types affect farm profitability across agroecological zones is essential for informing sustainable agricultural policy and investment decisions. *Methods*: This study used a non-parametric stochastic simulation approach with nationally representative data from the 2019/20 National Sample Census of Agriculture (NSCA). The analysis estimated income distributions for three seed types (local, improved, and recycled) while accounting for yield variability, maize prices, and production costs. Profitability was assessed using two income thresholds: a minimum threshold of TZS 0.6 million/ha and an optimal benchmark of TZS 1.2 million/ha. Simulations were disaggregated by agroecological zone to capture spatial differences in cost structures, productivity, and market dynamics. *Results*: The findings indicate that improved seeds modestly increase the probability of achieving profitable outcomes but, on their own, are insufficient to lift most farmers above the optimal income threshold. Nationally, 64% of improved seed users earned below the minimum profitability level, compared with 67% of local seed users and 77% of recycled seed users. Only 14% of improved seed users exceeded the profitability benchmark. Regional variations were substantial: the Lake and Southern Zones recorded relatively better profitability due to lower input costs and favorable maize prices, while the Eastern and Western Zones remained largely unprofitable across all seed categories. *Conclusion*: Although improved seeds are essential for enhancing maize productivity, they do not guarantee profitability in the absence of complementary inputs and supportive market conditions. Multiple interacting factors, including production costs, yield variability, and market access, shape profit outcomes. The study recommends integrated, zone-specific interventions, including bundled input support, targeted subsidies, and investment in rural infrastructure, to improve farm-level returns. These insights contribute to SDG 1 (No Poverty), SDG 2 (Zero Hunger), and SDG 12 (Responsible Consumption and Production) by promoting more resilient and inclusive agricultural systems in Tanzania.

Keywords: stochastic simulation, improved seed, recycled seeds, maize profitability, agroecological zones, Tanzanian seed system

Introduction

Maize (*Zea mays* L.) is one of the most important crops in Tanzania, serving as both a staple food and a primary source of income for more than 80% of smallholder farmers (URT, 2021). Despite its central role, maize yields and farm incomes remain persistently low, with farmers often achieving less than half of the potential yield attainable with improved seed varieties (Govereh and Jayne, 2003; Alia, 2017; Liverpool-Tasie *et al.*, 2017). Enhancing maize productivity and profitability is therefore critical for improving food security and reducing rural poverty. The use of improved maize seeds has been widely promoted as a key strategy toward this goal. However, whether improved seeds alone, independent of complementary inputs, can significantly improve farm-level profitability remains an open empirical question. Although improved varieties offer agronomic benefits such as drought tolerance, disease resistance, and early maturity (Lyimo *et al.*, 2014; Alia, 2017; Kabululu *et al.*, 2017; Kihara *et al.*, 2021), their economic performance depends on production costs, market access,

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and agroecological conditions (Holden and Lunduka, 2012; Kalinda *et al.*, 2014). Profitability, unlike productivity, captures the financial viability of technology adoption by accounting for both revenues and costs, making it a more relevant metric for smallholders operating under tight budget constraints and production risks (Utonga, 2022).

In many parts of sub-Saharan Africa (SSA), including Tanzania, farmers often hesitate to adopt improved technologies due to concerns about uncertain returns and high input costs (Duflo *et al.*, 2008; Abdoulaye *et al.*, 2018; Suleiman, 2018). These concerns are more pronounced in contexts where complementary inputs such as fertilizers, irrigation, and extension services are either unavailable or unaffordable (Beyene and Kassie, 2015). Even when improved seeds are subsidized, profitability may remain low due to price volatility and exposure to climatic shocks (Bai *et al.*, 2007; Thorne and Hennessy, 2007; Levkina *et al.*, 2019; Tack and Yu, 2021). Despite the importance of maize in Tanzania's agricultural transformation agenda, existing studies have largely focused on yield responses or adoption behavior, often under experimental or bundled-input conditions. Some of the studies that rely on experimental or plot-level data include Dittmer *et al.* (2023), Thompson and Gyatso (2020), Duflo *et al.* (2008), Burke and Lobell (2017), and Kihara *et al.* (2016), while studies that focus on mean yield or average returns include Stathers *et al.* (2020), Sheahan and Barrett (2017), and Abdoulaye *et al.* (2018). Other studies, such as Vanlauwe *et al.* (2010), Mugwe *et al.* (2020), Khonje *et al.* (2015), and Nin-Pratt (2016), often evaluate bundled interventions, making it difficult to isolate the independent financial contribution of improved seeds. As a result, there is limited empirical evidence on the standalone profitability of improved seed use under real-world smallholder farming conditions.

This study also has strong policy relevance because it tests the underlying assumptions of input subsidies and distribution programs. If improved seed adoption does not consistently yield higher net returns under prevailing smallholder conditions, policy adjustments may be needed to ensure more targeted, cost-effective interventions. Maize production in Tanzania is highly diverse, with agroecological zones differing in soil fertility, rainfall, and elevation, all of which affect seed performance (Vanlauwe *et al.*, 2014; Mungai *et al.*, 2016; URT, 2021). Price structures and exposure to production risks such as droughts, pests, and diseases also vary widely across zones (Abate *et al.*, 2015; Sheahan and Barrett, 2017). These variations make it essential to use analytical tools that capture the full range of possible outcomes rather than relying only on average effects.

To address the aforementioned gap, this study makes four key contributions. First, it provides a nationally representative assessment of maize profitability using data from the 2019/20 National Sample Census of Agriculture (NSCA), thereby capturing real-world farming conditions across Tanzania. Second, it applies a non-parametric stochastic simulation approach to model the full distribution of net farm income, rather than relying on average outcomes, allowing for a more realistic representation of production and market uncertainty. Third, it introduces a probabilistic profitability framework based on defined income thresholds (TZS 0.6 million/ha and TZS 1.2 million/ha), enabling classification of farmers into low-, medium-, and high-income categories. Fourth, the analysis is disaggregated across agroecological zones, capturing spatial heterogeneity in yields, costs, and prices, and providing location-specific insights for policy design.

These contributions advance the existing literature by shifting the focus from productivity gains and adoption rates to risk-adjusted profitability outcomes, which are more relevant for understanding smallholder decision making. By isolating the effect of improved seeds while holding other factors constant, the study provides new evidence on whether the adoption of improved seeds alone is sufficient to improve farm incomes. In addition, a non-parametric stochastic simulation approach was used to estimate the probability distribution of net farm income for maize producers using different seed types. This approach captures uncertainty arising from yield variability, price fluctuations, and cost differences, offering a more comprehensive assessment of profitability under real-world conditions (Richardson *et al.*, 2000; Antle, 2011; Kadigi *et al.*, 2020).

By modeling income distributions rather than point estimates, the analysis reflects the risks faced by smallholder farmers and supports more informed policy and investment decisions. Specifically, this study seeks to: (i) assess the profitability of maize production across different seed types (local, improved, and recycled) in Tanzania; (ii) evaluate the probability of achieving minimum and optimal income thresholds under each seed system; and (iii) examine how profitability outcomes vary across agroecological zones.

The findings of this study contribute to the Tanzania Seed Sector Development Strategy 2030 (TSSDS 2030), which emphasizes evidence-based policy making to strengthen the seed sector and promote sustainable adoption (Minde *et al.*, 2024). Identifying where and under what conditions improved maize seed yields lead to profitable outcomes can inform subsidy targeting, extension services and private-sector investment in seed systems. Furthermore, as Tanzania seeks to expand its role as a regional grain supplier, ensuring that productivity-enhancing technologies also translate into improved farm incomes is essential (Diao and Kennedy, 2016; Bryceson *et al.*, 2018).

The remainder of this article is structured as follows: Section "Methods" outlines a description of the study area, data sources, and simulation procedures; Section "Results" presents the main outcomes by agroecological zone; Section "Discussion" interprets the findings in the context of existing literature and policy implications, and Section "Conclusions" concludes this article and highlights the policy implications and recommendations for future studies.

Methods

STUDY AREA

This study examines maize production across Tanzania, covering all regions of the country and organizing them into eight agroecological zones (AEZs) to facilitate analysis (Suleiman, 2018; Mkonda, 2021). These zones include the Central Zone (Dodoma and Singida), Eastern Zone (Morogoro, Dar es Salaam, Tanga, and Coastal regions), Zanzibar (Unguja and Pemba islands), Western Zone (Kigoma and Tabora), Lake Zone (Mara, Shinyanga, Simiyu, Geita, Mwanza, and Kagera), Northern Zone (Arusha, Kilimanjaro, and Manyara), Southern Zone (Lindi and Mtwara), and Southern Highlands Zone (Mbeya, Iringa, Songwe, Njombe, Ruvuma, Katavi, and Rukwa). This classification reflects the diversity of Tanzania's agricultural landscape and provides a structured basis for assessing maize production systems across different ecological conditions.

Distinct climatic and environmental conditions, including variations in rainfall patterns, temperature, altitude, soil types, and seasonal dynamics, characterize these agroecological zones. Such differences strongly influence agricultural practices, crop performance, and input use. By grouping maize farms by these zones, the study examines how improved seed technologies perform across varying environmental and production contexts. This approach enables the analysis to reflect both national-level patterns and location-specific differences in productivity and profitability.

The use of AEZs also allows for a more detailed comparative analysis of farming outcomes across regions, highlighting how environmental and market conditions shape the effectiveness of different seed systems. This zonal disaggregation is particularly important for identifying areas where improved seeds perform well and where constraints persist. As a result, the study provides insights relevant to designing targeted, context-specific interventions to improve maize productivity and profitability, while also supporting the development of more resilient agricultural systems across Tanzania (Fig. 1).

DATA SOURCES

This study uses nationally representative data from the 2019/2020 National Sample Census of Agriculture (NSCA), conducted by

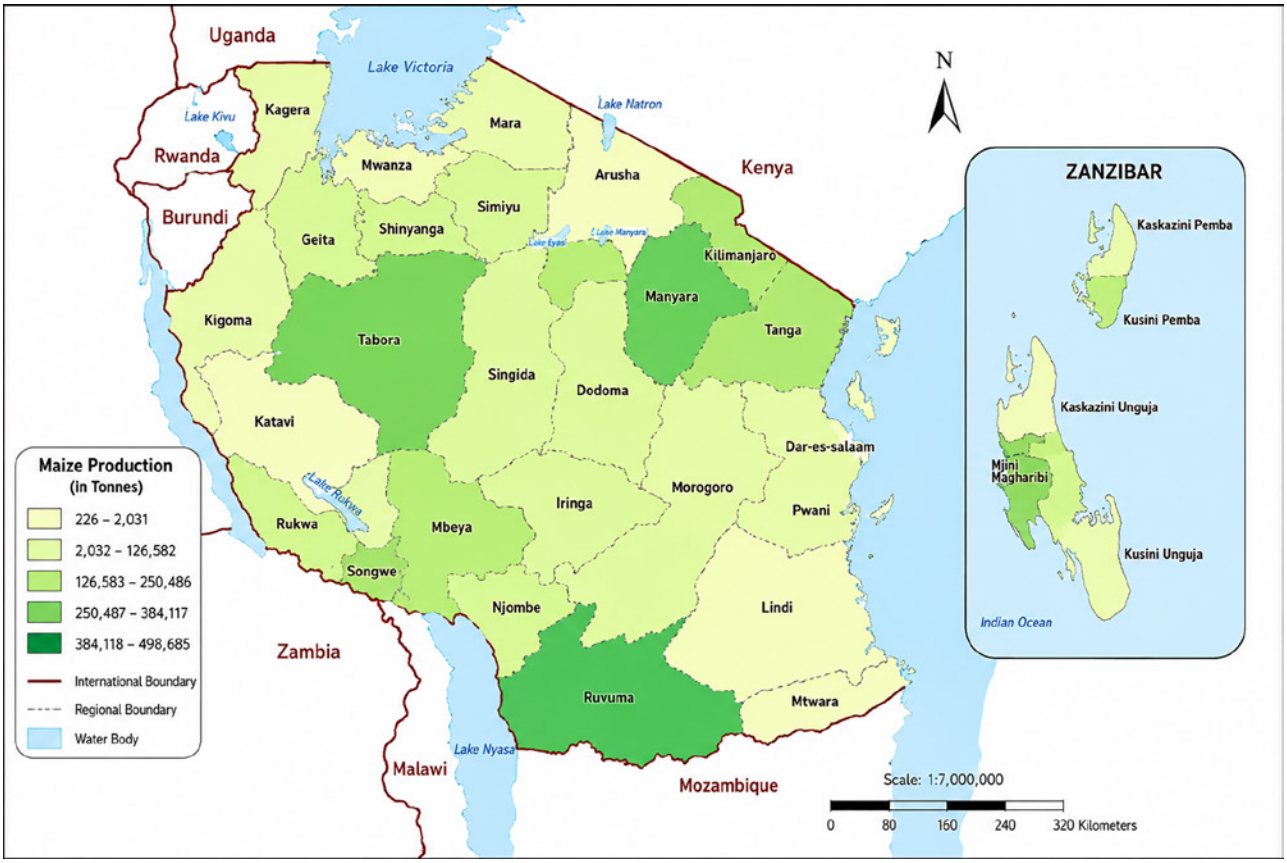


Fig. 1. The map of Tanzania showing the quantity of maize harvested by smallholder farmers by region during 2019/20, Agricultural Year, Tanzania (URT, 2021).

the National Bureau of Statistics (NBS) in collaboration with the Ministry of Agriculture. To enhance temporal robustness, selected indicators from the 2007/2008 NSCA were also incorporated for comparison and harmonization. The NSCA is the most comprehensive agricultural dataset in Tanzania, providing detailed information on farm characteristics, landholdings, crop production, livestock, and the use of key inputs, including fertilizers, irrigation, and improved seeds. It also captures data on rural infrastructure, access to extension services, market participation, and household socioeconomic conditions, which are essential for assessing agricultural performance and policy outcomes.

The survey employed a two-stage stratified sampling design to ensure national representativeness. In the first stage, Primary Sampling Units (PSUs), or Census Enumeration Areas (CEAs) were selected from the 2012 Population and Housing Census frame using stratified random sampling. In the second stage, agricultural households were randomly selected within each PSU, covering both crop and livestock producers. The NSCA included 2820 PSUs (2670 in Mainland Tanzania and 150 in Zanzibar). A probability proportional to size (PPS) approach was applied to prioritize areas with higher agricultural activity, thereby improving statistical efficiency and representativeness (URT, 2021).

DATA PROCESSING AND SIMULATION

Yield data simulation

Table 1 presents the distribution of maize farms by seed type across Tanzania's agroecological zones (AEZs) based on the 2019/20 NSCA. Of the 16,192 farms analyzed, 65% used local seeds, 33% used improved seeds, and 3% used recycled seeds, indicating continued dominance of traditional varieties but a growing adoption of improved seeds. The Southern Highlands Zone (SHZ) had the largest number of farms (4239), dominated by local seed users, with a substantial number adopting improved seed (1215). The Western Zone (WZ) also recorded a high number of farms (2841) that largely rely on local seeds. At the same time, the Lake Zone (LZ) showed a more balanced pattern, reflecting the gradual diffusion of improved varieties.

Adoption patterns vary considerably across zones. The Southern Zone (SZ) had the fewest users of improved seed, suggesting limited access to inputs and extension services. In contrast, the Northern Zone (NZ) recorded higher adoption of improved seeds than of local seeds, indicating stronger market linkages and input distribution systems. Overall, the distribution highlights significant spatial variation, with improved seed uptake more evident in regions with relatively well-developed agricultural support systems, such as SHZ, LZ, and NZ. Meanwhile, the consistently low use of recycled seeds across all zones suggests a gradual transition toward certified seed systems.

These patterns provide the basis for the stochastic simulation analysis, which models yield and income distributions across seed types and AEZs. By incorporating observed variability in yields, costs, and prices, the model assesses the economic performance of improved seeds under real-world smallholder conditions.

Deterministic yield computation

For each farming category, deterministic yield was calculated using Eqn 1, defined as the ratio of total tonnage harvested to the area harvested (in hectares):

$$yield\left(\bar{y}_{j,i}\right) = \frac{Tones\ harvested\ (tones)}{Hectares\ harvested\ (a)} \quad (1)$$

This step provided the base mean yield values per hectare across AEZs *i* and farming practices *j*, setting the foundation for subsequent stochastic simulations.

Table 1. Number of observations for maize farms using local vs. improved seeds per AEZ.

Agroecological zone	# of farms using local seeds (_S_0)	# of farms using improved seeds (_S_1)	# of farms using recycled seeds (_S_2)	Total
Central Zone (CZ)	1098	592	48	1738
Eastern Zone (EZ)	1223	372	20	1615
Western Zone (WZ)	2086	664	91	2841
Lake Zone (LZ)	1408	1046	46	2500
Northern Zone (NZ)	662	1269	73	2004
Southern Zone (SZ)	1064	124	18	1206
Southern Highlands SHZ)	2888	1215	136	4239
Zanzibar (ZNZ)	36	12	1	49
All Farms	**10,465**	**5,294**	**433**	**16,192**

Stochastic Yield Simulation using Independent Standard Normal Deviates (ISNDs)

Since we have several independent random yields from each AEZ, with different numbers of observations, a Univariate Empirical (UVE) was parameterized. The UVE was simulated to generate an independent, uncorrelated sample of 500 for each farming practice within each AEZ. The simulations were implemented using Latin Hypercube Sampling (LHS) with 500 iterations per random variable to ensure efficient coverage of the distribution space. While prior literature indicates that larger iteration sizes (e.g., 1000 to 10,000 or more) can be employed, empirical evidence suggests that approximately 500 iterations are sufficient to reproduce stable distributional properties and key statistical moments in agricultural risk modeling applications (Richardson *et al.*, 2008; Kadigi *et al.*, 2020; Kadigi, 2026). Additional trial simulations conducted during this study confirmed that increasing the number of iterations beyond this level yielded negligible changes in the estimated distributions, supporting the adequacy and computational efficiency of the chosen iteration count.

The deterministic yield computed in Eqn 1 was converted into stochastic form (Eqn 2), where a random shock factor (ε) was introduced to capture unexplained variability in yield. Eqn 3 expresses how the stochastic yields were simulated. The equation uses the EMP Simetar function to simulate yields, resulting in a percentage deviation from the mean.

$$\tilde{y}_{j,i} = \overline{y}_{j,i} * \varepsilon \tag{2}$$

Where the ε is a random shock factor expressed as $y_{j,i} - \overline{y}_{j,i}$

$$\tilde{y}_{j,i} = \overline{y}_{i,j} * \left(1 + EMP\left(S_{y,i,j}, P\left(S_{y,i,j}\right), ISND_{y,i,j}\right)\right) * \beta_{\tilde{y}_{0,i,j}} \tag{3}$$

Where ~ = a tilde represents a randomness (stochastic) variable; j = types of seeds used (local seeds, "_S_0" improved seeds, "_S_1", and recycled "_S_2"); i = represents farms in eight agroecological zones; $\tilde{y}_j$ = stochastic mean yield per ha for farming practice j; $\overline{y}_j$ = deterministic (mean) yield per ha for farming practice j; $\beta_{\tilde{y}_0}$ = the normalization factor, which is given by $\frac{\tilde{y}_{c,j}}{\tilde{y}_{h,j}}$ and it is used to scale/adjust the 2019/20 NCSA mean yield; $\tilde{y}_c$ = stochastic yield for the current survey (2019/20 NCSA); $\tilde{y}_h$ = stochastic yield for the historical or previous survey (2007/08 NCSA); S_y = fraction deviations from the mean or sorted array of random yields for farming practice i; $P(S_y)$ = cumulative probability function for the S_y values; $ISND_y$ = Simetar function to simulate the independent standard normal deviates; *EMP*() = Simetar function used to simulate a stochastic variable (yield).

The independent standard normal deviation (ISND) function was introduced in the UVE model to act as a source of randomness that derives variability in the model's output. The ISND function ensures that the simulated values reflect the probabilistic uncertainty around the empirical distribution of the variable being modelled. The ISND IS often denoted as $\varepsilon \sim N(0,1)$, which follows a standard normal distribution (mean = 0, standard deviation = 1) and is independent of all other random draws or variables in the simulation. To generate a sufficient sample for each farming practice using the Simetar, Eqn 3 was simulated with the Latin Hypercube Sampling (LHS) technique, following the procedures outlined by Richardson *et al.* (2007), Kadigi *et al.* (2020, 2025), and Kadigi and Sieber (2025). This study uses the LHS approach because it is efficient at generating representative samples from complex probability distributions with relatively few iterations. In this study, 500 iterations per farming system were deemed sufficient to accurately reproduce the key statistical properties of the parent yield distributions.

An essential component of the analytical process involved model validation. The UVE simulated yields were rigorously compared with historical observations using statistical goodness-of-fit tests and probability distribution functions (PDFs) to verify the consistency of the empirical and simulated distributions. The validation results confirmed that the stochastic model successfully captured both the magnitude and variability of observed yields while preserving the probabilistic structure introduced through Monte Carlo sampling. This alignment between simulated and actual data provided confidence that the simulated outcomes were representative, unbiased, and suitable for evaluating productivity performance across Tanzania's agroecological zones.

Correlated uniform standard deviation (CUSD) of random yields

Following validation, the new samples, comprising 500 iterations per farming system, were parameterized and simulated using the multivariate empirical (MVE) distribution. The MVE process involved computing residuals, defined as the percentage deviations of yields from their mean values, to derive the correlation matrix (Richardson *et al.*, 2000). The MVE approach is particularly advantageous in multivariable contexts because it enables simultaneous modeling of several variables while preserving realistic outcomes, such as avoiding implausible negative yields. The non-parametric MVE draws directly from observed NSCA data without imposing parametric assumptions (e.g., normal or

log-normal distributions). Following the LHS framework, this approach preserves the empirical shape, variability, and correlation structure of key variables, making it particularly suitable for modeling heterogeneous smallholder systems under uncertainty (Richardson *et al.*, 2000, 2007; Kadigi, 2026). This matrix was then applied to transform independent standard normal deviates (ISNDs) into correlated standard normal deviates (CSNDs). These CSNDs were subsequently inversely transformed into correlated uniform standard deviates (CUSDs), which were used to stochastically draw empirically ranked fractional deviates that supply the random (stochastic) component for generating simulated values. The Simetar software's built-in = *CUSD( )* function was used to simulate the correlated uniform standard deviations of the random variables.

The MVE framework effectively captured the inherent variability in yield records and reflected the probabilistic nature of crop productivity under diverse farming systems. Ultimately, this method enabled the generation of realistic, spatially explicit yield simulations that accounted for both environmental variability and management-related uncertainties. The final form of the MVE model is expressed in Eqn 4. The MVE framework is particularly well-suited for multivariable contexts because it maintains realistic intervariable relationships while preventing implausible outcomes, such as negative yield values. The MVE uses the empirical probability (EMP) function to simulate yields as percentage deviations from their means. The *EMP ()* function transforms all yield data into percentage deviations from their corresponding means before the simulation. This standardization allows the EMP to capture yield variability and its probabilistic distribution more accurately and ensures theoretical consistency with the methodology adopted by Richardson *et al.* (2000, 2007).

$$\tilde{y}_{sim,i,j} = \overline{y}_{c,i,j} * \left(1 + EMP\left(S_{y,i,j}, P\left(S_{y,i,j}\right), CUSD_{y,i,j}\right)\right) \quad (4)$$

Where *sim* = yield from the simulated dataset; $CUSD_y$ = Simetar function to simulate the correlated uniform standard deviation of random variables.

Finally, the simulated outputs from the MVE model were again validated against the original historical dataset to ensure that the statistical properties and distributional characteristics of the observed yields were preserved. This double-validation approach further reinforces the robustness and reliability of the simulated results. Results from this validation are detailed in Supplementary material 1 (SM 1), which utilizes both probability distribution functions (PDFs) and statistical tests (Student's t-tests and Chi-squared tests). Supplementary material 2 (SM 2) presents summary statistics of maize yields under different seed type uses for both historical (observed) and simulated datasets.

However, it is important to note that this study adopts a descriptive stochastic simulation framework rather than a causal identification strategy. As such, the results should be interpreted as probabilistic associations between seed types and income outcomes, rather than causal effects. Potential selection bias may arise because farmers who adopt improved seeds differ systematically from those who do not. While the simulation preserves the observed joint distribution of yields, costs, and prices, it does not control for unobserved heterogeneity. Therefore, the findings are best understood as indicative of likely economic outcomes under existing production conditions, rather than definitive estimates of treatment effects.

PRICE DATA SIMULATION

To evaluate farm-level profitability under different seed and fertilizer combinations, maize price data were collected for both local and improved varieties. The price differences between these varieties, although marginal, have meaningful implications for net income. Given the notable variability in maize prices across agroecological zones, seasons, and market conditions, prices were treated as stochastic variables. Typically, prices drop during the harvest period (April to September) due to increased supply, and rise from October to March when supply declines, a pattern aligned with Kadigi *et al.*'s (2020) findings.

To simulate this price variability, the Gray-Richardson-Klose-Schumann (GRKS) probability distribution function was applied in Simetar. The GRKS method accounts for minimum, maximum, and average price points, thus capturing the full spectrum of pricing dynamics rather than relying on a single average. This simulation approach, developed by Richardson *et al.* (2000, 2008) and refined by Kadigi *et al.* (2020), is particularly well-suited for modeling risky variables, such as maize prices. Equation (5) was used to simulate stochastic maize price distributions for farmers using different seed types: local, improved, and recycled.

$$\tilde{P}_j = \sum\left(GRKS\left(\min_j, Average_j, \max_j\right)\right) \quad (5)$$

Where GRKS = Gray, Richardson, Klose, and Schumann Simetar a function; *j* = prices for a variety *j* (local, recycled, or improved); Min = minimum price (in TZS/t), farmers would sell their maize; Max = the maximum price (in TZS/t) that farmers would sell their maize; Average = the average price (TZS/t) that farmers would sell their maize; $\tilde{P}_j$ = stochastic price for variety *j* (local, recycled, or improved) varieties.

PRODUCTION COST DATA SIMULATION

Production costs and input prices for each farming system were systematically compiled and analyzed. These costs included key input categories such as seed, land preparation, planting, seed cost, irrigation (where applicable), weeding, fertilizer, herbicides, harvesting, and transportation from farm to storage. Additional inputs, such as fungicides and insecticides, and miscellaneous costs were also considered, depending on farm-specific practices. Since production costs vary significantly across individual farms, they were treated as stochastic variables in the simulation model. This variability reflects differences among farmers in farming practices, resource use, and market access. The GRKS function was applied to estimate stochastic costs using three key values: the minimum, average, and maximum observed costs for each input, to capture this randomness.

The total stochastic production cost ($\tilde{C}$) for farming system *j* and AEZ *i* was calculated using Eqn 6:

$$\tilde{C}_{i,j} = \sum\left(GRKS\left(\min_{i,j}, Average_{i,j}, \max_{i,j}\right)\right) \quad (6)$$

Where GRKS = Gray, Richardson, Klose, and Schumann Simetar a function; *j* = production costs for farms using variety *j* (local, recycled, or improved); Min = minimum cost (in TZS/t) that farmers incur in producing maize for variety *j*; Max = the maximum cost (in TZS/t) that farmers incur in producing maize for variety *j*; Average = the average cost (TZS/t) that farmers incur in producing maize for variety *j*; $\tilde{C}_j$ = stochastic production cost for variety *j* varieties.

STOCHASTIC NET FARM INCOME SIMULATION

To estimate farm-level profitability, this study employed a stochastic simulation approach to calculate net farm income. The simulation process began by determining each farm's potential output, calculated as the simulated yield per hectare multiplied by the total cultivated area (Eqn 7). Following this, the gross revenue was estimated using Eqn 8, representing the total monetary value a farmer could earn if all harvested maize were sold at the prevailing simulated market price. This step captures revenue potential without deducting any input or production-related expenses. The

final step, outlined in Eqn 9, involved calculating the stochastic net farm income by subtracting the total simulated production costs from the gross revenue. This net income measure captures the variability in yield, market prices, and production costs, providing a realistic projection of farm profitability per hectare across different input-use scenarios.

$$\tilde{\mu}_{i,j} = \tilde{y}_{i,j} * a_{i,j} \quad (7)$$

$$\tilde{R}_{i,j} = \tilde{P}_{j} * \tilde{\mu}_{i,j} \quad (8)$$

$$\tilde{\pi}_{i,j} = \tilde{R}_{i,j} - \tilde{C}_{i,j} \quad (9)$$

Where $\tilde{\mu}_{i,j}$ = the stochastic output (in tons) for farming practice j, for the agroecological zone i ; $\tilde{y}_{i,j}$ = the stochastic yield per hectare for farming practice j, for the agroecological zone i ; $a_{i,j}$ = area cultivated by farmers in farming practice j, for the agroecological zone i ; $\tilde{R}_{i,j}$ = stochastic revenue gained by farmers in farming practice j, for the agroecological zone i ; $\tilde{P}_{j}$ = the stochastic price (TZS/ton) for maize variety j; $\tilde{C}_{i,j}$ = the stochastic production cost for farming practice j for the agroecological zone j.

RANKING OF TARGET PROBABILITIES USING THE STOPLIGHT FUNCTION

The stoplight chart function was used to rank the probabilities that maize farms would achieve the maximum profit threshold and fall below the minimum threshold per unit area (ha in this study) (Fig. 2). The stoplight function calculates the probabilities of (a) exceeding the upper target (*green*), (b) being less than the lower target (*red*), and (c) falling between the targets (*yellow*). The views of various maize actors, particularly farmers, and literature such as Utonga (2022) indicate that the average maize gross margin (profit) per ha in Tanzania ranges between TZS 1.0 and 1.2 million, with a minimum of TZS 0.5 to 0.7 million. Hence, we set the maximum threshold at TZS 1.2 million/ha and the minimum to TZS 0.6 million/ha. The maximum threshold was also close to that observed by Utonga (2022), who analyzed the gross margin of maize for smallholder farmers in Mbinga district and reported an average of TZS 1.18 million/ha.

Accordingly, the study focuses on probabilistic comparisons derived from simulated distributions rather than on formal hypothesis testing. PDFs and stop light charts are used to evaluate the likelihood of achieving defined income thresholds, consistent with established practices in non-parametric risk analysis. While formal statistical tests such as stochastic dominance or confidence interval estimation could complement this analysis, the present study emphasizes distributional interpretation and policy-relevant probability metrics.

Results

MAIZE PRODUCTIVITY

Figure 3 presents the probability distribution functions (PDFs) of simulated maize yields (t/ha) for farms using local (S_0), improved (S_1), and recycled seeds (S_2) across Tanzania's agroecological zones (AEZs). The figure illustrates differences in yield performance by showing the frequency, spread, and central tendency of outcomes across seed types. At the national level (Fig. 3i), the distribution for improved seeds is clearly shifted to the right relative to both local and recycled seeds, indicating a higher probability of achieving better yields, particularly within the 1.5–2.5 t/ha range. Recycled seeds exhibit intermediate performance with wider dispersion, while local seeds are more concentrated at lower yield levels, reflecting limited productivity potential.

At the zonal level, yield responses vary substantially. In the Central Zone, improved seeds show a clear advantage, with a higher frequency of moderate-to-high yields compared to local and recycled seeds. However, the broader spread of recycled seed yields suggests less consistency. In contrast, the Eastern Zone shows minimal differences among seed types, with distributions largely overlapping. This indicates that improved seeds provide only marginal gains, likely due to environmental or input-related constraints. Interestingly, recycled seeds in this zone perform comparably, suggesting that farmers may be effectively maintaining seed quality through recycling practices.

The Lake Zone presents a distinctive pattern in which both local and improved seed distributions overlap and exhibit bimodal characteristics. This suggests variability in production conditions, such as rainfall or management practices, limiting the effectiveness of improved seeds. A similar pattern is observed in the Southern Zone, where the three distributions nearly coincide, indicating that seed type has little influence on yields. In these zones, productivity appears to be driven more by non-seed factors, including soil fertility limitations and moisture constraints.

In contrast, the Northern and Southern Highlands Zones show strong responsiveness to improved seeds. In the Northern Zone, improved seeds exhibit a clear rightward shift, indicating higher yields and a greater likelihood of favorable outcomes. Recycled seeds also perform moderately well, suggesting partial retention of genetic potential. The Southern Highlands Zone demonstrates the highest overall yield potential, with improved and recycled seeds

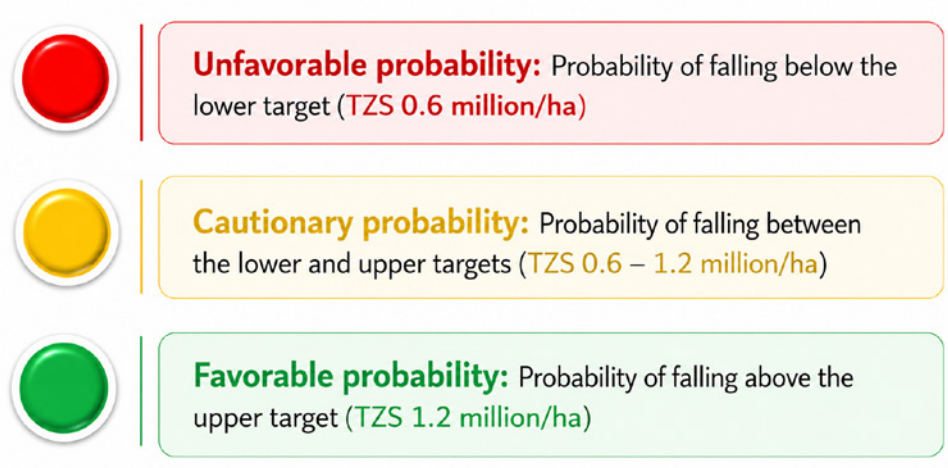


Fig. 2. Stoplight chart for ranking of target probabilities.

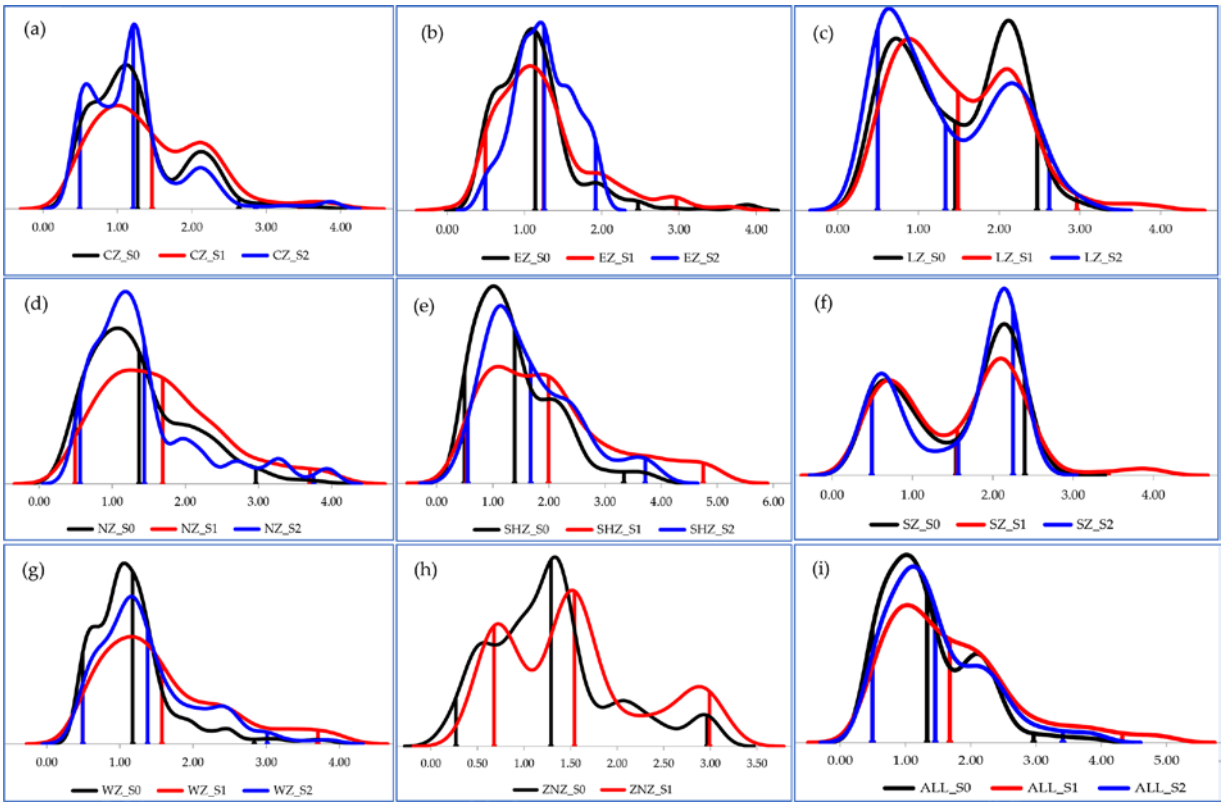


Fig. 3. Probability distribution functions (PDFs) showing yield distribution across the agroecological zones of Tanzania, for farms using local seeds (_S_0), improved seeds (_S_1), and those using recycled seeds (_S_2): (a) = Central Zone; (b) = Eastern Zone, (c) = Lake Zone, (d) = Northern Zone, (e) = Southern Highlands Zone, (f) = Southern Zone, (g) = Western Zone, (h) = Zanzibar, (i) = All aggregated maize farms across the Country.

producing broad distributions that extend to very high yield levels. This reflects favorable agroecological conditions, including good soils, reliable rainfall, and stronger access to inputs and extension services. The Western Zone follows a similar pattern, though with slightly lower yield gains. In Zanzibar, improved seeds also outperform local varieties, with a broader and more right-skewed distribution. This suggests that improved seeds can significantly enhance productivity in island systems with relatively supportive environmental conditions and market access.

The distributional patterns suggest that improved maize seeds generally outperform local varieties, although the magnitude of gains varies across zones. Strong benefits are observed in zones with favorable conditions, whereas limited improvements elsewhere highlight the influence of environmental and institutional constraints. Recycled seeds play an intermediate role, offering modest gains in some regions but showing inconsistent performance in others. These findings emphasize that improved seeds increase the likelihood of higher yields, but their effectiveness depends on agroecological conditions and complementary inputs, underscoring the need for targeted, context-specific interventions.

PRODUCTION COSTS AND MAIZE PRICES ACROSS AGROECOLOGICAL ZONES

Maize production costs (TZS/ha) and output prices (TZS/t) across seed types and agroecological zones, highlighting key economic conditions that shape farm-level profitability in Tanzania. Results on production costs and output prices are well presented in Supplementary material 3 (SM 3). The results reveal substantial variation in both cost structures and price outcomes, reflecting differences in input use, market access, and agroecological conditions.

Production costs (TZS/ha)

Production costs are consistently higher for farms using improved seeds (S_1) than for farms using local (S_o) or recycled seeds (S_2). At the national level, improved seed users incur an average cost of about TZS 318,148/ha, which is approximately 151% higher than that of local seeds and 32% higher than that of recycled seeds. This indicates that adoption of improved maize varieties requires significantly greater financial investment. The pattern holds across all zones, although the magnitude varies. For example, the Southern Highlands Zone (SHZ) and Zanzibar (ZNZ) record particularly high costs for improved seed users, reflecting higher input intensity and greater use of complementary technologies. In contrast, zones such as the Lake Zone (LZ) exhibit relatively low production costs, especially for local and recycled seed users, suggesting lower commercialization and input use (SM 3).

Despite higher average costs, improved seed systems show more stable expenditure patterns. The coefficient of variation for improved seed costs is generally lower than that for local and recycled seeds, indicating greater predictability in input use. This likely reflects more standardized production practices and better-developed supply chains. In contrast, local and recycled seed systems exhibit higher cost variability, particularly in zones such as LZ and SZ, where input use is less consistent. This variability increases uncertainty in production planning and contributes to uneven profitability outcomes among farmers.

Output prices (TZS/t)

Maize prices also vary considerably across seed types and zones. At the national level, maize produced from improved seeds commands the highest average price (approximately TZS 536,993/t), compared to about TZS 480,135/t for local seeds and TZS 478,361/t for recycled seeds. This price premium suggests that improved seed maize is often associated with better grain quality and stronger market demand. However, the extent of this advantage differs across regions. Zones such as the Northern Zone (NZ) and Zanzibar (ZNZ) record the highest prices for improved seed maize, reflecting favorable market conditions and

consumer preferences. Conversely, lower prices are observed in zones such as the Western (WZ) and Southern Highlands (SHZ), where factors such as market access, grain quality, and post-harvest handling may constrain price realization. Importantly, price premiums are not determined solely by seed type. Recycled seed maize, for instance, often commands prices comparable to local maize and, in some cases, higher prices, particularly in zones such as LZ and EZ. This suggests that regional demand, grain characteristics, and market integration play a significant role in shaping price outcomes (SM 3).

Price variability remains substantial across all seed systems, with moderate-to-high market volatility observed. Improved seed maize, despite attracting higher average prices, exhibits similar variability to local maize, indicating that adoption of improved seeds does not necessarily reduce exposure to price risk. Variability is particularly pronounced in zones such as the Lake Zone, while relatively stable price patterns are observed in the Southern Zone, possibly due to localized market dynamics.

Overall, the combined cost and price patterns highlight a critical trade-off in maize production systems. Improved seeds are associated with higher and more stable production costs, as well as modest price advantages, but these gains can be offset by market volatility and regional constraints. Consequently, profitability outcomes depend not only on seed choice but also on the interaction between cost structures, price dynamics, and agroecological conditions. These findings underscore the importance of integrating both cost and price variability into profitability analysis and highlight the need for policies that improve input affordability, strengthen market systems, and enhance price stability for smallholder farmers.

PROFITABILITY OF MAIZE FARMS USING LOCAL SEEDS

Figure 4 presents the simulated probability distribution of per-hectare net farm income (NFI) for maize farmers using local seeds (S_0) across Tanzania's agroecological zones. Income outcomes are categorized into three ranges: below TZS 0.6 million/ha, between TZS 0.6 and 1.2 million/ha, and above TZS 1.2 million/ha. At the national level, the distribution indicates a high likelihood of low-income outcomes among local seed users. Specifically, there is an estimated 67% probability that farmers fall below the minimum profitability threshold, a 24% probability of falling within the intermediate range, and only a 8% probability of exceeding the upper threshold. This distributional pattern suggests that maize production under local seed systems is predominantly associated with low expected returns.

At the zonal level, the likelihood of falling below the minimum income threshold varies substantially. In the Eastern Zone, there is approximately a 77% probability that farmers fall below TZS 0.6 million/ha. In contrast, in the Western Zone, the probability increases slightly to 78%, indicating a strong concentration of outcomes in the lower tail of the income distribution. These patterns reflect the unfavorable price-cost dynamics observed earlier, in which relatively low maize prices and moderate production costs reduce the likelihood of achieving positive margins. In the Eastern Zone, where production costs closely align with output prices, the probability of transitioning into higher-income categories remains particularly low.

In contrast, some zones exhibit more favorable distributional shifts. In the Lake Zone, there is a 32% probability that farmers fall within the intermediate income range and an 18% probability of exceeding the upper threshold, indicating a moderate shift toward improved income outcomes. Similarly, in Zanzibar, the distribution is more balanced, with a 44% probability of falling within the middle-income category and an 18% probability of exceeding TZS 1.2 million/ha. However, 39% remain below the minimum threshold. More favorable price-cost relationships largely drive these outcomes. In the Lake Zone, lower production costs increase the likelihood of achieving positive returns, while in Zanzibar, higher maize prices shift the income distribution to the right.

The Southern Zone also demonstrates a relatively favorable income distribution. Here, the probability of falling below the minimum threshold is about 42%. In comparison, the likelihood of exceeding the upper threshold rises to 29%, reflecting a wider price-cost margin that supports improved income outcomes. However, in the Southern Highlands Zone, the probability of falling below the minimum threshold is approximately 74%, while in the Northern Zone, it is about 65%. In these zones, higher production costs and yield variability reduce the likelihood of achieving profitability, even where maize prices are relatively favorable.

At the national level, the income distribution among local seed users remains heavily skewed toward lower-income outcomes, with roughly a two-thirds probability of falling below the minimum threshold. This reflects the combined effects of relatively low yields, high variability in production costs, and limited market advantages. In zones such as the Eastern and Western regions,

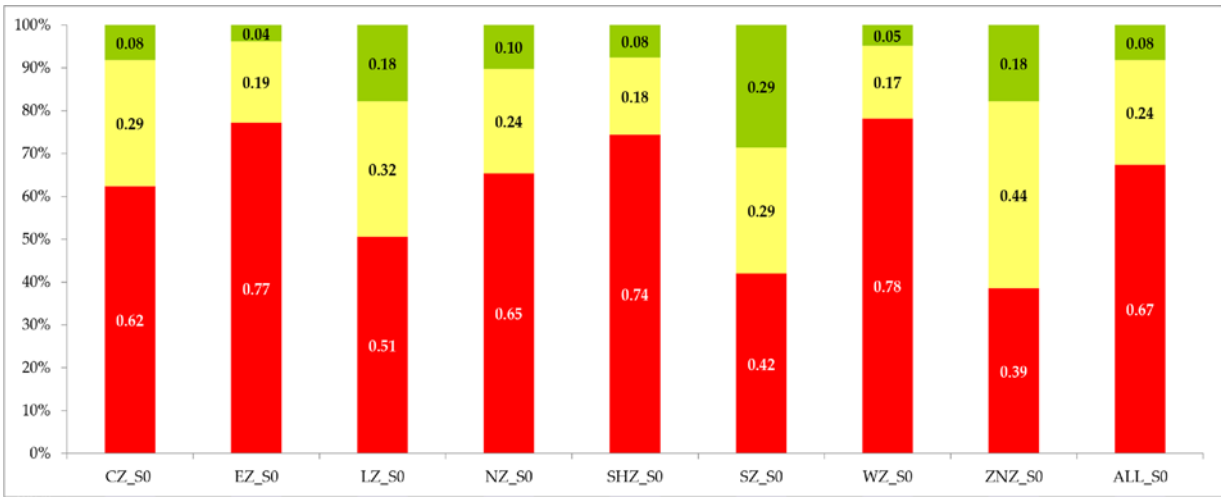


Fig. 4. The probabilities of income falling above the maximum threshold of TZS 1.2 million/ha (*in green*) and less than the minimum income of TZS 0.60 million/ha (*in red*), and the probability of falling between the two thresholds for maize farmers using local seeds (_S_0) in all agroecological zones of Tanzania. CZ_S_0 = farms using local seeds in Central Zone; EZ_S_0 = farms using local seeds in Eastern Zone; LZ_S_0 = farms using local seeds in Lake Zone; SHZ_S_0 = farms using local seeds in Southern Highlands Zone; SZ_S_0 = farms using local seeds in Southern Zone, WZ_S_0 = farms using local seeds in Western Zone; ZNZ_S_0 = farms using local seeds in Zanzibar and ALL_S_0 = all farms using local seeds across the Country.

these constraints create a cost-price imbalance that limits upward movement in the income distribution. Conversely, zones such as Zanzibar and the Southern Zone illustrate that favorable market conditions and cost structures can increase the likelihood of achieving moderate-to-high income outcomes.

The results indicate that reliance on local seeds is associated with a high probability of low-income outcomes across most agroecological zones. While some regions exhibit more favorable distributional patterns, the overall trend suggests limited economic viability for most smallholder farmers using traditional seed systems. These findings highlight the importance of transitioning toward improved or alternative seed systems. However, such transitions must be supported by complementary interventions, including improved access to inputs, credit, and market linkages, to effectively shift income distributions upward and increase the likelihood of achieving sustainable farm profitability.

PROFITABILITY OF MAIZE FARMS USING IMPROVED SEEDS

Figure 5 presents the simulated probability distribution of per-hectare net farm income (NFI) for maize farmers using improved seeds (S_1) across Tanzania's agroecological zones. The results indicate that although improved seeds are associated with higher yields and better price outcomes, there remains a substantial likelihood that farmers fall below the minimum profitability threshold of TZS 0.6 million/ha. At the national level, there is approximately a 64% probability that farmers using improved seeds fall below the minimum threshold, compared with 67% among local seed users, indicating only a modest downward shift in the lower tail of the income distribution. Despite this, improved seeds increase the likelihood of achieving higher income outcomes. Nationally, there is about a 14% probability of exceeding the upper threshold of TZS 1.2 million/ha, compared to 8% under local seeds, reflecting a modest rightward shift in the income distribution. The probability of falling within the intermediate income range is approximately 22%, indicating a slight expansion of the middle-income category. These results suggest that improved seeds contribute to an upward redistribution of income. However, the magnitude of this shift is limited once production costs and market variability are taken into account.

At the zonal level, the distributional patterns vary considerably, ranging between 5% and 17% probabilities of exceeding the upper threshold and between 51% and75% probabilities of falling below the minimum threshold. In Zanzibar (ZNZ), the probability of exceeding the upper threshold is approximately 16%, whereas in the Southern, Northern, and the Southern Highlands Zones, the likelihood is between 15% and 17%. These relatively favorable outcomes correspond to earlier findings of higher maize prices in these regions, which shift the income distribution toward higher ranges despite relatively elevated production costs. The Southern Zone displayed a slightly more balanced distribution with an approximately 32% probability of falling within the intermediate range, a 17% probability of exceeding the upper threshold, and a 51% likelihood of falling below the lower threshold, indicating a moderate upward shift supported by relatively stable prices and manageable cost structures.

In contrast, the Eastern Zone (EZ) remains the most constrained, with a 75% probability of farmers falling below the minimum threshold and only a 5% probability of exceeding the upper threshold. This reflects a distribution heavily concentrated in the lower-income range, driven by high production costs and limited yield gains. Similarly, in the Western Zone (WZ), the distribution shows only a marginal improvement compared to local seeds, indicating that improved seed adoption alone does not substantially alter income outcomes in areas characterized by weak market linkages and cost constraints.

Comparing Figs 4 and 5 highlights the incremental nature of improvements associated with improved seeds. In the Southern Highlands Zone, the probability of exceeding the upper threshold increases from 8% under local seeds to 17% under improved seeds, while the likelihood of falling below the minimum threshold declines from 74% to 64%, indicating a clear upward shift in the distribution. In Zanzibar, the probability of falling below the threshold changes from 39% to 57%, while the likelihood of exceeding the upper threshold remains relatively stable, suggesting a more complex redistribution influenced by higher costs. Although these shifts are modest, they demonstrate that improved seeds can increase the likelihood of better income outcomes under favorable conditions.

The results indicate that improved seeds are associated with a higher probability of achieving moderate- and high-income

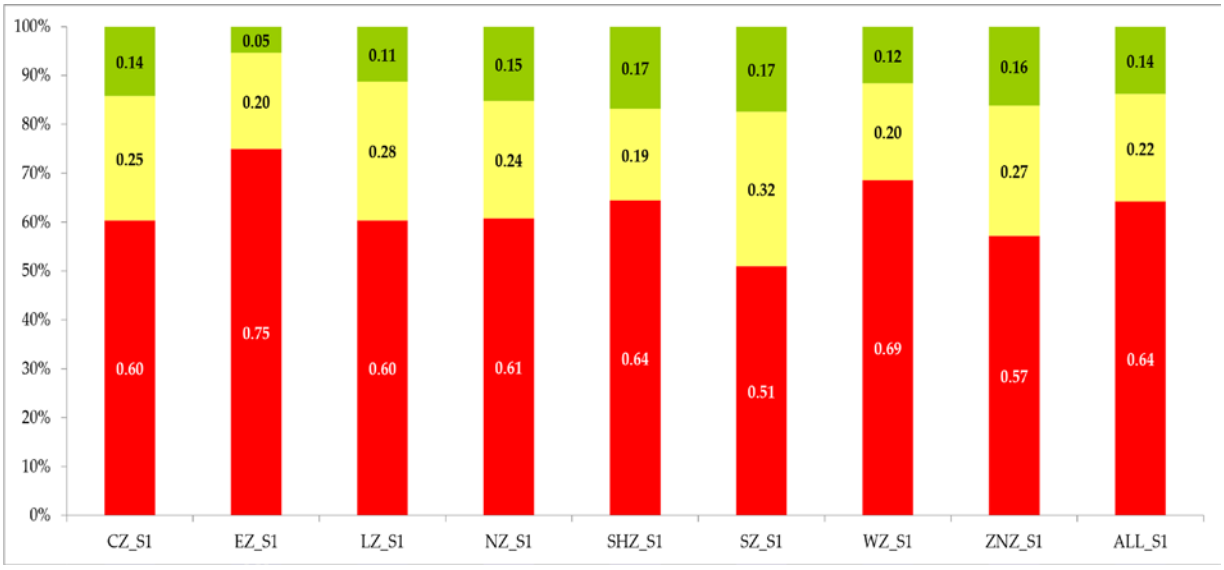


Fig. 5. The probabilities of income falling above the maximum threshold of TZS 1.2 million/ha (*in green*) and less than the minimum income of TZS 0.60 million/ha (*in red*), and the probability of falling between the two thresholds for maize farmers using improved seeds (*_S1*) in all agroecological zones of Tanzania. CZ_S_1 = farms using improved seeds in Central Zone; EZ_S_1 = farms using improved seeds in Eastern Zone; LZ_S_1 = farms using improved seeds in Lake Zone; SHZ_S_1 = farms using improved seeds in Southern Highlands Zone; SZ_S_1 = farms using improved seeds in Southern Zone, WZ_S_1 = farms using improved seeds in Western Zone; ZNZ_S_1 = farms using improved seeds in Zanzibar and ALL_S_1 = all farms using improved seeds across the Country.

outcomes compared to local seeds. However, the income distribution remains heavily skewed toward the lower end, with more than a 64% probability that farmers fall below the profitability threshold nationally. This suggests that improved seeds alone are insufficient to guarantee profitable outcomes across all zones. The effectiveness of improved seed adoption is highly context-dependent, influenced by interactions between yield potential, input costs, and market conditions.

These findings highlight the need for integrated interventions that go beyond seed provision. Policies that improve access to complementary inputs, strengthen market linkages, and reduce production costs are essential to further shifting income distributions upward. Without such support, the observed gains from improved seeds are likely to remain modest, limiting their potential to transform smallholder profitability across Tanzania's diverse agroecological zones.

PROFITABILITY OF MAIZE FARMS USING RECYCLED SEED

Figure 6 presents the simulated probability distribution of per-hectare net farm income (NFI) for maize farmers using recycled seeds (S_2) across Tanzania's agroecological zones. The results indicate a high likelihood of low-income outcomes among farmers relying on recycled seeds. At the national level, there is approximately a 77% probability that farmers fall below the minimum threshold of TZS 0.6 million/ha, a 17% probability of falling within the intermediate range, and only about a 6% probability of exceeding the upper threshold of TZS 1.2 million/ha. This distribution shows that income outcomes under recycled seed systems are heavily concentrated in the lower tail, reflecting limited profitability prospects for most farmers.

At the zonal level, the likelihood of falling below the minimum income threshold remains high across most regions. In the Eastern Zone, there is an estimated 81% probability that farmers will fall below the threshold, with virtually no likelihood of exceeding the upper benchmark. This pattern suggests that the use of recycled seed in this zone is associated with persistently low-income outcomes, driven by a combination of low yields, weak market prices, and relatively high production costs. Similarly, the Western Zone and Northern Zone show high probabilities of low-income outcomes, at approximately 80% and 76%, respectively, indicating that recycled seeds in these regions are unlikely to generate sufficient returns to offset production costs. These patterns are consistent with earlier findings highlighting structural constraints, including limited access to quality inputs, high-cost variability, and yield uncertainty.

In contrast, a few zones exhibit relatively more favorable distributional patterns. The Lake Zone stands out, with a 23% probability of exceeding the upper threshold and about a 52% probability of falling below the minimum threshold, indicating a more balanced distribution compared to other regions. This outcome reflects relatively low production costs and moderately favorable maize prices, increasing the likelihood of achieving higher income outcomes even with the use of recycled seed. The Southern Zone also shows a distinct pattern, with approximately 51% probability of falling within the intermediate income range and no observed probability of exceeding the upper threshold. This suggests more stable but modest income outcomes, likely supported by lower cost variability and localized market conditions. The Southern Highlands Zone exhibits a moderate distributional shift, with about a 17% probability of falling within the intermediate range and an 8% probability of exceeding the upper threshold, indicating some potential for improved income outcomes relative to other zones. However, the overall distribution in this zone still indicates a considerable likelihood of low-income outcomes, driven by relatively higher production costs and greater variability.

The results suggest that recycled seeds can provide modest income opportunities under specific conditions, particularly in zones with low production costs and relatively favorable market conditions. However, at the national level, the income distribution remains heavily skewed toward lower outcomes, indicating that reliance on recycled seed systems is associated with a high likelihood of limited profitability. While recycled seeds offer a cost-saving alternative to purchasing improved seeds, their economic performance is highly variable and strongly dependent on local conditions.

These findings highlight that using recycled seed alone is unlikely to substantially shift income distributions toward higher profitability for most smallholder farmers. To improve outcomes, complementary interventions are necessary, including better access to fertilizers, improved soil management practices, and stronger extension services. In addition, policies that support periodic seed renewal and improve access to certified seed systems could help shift income distributions upward and enhance the likelihood of

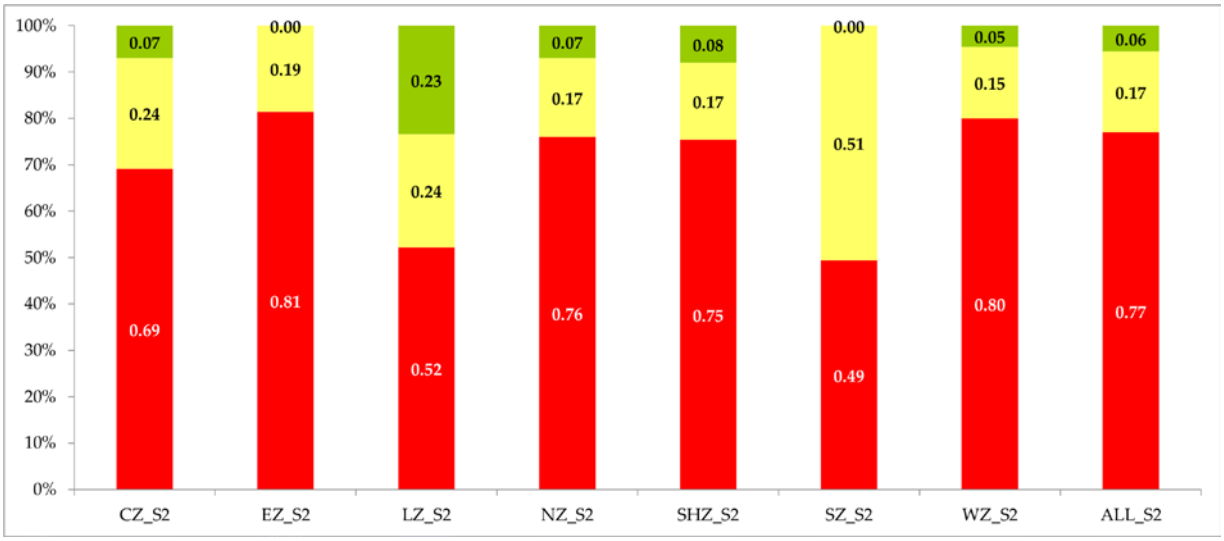


Fig. 6. The probabilities of income falling above the maximum threshold of TZS 1.2 million/ha (*in green*) and less than the minimum income of TZS 0.60 million/ha (*in red*), and the probability of falling between the two thresholds for maize farmers using recycled seeds (_S_2) in all agroecological zones of Tanzania. CZ_S_2 = farms using recycled seeds in Central Zone; EZ_S_2 = farms using recycled seeds in Eastern Zone; LZ_S_2 = farms using recycled seeds in Lake Zone; SHZ_S_2 = farms using recycled seeds in Southern Highlands Zone; SZ_S_2 = farms using recycled seeds in Southern Zone, WZ_S_2 = farms using recycled seeds in Western Zone; ZNZ_S_2 = farms using recycled seeds in Zanzibar and ALL_S_2 = all farms using recycled seeds across the Country.

achieving sustainable profitability across Tanzania's diverse agroecological zones.

Discussion

The analysis of profitability distributions across seed types (Figs 4–6) reveals substantial heterogeneity in income outcomes among Tanzanian maize farmers. Rather than focusing on point estimates, the results highlight distributional patterns, indicating that a large proportion of farmers, regardless of seed type, are likely to remain below viable income thresholds. This underscores the structural nature of profitability constraints in smallholder maize systems. While improved seed users generally exhibit a higher probability of achieving moderate- or upper-income outcomes than those using local or recycled seeds, the magnitude of this distributional shift remains modest. The observed upward movement in income probabilities not only suggests potential gains from improved seeds but also indicates that most adopters are likely to remain within low-income ranges. These findings are consistent with earlier studies emphasizing that the economic performance of improved technologies depends critically on access to complementary inputs such as fertilizers, extension services, and post-harvest management (Beyene and Kassie, 2015; Liverpool-Tasie *et al.*, 2017; Abdoulaye *et al.*, 2018).

The modest redistribution of income outcomes associated with improved seeds must be interpreted alongside their higher production costs. Although improved seeds provide yield and quality advantages, they also entail higher, more standardized input costs. This creates a trade-off where gains in productivity do not always translate into proportional improvements in net income. In environments characterized by weak or volatile output markets, this cost burden reduces the likelihood that farmers will transition into higher-profitability categories. For instance, in the Eastern Zone, where improved seeds are associated with only marginal yield gains, there remains a high probability that farmers will fall below the profitability threshold due to low maize prices and relatively high input costs. This pattern reflects the broader argument by Sheahan and Barrett (2017) that technology adoption, in the absence of effective market integration, is unlikely to deliver sustained income improvements among smallholders.

The role of recycled seeds adds further nuance to these findings. While recycled seeds are generally associated with lower productivity, their relatively lower cost structure can increase the likelihood of achieving moderate income outcomes in specific contexts. In zones such as the Lake and Southern Zones, the income distributions for recycled seed users show a higher probability of reaching middle- or upper-income thresholds than in other regions. This suggests that seed recycling can serve as a cost-saving strategy under conditions of moderate yields and favorable price-cost relationships. However, this advantage is inherently limited. Evidence shows that repeated recycling of hybrid seeds leads to genetic degeneration, reducing yield potential over time and increasing the likelihood of lower income outcomes in the long run (Lyimo *et al.*, 2014; Kabululu *et al.*, 2017; Kihara *et al.*, 2021).

A key insight from this analysis is the strong spatial variation in profitability outcomes across agroecological zones. National-level averages mask substantial regional disparities. For example, the Lake Zone consistently shows a higher likelihood of moderate- and upper-income outcomes across seed types, largely due to lower production costs and relatively stable yield conditions. In contrast, the Eastern and Western Zones exhibit persistent concentration of income outcomes in the lower range, regardless of seed type. These patterns reflect deeper structural constraints, including poor soil fertility, erratic rainfall, limited access to quality inputs, and weak market linkages (Gowing and Palmer, 2008; Abate *et al.*, 2015; Alia, 2017). The results, therefore, suggest that agroecological and market conditions play a more decisive role in shaping profitability than seed type alone.

Overall, the findings reinforce the view that improved seeds are a necessary but not sufficient condition for achieving profitable maize production among smallholders. The probability of achieving higher income outcomes increases with improved seed use, but remains highly dependent on complementary factors. Translating yield potential into sustained income gains requires an enabling environment that supports input affordability, effective extension systems, and well-functioning markets. Strengthening seed quality regulation, improving access to fertilizers, and enhancing price-stability mechanisms are critical to shifting income distributions upward. This conclusion aligns with broader literature emphasizing that input intensification strategies are most effective when embedded within supportive institutional and policy frameworks (Vanlauwe *et al.*, 2019; Schut and Giller, 2020).

The results also highlight the importance of risk and uncertainty in shaping farm-level outcomes. The observed variability in yield and income distributions indicates that farmers face significant exposure to climatic shocks, market price fluctuations, and constraints on input access. Even among improved seed users, there remains a substantial likelihood of falling into low-income categories due to these uncertainties. Addressing this challenge requires integrating risk management strategies into agricultural interventions, including index-based insurance, access to affordable credit, and improved market information systems (Antle, 2011; Levkina *et al.*, 2019). Such measures can reduce income volatility and increase the likelihood of achieving stable, sustainable profitability.

Despite these insights, several limitations must be acknowledged. First, the stochastic simulation framework relies on historical yield, price, and cost distributions derived from NSCA data. While this approach effectively captures variability and uncertainty, it assumes that past patterns are representative of future conditions, which may not hold as climatic and economic environments change. Second, the use of observational cross-sectional data implies that potential selection bias cannot be ruled out, as farmers adopting improved seeds may differ systematically from others in terms of resources, access to services, and management practices. Accordingly, the results should be interpreted as probabilistic associations rather than causal effects. Third, the simulation framework does not fully capture unobserved heterogeneity, such as intra-zone soil differences and farm-level decision making behavior. Finally, profitability outcomes remain sensitive to price and cost assumptions, as well as to the chosen income thresholds (TZS 0.6 and 1.2 million/ha), which serve as analytical benchmarks rather than fixed welfare standards. These limitations suggest that while the findings robustly capture general distributional patterns, caution is required when interpreting exact magnitudes of income outcomes.

CONCLUSIONS

This study assessed the profitability of maize production in Tanzania by modeling the probability distribution of farm income for users of local, improved, and recycled seeds across diverse agroecological zones. Using a stochastic simulation framework, the results indicate that improved seeds increase the likelihood of achieving higher income outcomes relative to local and recycled seeds. However, a substantial proportion of farmers still face a high probability of remaining below the minimum profitability threshold of TZS 0.6 million/ha. At the national level, there is an estimated 64% probability that improved seed users fall below this threshold, compared to 67% for local seeds and 77% for recycled seeds, indicating only a modest upward shift in income distributions. These findings suggest that while improved seeds contribute to improved performance, they are insufficient on their own to ensure economically viable outcomes for most smallholder farmers.

The results further demonstrate that profitability outcomes are highly heterogeneous across agroecological zones. The likelihood of achieving moderate- or high-income levels varies significantly depending on local conditions, including production costs, maize prices, and market access. Zones such as the Lake and Southern Zones show relatively higher probabilities of improved income outcomes, partly due to lower cost structures and more stable production environments. In contrast, the

Eastern and Western Zones remain characterized by a high likelihood of low-income outcomes across all seed systems, reflecting persistent structural constraints, such as poor soil fertility, limited access to inputs, and weak market integration. These patterns highlight that agroecological and institutional factors play a critical role in shaping farm-level profitability beyond seed choice alone.

The findings contribute to the Tanzania Seed Sector Development Strategy (TSSDS 2030) and align with key Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger), and SDG 12 (Responsible Consumption and Production). Empirically, the high probability of farmers operating below minimum income thresholds underscores persistent income vulnerability (SDG 1). At the same time, the limited ability of improved seeds alone to shift income distributions upward underscores the need for integrated approaches to enhance productivity and resilience (SDG 2). Furthermore, the observed variation in profitability across zones reflects differences in input-use efficiency and cost management, emphasizing the importance of context-specific strategies to improve resource productivity (SDG 12). These insights suggest that achieving these development objectives requires not only technological adoption but also improvements in market conditions, cost structures, and institutional support systems.

To improve the profitability and sustainability of maize production, several policy directions emerge. First, there is a need to promote integrated input support packages that combine improved seeds with fertilizers, extension services, and agronomic training to realize productivity gains fully. Second, interventions should be tailored to agroecological conditions, recognizing spatial differences in yield potential, cost structures, and market access. Third, strengthening seed systems and farmer capacity is essential, including promoting access to certified seeds while raising awareness of the limitations of prolonged seed recycling. Finally, enhancing market linkages and financial access, including credit and price-stabilization mechanisms, will be critical to shifting income distributions toward more favorable outcomes.

While the study provides important insights, the findings should be interpreted in light of several limitations. The stochastic simulation relies on historical data and assumes stability in yield, price, and cost distributions, which may not fully capture future dynamics. In addition, the use of observational cross-sectional data implies that potential selection bias cannot be ruled out, and the results should therefore be interpreted as probabilistic associations rather than causal effects. The analysis is also sensitive to price and cost assumptions, as well as to the selected income thresholds, which serve as analytical benchmarks rather than fixed economic standards. Future research should incorporate causal identification strategies (e.g., quasi-experimental methods such as propensity score matching and panel models), longitudinal datasets, and sensitivity analyses to strengthen the robustness of findings.

In conclusion, improved maize seeds offer a pathway toward higher productivity and modestly improved income probabilities. However, sustainable profitability depends on broader systemic conditions, including access to inputs, market integration, and risk management. A holistic, context-specific approach that integrates seed technology with supportive institutional frameworks is essential to shifting income distributions upward and enhancing the economic resilience of smallholder farmers in Tanzania.

CONFLICTS OF INTEREST

The author reports no competing interests to declare.

ETHICS STATEMENT

The author confirms that the research complies with all required ethical guidelines, including adherence to the legal requirements of the study country.

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AUTHOR CONTRIBUTIONS

Not applicable as this paper has one author.

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DATA AVAILABILITY

Data will be made available on request.

SUPPLEMENTARY MATERIAL

The supplementary material is available in the online version of this article.

Please note: CABI is not responsible for the content or functionality of supplementary files provided by the authors and any queries should be directed to the corresponding author.

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