Maize Yield in Tanzania-Mainland: Can Farms Exceed the 3.5 t/ha Potential? A Multivariate Empirical (MVE) Simulation Approach

Kadigi, I.L.

Department of Business Management, College of Humanities and Business Studies,
Mbeya University of Science and Technology (MUST),
P.O. Box 131, Mbeya, Tanzania

*Corresponding author's email: *kideannito@gmail.com / ibrahim.kadigi@must.ac.tz*

Abstract

This study evaluates the probability that maize yields exceed a policy-relevant threshold of 3.5 t/ha across Tanzania Mainland's agro-ecological zones using data from the 2019/20 National Sample Census of Agriculture. Six farming systems were analyzed, combining local and improved seed types with three fertilizer regimes (none, organic, and inorganic). A Monte Carlo Simulation approach was applied to estimate zone-specific yield distributions and associated production risks. The results show that farms using improved seeds with inorganic fertilizers (Farming_5) consistently achieved the highest probabilities of exceeding 3.5 t/ha and the lowest risk of yields falling below 1.5 t/ha across all zones. Improved seeds combined with organic fertilizers (Farming_4) also generated moderate yield gains, particularly in livestock-dense zones such as the Northern Highlands and Lake Zone, although performance remained lower than inorganic fertilizer-based systems. Strong regional heterogeneity was observed, with the Southern Highlands exhibiting high responsiveness to improved input use, while the Eastern–Coastal Zone showed persistently low yield probabilities under all farming systems. Based on these findings, the study identifies three actionable policy priorities: (i) scale up access to improved seeds and inorganic fertilizers in high-potential zones; (ii) promote integrated nutrient management, including organic fertilizers, in livestock-rich areas with limited fertilizer access; and (iii) operationalize agro-ecology-specific input and extension strategies through local government and extension systems. The study provides evidence to support not only Tanzania's Seed Sector Development Strategy 2030, but also contributes to SDG 2 (Zero Hunger) by informing targeted, risk-aware maize intensification policies.

Keywords: Probabilistic Simulation, Maize yield, Local seeds, Improved seeds, Fertilizers, Tanzania

Introduction

Maize (*Zea mays* L.), locally known as mahindi, is Tanzania's most important staple crop and a cornerstone of national food security and rural livelihoods. It contributes substantially to household calorie intake, farm income, and employment for millions of smallholder farmers (Mkonda & He, 2018; Kadigi *et al*., 2020a). Despite its central role in the agrarian economy, maize yield performance in Tanzania remains persistently low, averaging below 2 t/ha, well below yield levels considered attainable under improved but scalable agronomic practices (Sheahan & Barrett, 2017). This persistent yield gap poses a major challenge to achieving national development objectives, including Tanzania's ambition to double crop productivity by 2030 under the Agricultural Sector Development Programme Phase Two (ASDP-II) (URT, 2016).

A large body of agronomic and economic literature attributes low maize yields in Sub-Saharan Africa to limited use of modern inputs, particularly improved seed varieties and fertilizers, compounded by soil nutrient depletion and climate variability (Vanlauwe *et al*., 2015; Zerssa *et al*., 2021; Michelson *et al*., 2024). Tanzania's soils are characterized by declining fertility due to continuous cultivation, limited replenishment of organic matter, and historically low fertilizer application rates, estimated at only 15–20 kg/ha, far below the global average (AGRA, 2020a; AGRA, 2020b). Empirical evidence shows that targeted fertilizer application, especially nitrogen-based fertilizers, can raise maize yields by up to 50% in many African contexts (Tovihoudji *et al*., 2017; Habtewold & Heshmati, 2023; Kalonga *et al*., 2024).

In parallel, improved maize seed varieties, bred for higher yield potential and tolerance to drought, pests, and diseases, are widely recognized as a critical pathway for yield enhancement and climate resilience (Badu-Apraku *et al*., 2023; Prasanna *et al*., 2022). Studies in Tanzania and comparable agro-ecological settings indicate that improved seeds can substantially outperform local varieties when complemented by appropriate agronomic management (Mwakatwila, 2016; Ahmed, 2022; Ricker-Gilbert, 2020). However, evidence also suggests that improved seeds alone are often insufficient to overcome soil nutrient constraints, highlighting the importance of complementary fertilizer use (Vanlauwe *et al*., 2015; Tittonell & Giller, 2013).

Tanzania's maize production landscape is further shaped by pronounced agro-ecological heterogeneity. Distinct zones, including the Northern Highlands, Eastern-Coastal, Central, Southern Highlands, Lake, and Western zones, differ markedly in rainfall patterns, soil characteristics, market access, and dominant farming systems (Mkonda, 2022; Mango *et al*., 2014; Heisse & Morimoto, 2024). These differences influence both the responsiveness of maize yields to input use and the risks associated with low productivity, particularly in semi-arid and coastal environments where climatic stress limits input efficiency (Golla, 2021; Adzawla *et al*., 2024). While this literature provides valuable insights into drivers of maize performance, a critical gap remains. Most existing studies focus on average yield or productivity effects using regression-based approaches, offering limited insight into the probability that farms can realistically achieve policy-relevant yield thresholds or the risk distribution of low yields under alternative farming systems. For policymakers and development practitioners operating under climate uncertainty, understanding yield variability and downside risk is often more informative than mean outcomes alone (Hardaker *et al*., 2015; Holden, 2018).

To address this gap, this study focuses explicitly on maize yield, defined as output per unit area (t/ha), rather than broader measures of productivity that incorporate labor or capital inputs. Using yield ensures conceptual clarity and direct alignment with agronomic benchmarks and national policy targets. The study evaluates whether maize farms can exceed a yield threshold of 3.5 t/ha, a benchmark commonly used to represent attainable yield levels under improved but scalable input use, while also assessing the likelihood of yields falling below a minimum threshold of 1.5 t/ha (Sheahan & Barrett, 2017).

Methodologically, the study departs from conventional econometric impact evaluation and applies a non-parametric Monte Carlo Simulation framework to nationally representative data from the 2019/20 National Sample Census of Agriculture (NSCA) (URT, 2021). This probabilistic simulation approach is particularly suitable for heterogeneous, data-constrained smallholder systems, where yield outcomes are stochastic and shaped by interacting agro-ecological and management factors (Richardson *et al*., 2006; 2007; Kadigi *et al*., 2025). Rather than testing causal hypotheses in the classical regression sense, the model evaluates yield distributions, threshold exceedance probabilities, and downside risk across alternative maize farming systems. Specifically, six maize farming systems are analyzed, defined by combinations of seed type (local versus improved) and fertilizer use (none, organic, or inorganic). The study addresses three core research questions: (i) what is the probability that maize yields are equal to or exceed 3.5 t/ha; (ii) what is the probability that yields fall below 1.5 t/ha; and (iii) what proportion of outcomes lies between these thresholds. By applying this framework across Tanzania's major agro-ecological zones, the study provides a comparative assessment of farming systems in terms of both upside potential and downside risk.

Building on Kadigi *et al*. (2025), which examined improved seed effects using National Panel Survey data, this study extends the analysis by incorporating fertilizer use and applying a non-parametric probabilistic simulation framework to nationally representative census data with broader spatial coverage. The resulting evidence directly informs Tanzania's Seed Sector Development Strategy (SSDS) 2030 (Minde *et al*., 2024), the Fertilizer Sector Development Strategy (Meredia *et al.*, 2022; AGRA, 2020a), and the Agricultural Sector Development Programme Phase Two (ASDP-II) (URT, 2016), all of which emphasize productivity growth through improved input access and targeted support. Beyond national policy relevance, the study contributes to global development agendas by supporting SDG 2 (Zero Hunger), particularly Targets 2.3 (doubling agricultural productivity and incomes of small-scale food producers) and 2.4 (ensuring sustainable and resilient food production systems), as well as SDG 13 (Climate Action) through evidence on climate-resilient and risk-reducing maize production strategies. By highlighting zone-specific yield distributions and downside risks, the study provides actionable insights for sustainable agricultural intensification and adaptive capacity building in Tanzania and across Sub-Saharan Africa.

Materials and Methods

Description of the study area

The study covers all regions of Tanzania Mainland and classifies them into six major agro-ecological zones to capture the country's diverse maize-growing environments. These zones differ markedly in rainfall patterns, soil characteristics, dominant farming systems, and biotic stresses, all of which influence maize yield outcomes and responsiveness to seed and fertilizer inputs. The Northern Highlands Zone (NHZ) is characterized by relatively high and reliable rainfall, volcanic and moderately fertile soils, and mixed crop–livestock systems. These conditions generally favor higher maize yield potential but are also associated with increased pest and disease pressure, including fall armyworm. The Eastern–Coastal Zone (ECZ) experiences bimodal, often erratic rainfall, predominantly sandy, low-fertility soils, and mixed subsistence–market-oriented farming systems. High humidity and temperature variability contribute to yield instability and weaker responses to inorganic fertilizer use.

The Central Zone (CZ) is semi-arid, with low and highly variable rainfall and widespread soil nutrient depletion. Farming systems are predominantly rainfed and risk-prone, making maize production highly sensitive to climate variability and input availability (Fig. 1). The Southern Highlands Zone (SHZ) represents one of Tanzania's most important maize surplus areas, characterized by relatively fertile soils, cooler temperatures, and well-distributed rainfall. The zone supports intensified maize systems and is highly responsive to improved seed and fertilizer use. The Lake Zone (LZ) has moderate to high rainfall, extensive crop–livestock integration, and greater availability of organic nutrient sources such as manure. These characteristics influence fertilizer choice and contribute to heterogeneity in yield performance across farming systems. The Western Zone (WZ) is characterized by moderate rainfall, variable soil fertility, and relatively low market access. Maize systems in this zone are predominantly smallholder-based and often constrained by limited access to improved inputs and extension services.

The inclusion of all six agro-ecological zones ensures that the analysis captures the full range of biophysical and management conditions under which maize is produced in Tanzania Mainland, thereby enhancing the study's national relevance and policy applicability. Likewise, accounting for these variations, the study identifies the most effective interventions to improve maize yields and supports evidence-based policy decisions to close the yield gap in Tanzania's maize production.

Data Sources

The data utilized in this study come from the 2019/20 National Sample Census of Agriculture (NSCA), conducted by Tanzania's National

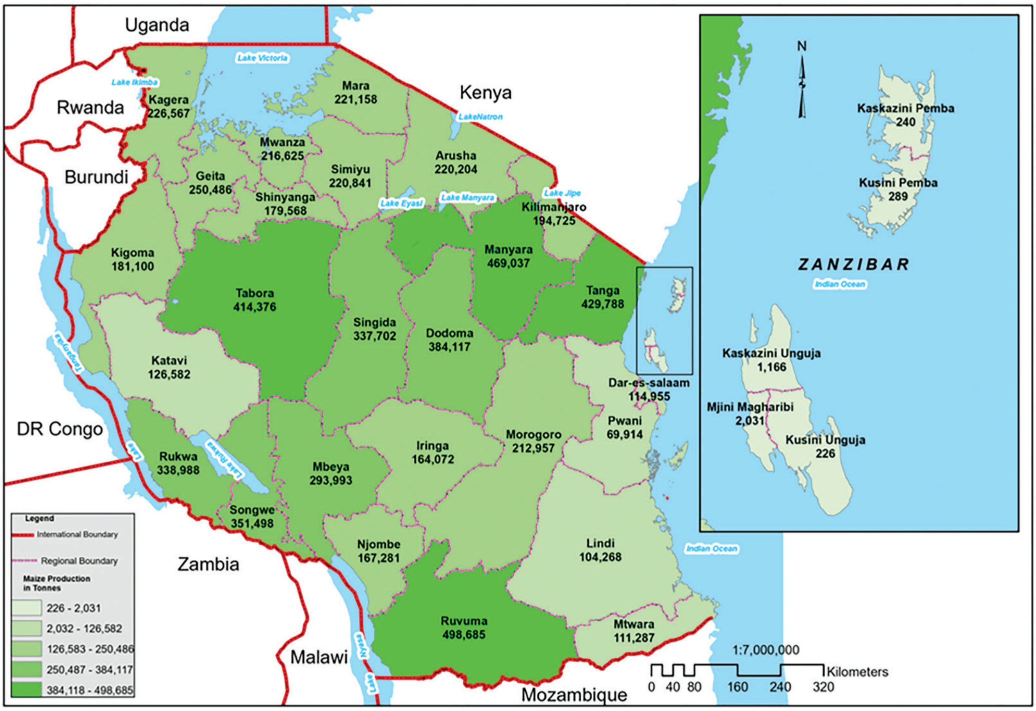

Figure 1: Map of Tanzania showing the quantity of maize harvested by Smallholder Farmers by Region during the 2019/20 Agricultural Year (URT, 2021)

Bureau of Statistics (NBS). The NSCA serves as a comprehensive repository of information, capturing key aspects of agricultural households, including farm size, crop production, livestock holdings, and the use of agricultural inputs such as fertilizers and seeds. Additionally, the census examines rural infrastructure improvements and the living standards of farming households, therefore, offering valuable benchmarks for evaluating agricultural yield and the impact of agricultural interventions implemented by various stakeholders, including Agricultural Sector Lead Ministries (ASLMs).

To ensure nationwide representativeness, the 2019/20 National Sample Census of Agriculture (NSCA) employed a two-stage sampling design. In the first stage, Census Enumeration Areas (CEAs) from the 2012 Population and Housing Census were selected as Primary Sampling Units (PSUs) using probability-based methods and proportionally allocated across regions and districts to ensure geographical balance. In the second stage, a household listing exercise was conducted within each selected PSU to identify agricultural households actively engaged in crop cultivation and/or livestock production. This step constituted a purposive definition of the sampling frame, consistent with the objectives of the agricultural census. From this predefined frame of agricultural households, households were then randomly selected, ensuring that each eligible agricultural household had an equal probability of selection. This approach allowed the NSCA to maintain both sectoral relevance and statistical representativeness.

The sampling process covered a total of 2,820 PSUs, comprising 2,670 PSUs from Mainland Tanzania and 150 PSUs from Tanzania Zanzibar. However, this study exclusively analyzes data from Mainland Tanzania, aligning with its research objectives. The sampling strategy employed a Probability Proportional to Size (PPS) technique, which prioritized areas with higher agricultural activity, thereby enhancing data reliability and accuracy. Details of the sampling procedure, including design and implementation, can be found in the official NSCA report (URT, 2021).

Data Processing and Simulation

The dataset used in this study was derived from the 2019/2020 NSCA and was categorized into six distinct maize farming practices to enable disaggregated simulation analysis across agro-ecological zones. These farming practices were defined by seed type (local or improved) and fertilizer application (none, organic, or inorganic). Specifically, Farming_0 refers to farms using local seeds without any fertilizers; Farming_1 includes farms using local seeds with organic fertilizers; and Farming_2 covers those using local seeds with inorganic fertilizers. Meanwhile, improved seed users were grouped into Farming_3 (no fertilizer), Farming_4 (organic fertilizers), and Farming_5 (inorganic fertilizers). This classification enabled the simulation model to capture nuanced differences in input use across the farming systems.

As summarized in Table 1, a total of 15,927 maize farm observations were analyzed across six agro-ecological zones: the Northern Highlands Zone (NHZ), Eastern–Coastal Zone (ECZ), Central Zone (CZ), Southern Highlands Zone (SHZ), Lake Zone (LZ), and Plateau Zone (PL). The largest share of observations falls under Farming_0 (7,392), representing local seed systems without fertilizer use, followed by Farming_3 (2,696) and Farming_2 (2,145). The large sample size, combined with substantial variation in agro-ecological conditions and input-use patterns, provides a strong empirical foundation for non-parametric stochastic analysis. This heterogeneity enables the construction of empirical yield distributions for each farming system and zone, which are subsequently simulated using a Monte Carlo framework. Unlike deterministic or regression-based methods that focus on average effects, the Monte Carlo–based stochastic simulation explicitly captures yield variability, downside risk, and the probability of exceeding policy-relevant yield thresholds under real-world conditions. Consequently, this approach is particularly well-suited for evaluating maize yield outcomes across diverse farming typologies characterized by climatic, management, and resource uncertainty.

Deterministic Yield Computation

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

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

This step provided the base mean yield values per hectare across Agro-ecological zones (AEZs) and farming practices, setting the foundation for subsequent stochastic simulations.

Stochastic Yield Simulation using Independent Standard Normal Deviates (ISNDs)

Since we have several independent random yield observations from each agro-ecological zone, a Univariate Empirical (UVE) distribution, following the Simetar risk simulation framework, was parameterized. The UVE was simulated to

Table 1: Number of observations for six maize farming practices per agroecological zone

Farming practices	NHZ	ECZ	CZ	SHZ	LZ	WZ	All Zones
Farming_0	539	2,085	949	908	1,134	1,777	7,392
Farming_1	62	63	140	179	231	233	908
Farming_2	64	141	10	1,429	46	455	2,145
Farming_3	744	353	350	171	712	366	2,696
Farming_4	256	79	189	47	229	117	917
Farming_5	324	95	81	791	137	441	1,869
Total	1,989	2,816	1,719	3,525	2,489	3,092	15,927

Note: Farming_0 = farms using local seeds with no fertilizer; Farming_1 = farms using local seeds with organic fertilizer; Farming_2 = farms using local seeds with inorganic fertilizer; Farming_3 = farms using improved seeds with no fertilizer; Farming_4 = farms using improved seeds with organic fertilizer; Farming_6 = farms using improved seeds with inorganic fertilizer.

develop an independent, uncorrelated sample size of 500 for each farming practice per AEZ. The deterministic yield computed in Equation 1 was converted into stochastic form (Equation 2), where a random shock factor (ε) was introduced to capture unexplained variability in yield. Equation 3 expresses how the stochastic yields were simulated. The equation uses the Empirical Probability Distribution (EMP) function in Simetar to simulate yields, resulting in a percentage deviation from the mean.

$$\tilde{y}_{i,\omega} = \bar{y}_{c,i,\omega} * \varepsilon \quad (2)$$

Where the ε is a random shock factor expressed as $\bar{y}_{i,\omega}$-$\bar{y}_{c,i,\omega}$

$$\tilde{y}_{i,\omega} = \bar{y}_{c,i,\omega} * \left(1 + EMP\left(S_{y,i,\omega}, P\left(S_{y,i,\omega}\right), ISND_{y,i,\omega}\right)\right) * \beta_{\tilde{y}_0} \quad (3)$$

Where:

~ = A tilde represents a randomness (stochastic) variable.

i = Types of seeds used ((Farming_0, Farming_1, Farming_2, Farming_3, Farming_4, and Farming_5).

ω = Represents farms in eight agroecological zones

ai = Hectares (ha) allocated for farming practice i

$\bar{y}$ = Stochastic mean yield per ha for farming practice i

$\bar{Y}_i$ = Deterministic (mean) yield per ha for farming practice i

$\beta_{\tilde{y}0}$ = The normalization factor, which is given by $\bar{y}_{c,i}/\bar{y}_{h,i}$ and it is used to scale/adjust the 2019/20 NCSA mean yield.

$\bar{y}_c$ = Stochastic yield for the current survey (2019/20 NCSA)

$\bar{y}_h$ = Stochastic yield for the historical or previous survey (2007/08 NCSA)

Sy = Fraction deviations from the mean or sorted array of random yields for farming practice i

P(Sy) = Cumulative probability function for the Sy values

ISNDy = 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 provide a source of randomness that generates 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 ε ~ 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, Equation 3 was simulated with the Latin Hypercube Sampling (LHS) technique, following the procedures outlined by Richardson *et al*. (2007) and Kadigi *et al*. (2020b, 2025). This study uses the LHS approach because it is efficient at generating representative samples from complex probability distributions with relatively fewer 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 density 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 yield performance across Tanzania's agro-ecological 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 multi-variable contexts because it enables simultaneous modeling of several variables while preserving realistic outcomes, such as avoiding implausible negative yields. 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 yield 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 Equation 4. The MVE framework is particularly well-suited for multi-variable contexts because it maintains realistic inter-variable 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 prior to the simulation. This standardization enables the EMP to capture the variability and probabilistic distribution of yield outcomes more accurately, ensuring theoretical consistency with the methodology adopted by Richardson et al. (2000; 2003; 2007).

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

Where:
sim = Yield from the simulated dataset.
CUSDy = 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. Additionally, it is acknowledged that some maize-producing households apply both organic and inorganic fertilizers within the same season, particularly in crop–livestock systems. However, due to data constraints and the need to define mutually exclusive farming system categories for stochastic simulation, fertilizer use in this study was classified as none, organic-only, or inorganic-only. The combined use of organic and inorganic fertilizers was therefore not modeled explicitly and represents an important area for future research.

Ranking of Target Probabilities Using the Stoplight Function

This study employed the Stoplight Chart approach to rank the probabilities of achieving specific yield targets and to evaluate the performance of different maize farming systems. This method involves setting two key thresholds, a lower target and an upper target, which are used to classify the outcomes into three distinct categories: The stoplight function calculates the probabilities of (a) exceeding the upper target (green), (b) being less than the lower target (red), and (c) observing values between the targets (yellow). Since our target is to identify farms in Tanzania that have reached a potential yield of 3.5 t ha^{-1}, we set our upper target at 3.5 t ha^{-1} and a minimum of 1.5 t ha^{-1} (slightly higher than the average of 1.2 t ha^{-1}).

Results

Model Validation

To validate the Monte Carlo simulation model, a comparison between observed and simulated data was conducted using probability density functions (PDFs). Figure 2 illustrates this comparison for farms using local seeds with no fertilizer (Farming_0) across four agro-ecological zones: the Northern Highlands (NHZ), Southern Highlands (SHZ), Central Zone (CZ), and Western Zone (WZ). The PDFs for both observed and simulated data exhibit strong alignment, with overlapping distributions that capture the key features of yield variability. This strong visual correlation confirms the model's ability to effectively replicate the observed yield data's underlying statistical properties.

The consistency between the observed and simulated PDFs demonstrates that the simulation model accurately captures the stochastic nature of maize yield distributions across varying agro-ecological conditions. Across all four zones, the peak and spread of the simulated distributions closely match those of the observed data, indicating that the model captures key factors influencing yield variability, including environmental conditions and farming practices. This validation ensures the robustness and reliability of the model, reinforcing its suitability for assessing the performance of different farming systems and informing policy decisions to optimize maize yield across Tanzania's diverse agro-ecological zones.

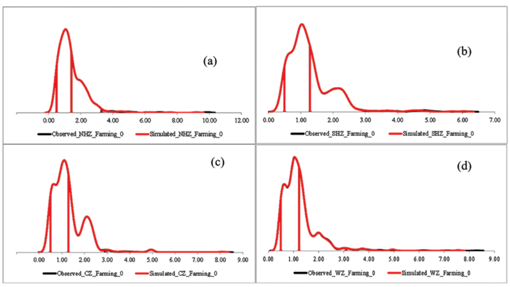

Figure 2: Comparison of observed and simulated distributions for yield of farms using local seeds with no fertilizer (Farming_0) for selected agroecological zones: (a) Northern Highlands (NHZ), (b) Southern Highlands Zone (SHZ), (c) Central Zone (CZ), and (d) Western Zone (WZ).

Overall Yield Status of Maize Farms in Tanzania

The results in Figure 3 provide critical insights into the overall yield of maize farms in Tanzania across different combinations of seed type (local vs. improved) and fertilizer application (organic, inorganic, or none). The findings reveal significant variations in yield based on the farming practices employed. Most farms using local seeds without fertilizers (Farming_0) consistently fall into the low yield category, with a 70% probability of yields below 1.5 t ha^{-1}. Adding organic fertilizers (Farming_1) or inorganic fertilizers (Farming_2) to farms with local seeds marginally reduces this probability to 68% and 61%, respectively, highlighting the limited effectiveness of fertilizers when used with local seeds. Even without fertilizers (Farming_3), improved seeds show a noticeable reduction in the probability of low yield to 60%. This highlights the inherent yield advantage of improved seeds over local seeds, even in suboptimal conditions.

At moderate yield levels (1.5–3.5 t ha^{-1}), a clear improvement is observed with fertilizer use. Farms using improved seeds with organic fertilizers (Farming_4) and a combination of fertilizers (Farming_5) show significantly higher probabilities of moderate yields at 35% and 42%, respectively. Compared with local seed setups, even with fertilizers (Farming_1 and Farming_2), local seed setups perform worse, yielding only 28% and 33%, respectively. High-yield levels exceeding 3.5 t ha^{-1} (green zone) are rare across all setups but become more achievable with improved seed and fertilizer use.

Farming setups that combine improved seeds and fertilizers, particularly Farming_5 (improved seeds + fertilizers), demonstrate the highest probability (15%) of achieving yields above the potential threshold of 3.5 t ha^{-1}. This is followed by Farming_4 (improved seeds + organic fertilizers) at 9%. These setups also show a lower probability of yields falling below 1.5 t ha^{-1} compared to farming practices relying on local seeds by 44% for Farming_5 and 56% for Farming_4. Farming systems without fertilizers, such as Farming_0 and Farming_3, exhibit negligible probabilities of high yield at just 2% and 5%, respectively.

These results show clear differences in maize yield outcomes across farming setups defined by seed type and fertilizer use. Farms using local seeds without fertilizer (Farming_0) exhibit the highest probability of low yield, with yields predominantly below 1.5 t ha^{-1}. The inclusion of organic or inorganic fertilizers with local seeds (Farming_1 and Farming_2) reduces the probability of very low yields but does not substantially increase the likelihood of achieving yields above 3.5 t ha^{-1}. On the other hand, improved seed systems display more favorable yield distributions. Farms using improved seeds without fertilizer (Farming_3) show a lower probability of yields below 1.5 t ha^{-1} compared with local seed systems, although the probability of exceeding 3.5 t ha^{-1} remains limited. The highest probabilities of achieving yields above the 3.5 t ha^{-1} threshold are observed in Farming_5 (improved seeds with inorganic fertilizers), followed by Farming_4 (improved seeds with organic fertilizers). These farming setups also exhibit comparatively lower probabilities of yields falling below the minimum threshold. The probability distributions indicate that yield outcomes improve progressively as one moves from local to improved seed systems and from no fertilizer to fertilizer application, with the most favorable yield distributions observed under improved seed–fertilizer combinations.

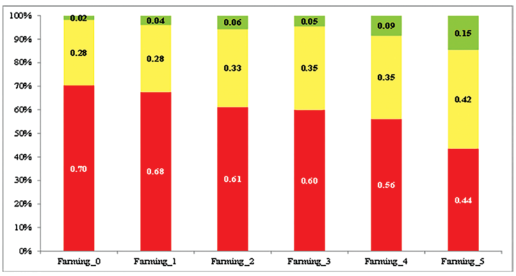

Figure 3: Probabilities of maize farm's yield being greater than the potential yield of 3.5 t ha^{-1} (Green), less than the lower cut-off value of 1.5 t ha^{-1} (Red), and the probabilities of falling between the two thresholds for farmers using different farming setups across all agroecological zones.

*(**Note:** Farming_0 = Farms used local seeds + No fertilizers, Farming_1 = Farms used local seeds + Organic Fertilizers, Farming_2 = Farms used local seeds + Inorganic Fertilizers, Farming_3 = Farms used improved seeds + No fertilizers, Farming_4 = Farms used improved seeds + Organic Fertilizers, Farming_5 = Farms used improved seeds + Inorganic Fertilizers).*

Yield of Maize Farms per Agro-ecological Zones

The Northern Highlands of Tanzania

Figure 4 presents the probabilities of maize farm yield levels, specifically in the Northern Highlands of Tanzania. The results show that organic fertilizers (Farming_1 and Farming_4) with either local or improved seeds play a significant role in helping farms surpass the potential yield of 3.5 t ha^{-1}. Specifically, farms using local seeds with organic fertilizers (Farming_1) achieve a probability of 16%, exceeding the maximum threshold, while farms combining improved seeds with organic fertilizers (Farming_4) record a nearly similar high probability of 14%. The likelihood of yields falling below the minimum of 1.5 t ha^{-1} for farms using organic fertilizers within the region is also slightly lower, at 54% and 45% for Farming_1 and Farming_4, respectively. This strong performance of organic fertilizers can be attributed to the Northern Highlands' high livestock population, which provides ample access to manure and other organic inputs. Such resources allow farmers to leverage economies of scale by using locally available organic fertilizers more effectively (Rufino *et al*., 2007).

The results for Farming_5 (improved seeds + fertilizers) indicate a 11% probability of achieving yields above 3.5 t ha^{-1}. While this is notable, it is slightly lower than Farming_1 and Farming_4, suggesting that organic inputs may provide unique advantages in this zone, potentially due to soil structure or complementary nutrients from manure-based fertilizers. In the low-yield (<1.5 t ha^{-1}, red zone), farms with no fertilizer inputs, whether using local seeds (Farming_0) or improved seeds (Farming_3), have the highest probabilities of low yield at 69% and 55%, respectively. This reinforces the importance of fertilizer application in mitigating the risk of low yield. Farming setups using improved seeds with fertilizers perform better for moderate yield (1.5–3.5 t ha^{-1}) in the yellow zone. For example, Farming_5 (improved seeds + inorganic fertilizers) has a 43% probability of moderate yields, while Farming_4 (improved seeds + organic fertilizers) has a 41% probability. These results suggest that combining improved seeds with fertilizers can consistently elevate farm yield to a moderate level in the NHZ.

These results highlight that the probability distributions for the Northern Highlands indicate that farming systems using organic fertilizers have relatively higher probabilities of achieving yields above the 3.5 t ha^{-1} threshold than systems that apply no fertilizer. In particular, farms using local seeds with organic fertilizers (Farming_1) and those using improved seeds with organic fertilizers (Farming_4) show higher probabilities of exceeding the threshold than their corresponding non-fertilized systems. Improved seed systems without fertilizer (Farming_3) demonstrate lower probabilities of high yields and higher probabilities of yields below 1.5 t ha^{-1} relative to fertilized improved seed systems. Among all farming setups, Farming_5 (improved seeds with inorganic fertilizers) exhibits one of the highest probabilities of achieving yields above 3.5 t ha^{-1}

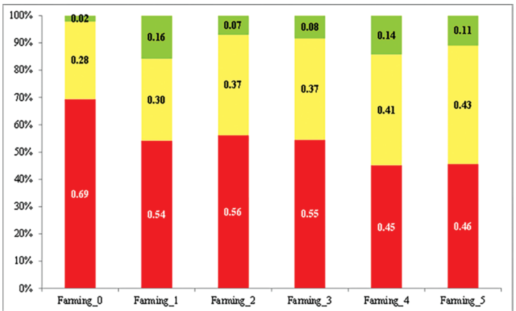

Figure 4: Probabilities of maize farm's yield being greater than the potential yield of 3.5 t ha^{-1} (Green), less than the lower cut-off value of 1.5 t ha^{-1} (Red), and the probabilities of falling between the two thresholds in the Northern Highlands of Tanzania.

*(**Note:** Farming_0 = Farms used local seeds + No fertilizers, Farming_1 = Farms used local seeds + Organic Fertilizers, Farming_2 = Farms used local seeds + Inorganic Fertilizers, Farming_3 = Farms used improved seeds + No fertilizers, Farming_4 = Farms used improved seeds + Organic Fertilizers, Farming_5 = Farms used improved seeds + Inorganic Fertilizers).*

and a comparatively lower probability of low-yield outcomes. The results, therefore, show that yield outcomes in the Northern Highlands vary systematically by fertilizer type and seed category, with fertilized systems, both organic and inorganic, displaying more favorable yield distributions than non-fertilized systems.

The Southern Highlands of Tanzania

In the Southern Highlands Zone (Fig. 5), Farming_5 (improved seeds + inorganic fertilizers) is the most promising setup for achieving high yields, followed closely by Farming_4 (improved seeds + organic fertilizers). These setups demonstrate probabilities of 21% and 20% of exceeding the 3.5 t ha^{-1} potential yield, respectively. At the same time, these setups have the lowest probabilities of yields below 1.55 t ha^{-1}, at 38% (Farming_5) and 40% (Farming_4). These findings highlight the importance of combining improved seeds with inorganic or organic fertilizers to achieve sustainable high yields in the Southern Highlands. This pairing of improved seeds with fertilizers reduces the risk of low yield and enhances yield potential.

In contrast, Farming_0 (local seeds + no fertilizers) exhibits the poorest performance, with only 2% of farms exceeding 3.5 t ha-1 and a very high probability of 76% that yields fall below 1.5 t ha^{-1}. Similarly, Farming_1 (local seeds + organic fertilizers) and Farming_2 (local seeds + inorganic fertilizers) show limited potential, achieving only a 6% probability of yields above 3.5 t ha^{-1} while maintaining relatively high probabilities of low yield at 70% and 60%, respectively. Results in this zone confirm that farms using local seeds without fertilizer (Farming_0) exhibit the lowest yield, with only 2% of farms achieving yields above 3.5 t ha^{-1} and a high probability (76%) that yields fall below 1.5 t ha^{-1}. Similarly, farms using local seeds with organic fertilizers (Farming_1) and inorganic fertilizers (Farming_2) show limited probabilities of exceeding the 3.5 t ha^{-1} threshold (6%), while maintaining relatively high probabilities of low yields at 70% and 60%, respectively.

Likewise, farms using improved seeds without fertilizer (Farming_3) show a marginal improvement relative to local seed systems, with 2% of farms exceeding 3.5 t ha⁻¹ and a 67% probability of yields below 1.5 t ha⁻¹. In contrast, improved seed systems combined with fertilizers display more favorable yield distributions. Farming_4 (improved seeds with organic fertilizers) and Farming_5 (improved seeds with inorganic fertilizers) record the highest probabilities of achieving yields above 3.5 t ha⁻¹ in the Southern Highlands, alongside lower probabilities of low-yield outcomes compared with other farming setups. The probability distributions indicate that fertilized improved seed systems outperform non-fertilized and local seed systems in the Southern Highlands, both in terms of reducing the likelihood of low yields and increasing the probability of higher yield outcomes.

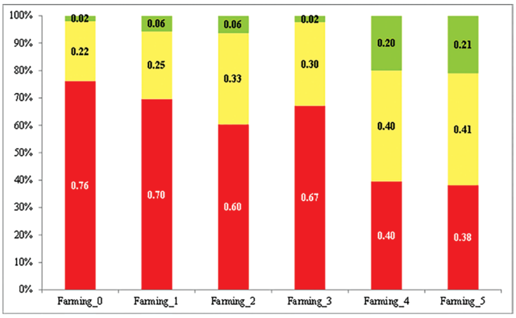

Figure 5: Probabilities of maize farm's yield being greater than the potential yield of 3.5 t ha⁻¹ (Green), less than the lower cut-off value of 1.5 t ha⁻¹ (Red), and the probabilities of falling between the two thresholds in the Southern Highlands of Tanzania.

(***Note:*** *Farming_0 = Farms used local seeds + No fertilizers, Farming_1 = Farms used local seeds + Organic Fertilizers, Farming_2 = Farms used local seeds + Inorganic Fertilizers, Farming_3 = Farms used improved seeds + No fertilizers, Farming_4 = Farms used improved seeds + Organic Fertilizers, Farming_5 = Farms used improved seeds + Inorganic Fertilizers).*

The Eastern – Coastal Zones of Tanzania

The Eastern–Coastal Zone records relatively low yield outcomes across all farming setups (Figure 6). Farms using improved seeds with inorganic fertilizers (Farming_5) show a 4% probability of achieving yields above 3.5 t ha⁻¹, while the remaining farming systems exhibit probabilities of 1–2%. Across all setups, the probability of achieving moderate yields (1.5–3.5 t ha⁻¹) ranges from 26% to 43%, with Farming_4 (improved seeds with organic fertilizers) recording the lowest probability at 18%. In contrast, the probability of yields falling below the minimum threshold of 1.5 t ha⁻¹ remains high across all farming systems. Farming_4 exhibits the highest probability of low yields at 79%, while the remaining farming setups range between 64% and 73%. Overall, the probability distributions indicate limited differentiation in high-yield outcomes among farming systems in the Eastern–Coastal Zone, with all setups characterized by a high likelihood of low yield and a low likelihood of exceeding the 3.5 t ha⁻¹ threshold.

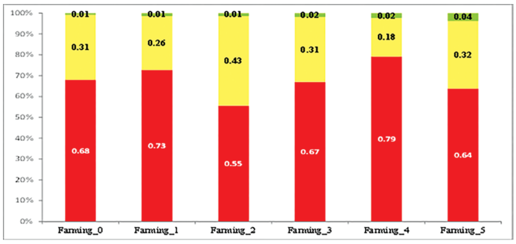

Figure 6: Probabilities of maize farm's yield being greater than the potential yield of 3.5 t ha⁻¹ (Green), less than the lower cut-off value of 1.5 t ha⁻¹ (Red), and the probabilities of falling between the two thresholds in the Eastern Coastal Zones of Tanzania.

(***Note:*** *Farming_0 = Farms used local seeds + No fertilizers, Farming_1 = Farms used local seeds + Organic Fertilizers, Farming_2 = Farms used local seeds + Inorganic Fertilizers, Farming_3 = Farms used improved seeds + No fertilizers, Farming_4 = Farms used improved seeds + Organic Fertilizers, Farming_5 = Farms used improved seeds + Inorganic Fertilizers).*

The Central Part of Tanzania

Figure 7 presents the probability distributions of maize yield across different farming setups in the Central Zone. Among all farming systems, Farming_2 (local seeds with inorganic fertilizers) records the highest probability of achieving yields above 3.5 t ha⁻¹ (16%) and a relatively lower probability of yields below 1.5 t ha^{-1} (38%). Farming_5 (improved seeds with inorganic fertilizers) follows, with an 11% probability of exceeding the 3.5 t ha^{-1} threshold and a 40% probability of yields falling below 1.5 t ha^{-1}. These two farming systems also exhibit the highest probabilities of yields within the moderate range (1.5–3.5 t ha^{-1}), at 47% and 48%, respectively. The remaining farming setups show a low probability of achieving yields above 3.5 t ha^{-1} (less than 10%). Farming_0 (local seeds with no fertilizer) displays the highest probability of low yield, followed by Farming_1 (local seeds with organic fertilizers) and Farming_3 (improved seeds with no fertilizer). Farming_4 (improved seeds with organic fertilizers) shows a modest improvement relative to non-fertilized systems, with a 6% probability of exceeding 3.5 t ha^{-1} and a 61% probability of yields below 1.5 t ha^{-1}. Overall, the probability distributions indicate that farming systems combining fertilizer application with either local or improved seeds exhibit more favorable yield outcomes in the Central Zone than non-fertilized systems.

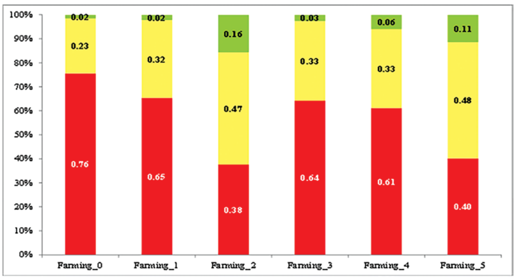

Figure 7: Probabilities of maize farm's yield being greater than the potential yield of 3.5 t ha^{-1} (Green), less than the lower cut-off value of 1.5 t ha^{-1} (Red), and the probabilities of falling between the two thresholds in the Central Zones of Tanzania.

*(**Note:** Farming_0 = Farms used local seeds + No fertilizers, Farming_1 = Farms used local seeds + Organic Fertilizers, Farming_2 = Farms used local seeds + Inorganic Fertilizers, Farming_3 = Farms used improved seeds + No fertilizers, Farming_4 = Farms used improved seeds + Organic Fertilizers, Farming_5 = Farms used improved seeds + Inorganic Fertilizers).*

The Western Zone of Tanzania

Maize yield outcomes in the Western Zone under different farming setups are presented in Figure 8. Farming_5 (improved seeds with inorganic fertilizers) exhibits the highest probability of achieving yields above 3.5 t ha^{-1} (12%) and the lowest probability of yields falling below 1.5 t ha^{-1} (46%), alongside a relatively high probability (43%) of yields in the moderate range (1.5–3.5 t ha^{-1}). Farming_2, Farming_3, and Farming_4 record probabilities of 5–7% for yields exceeding 3.5 t ha^{-1}, while maintaining high probabilities of low-yield outcomes ranging from 64% to 68%. Farming systems relying on local seeds without fertilizer (Farming_0) show the highest probability of low yield, with 82% of yields below 1.5 t ha^{-1} and only a 2% probability of yields above 3.5 t ha^{-1}. Similarly, Farming_1 (local seeds with organic fertilizers) records a 79% probability of yields below 1.5 t ha^{-1} and a 2% probability of achieving yields above 3.5 t ha^{-1}. The results indicate that Farming_5 yields the most favorable outcomes in the Western Zone, with a higher likelihood of exceeding the 3.5 t ha^{-1} threshold and a lower likelihood of low-yield outcomes.

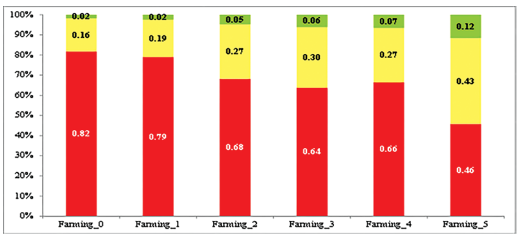

Figure 8: Probabilities of maize farm's yield being greater than the potential yield of 3.5 t ha^{-1} (Green), less than the lower cut-off value of 1.5 t ha^{-1} (Red), and the probabilities of falling between the two thresholds in Western Zones of Tanzania.

*(**Note:** Farming_0 = Farms used local seeds + No fertilizers, Farming_1 = Farms used local seeds + Organic Fertilizers, Farming_2 = Farms used local seeds + Inorganic Fertilizers, Farming_3 = Farms used improved seeds + No fertilizers, Farming_4 = Farms used improved seeds + Organic Fertilizers, Farming_5 = Farms used improved seeds + inorganic Fertilizers).*

The Lake Zone of Tanzania

Maize yield outcomes in the Lake Zone across different farming setups are presented in Figure 9. Farming_2 (local seeds with inorganic fertilizers) and Farming_5 (improved seeds with inorganic fertilizers) record the highest probabilities of achieving yields above 3.5 t ha^{-1}, at 5% and 7%, respectively. These farming systems also exhibit the lowest probabilities of yields falling below 1.5 t ha^{-1}, at 41% for Farming_2 and 48% for Farming_5. In addition, they show relatively high probabilities of yields within the moderate range (1.5–3.5 t ha^{-1}), at 54% and 45%, respectively.

Farming_4 (improved seeds with organic fertilizers) shows a 6% probability of achieving yields above 3.5 t ha^{-1}, with a higher probability (54%) of yields below 1.5 t ha^{-1} compared with Farming_2 and Farming_5. The remaining farming systems, Farming_0 (local seeds with no fertilizer), Farming_1 (local seeds with organic fertilizers), and Farming_3 (improved seeds with no fertilizer), exhibit negligible probabilities (3%) of exceeding the 3.5 t ha^{-1} threshold and relatively higher probabilities of low-yield outcomes, ranging from 49% to 56%. These probability distributions indicate that fertilized farming systems, particularly those using inorganic fertilizers, exhibit more favorable yield outcomes in the Lake Zone compared with non-fertilized systems.

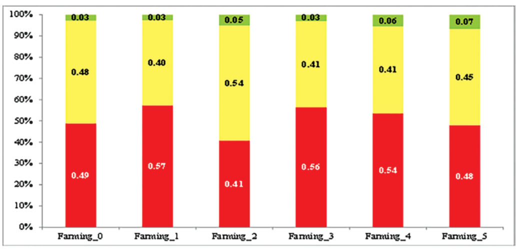

Figure 9: Probabilities of maize farm's yield being greater than the potential yield of 3.5 t ha^{-1} (Green), less than the lower cut-off value of 1.5 t ha^{-1} (Red), and the probabilities of falling between the two thresholds in the Lake Zone of Tanzania.

*(**Note:** Farming_0 = Farms used local seeds + No fertilizers, Farming_1 = Farms used local seeds + Organic Fertilizers, Farming_2 = Farms used local seeds + Inorganic Fertilizers, Farming_3 = Farms used improved seeds + No fertilizers, Farming_4 = Farms used improved seeds + Organic Fertilizers, Farming_5 = Farms used improved seeds + Fertilizers).*

Cross-zone Comparison Summary

A comparison across agro-ecological zones reveals substantial heterogeneity in maize yield responses to farming systems. The Southern Highlands consistently exhibit the highest probabilities of achieving yields above 3.5 t ha^{-1}, particularly under improved seed–fertilizer combinations (Farming_4 and Farming_5). The Northern Highlands and Lake Zone also show relatively higher responsiveness to fertilized systems, including organic fertilizer-based setups, with moderate probabilities of achieving yields above the threshold and reduced risks of low yield. In contrast, the Eastern–Coastal Zone displays uniformly low probabilities of exceeding 3.5 t ha^{-1} across all farming systems, alongside consistently high probabilities of low-yield outcomes. The Central and Western Zones show intermediate performance, where fertilized systems, especially Farming_5, demonstrate improved yield distributions relative to non-fertilized systems, though with lower probabilities of high yields compared with the Southern Highlands. The results indicate that yield responses to improved seeds and fertilizer use vary markedly across zones, with highland and lake-adjacent zones showing stronger yield responses than coastal and semi-arid regions.

Discussion

This study assessed the probability that maize farms in Tanzania Mainland can reach or exceed a yield threshold of 3.5 t ha^{-1} under alternative seed and fertilizer management regimes using a nonparametric Monte Carlo simulation applied to nationally representative NSCA 2019/20 data. The results reveal substantial heterogeneity in yield outcomes across agro-ecological zones and farming systems, underscoring the importance of both input combinations and local agro-ecological conditions. Across all zones, farming systems combining improved seeds with inorganic fertilizers consistently had the highest probability of exceeding the 3.5 t ha^{-1} benchmark and the lowest risk of yields falling below 1.5 t ha^{-1}. This pattern was particularly pronounced in the Southern Highlands, Northern Highlands, and Lake Zone, where yield distributions were more responsive to intensified input use. These findings align with empirical evidence indicating that yield gains from modern inputs are strongest in ecologically favorable and input-responsive environments (Ariga & Jayne, 2011; Vanlauwe *et al*., 2014; Sheahan & Barrett, 2017; Gadanakis, 2015; Bayne & Renwick, 2021).

Conversely, farming systems relying on local or recycled seeds without fertilizer inputs exhibited persistently low probabilities of achieving high yields across all zones. Even when fertilizers were applied, local seed systems showed limited capacity to surpass the yield threshold, reinforcing existing evidence that seed quality and nutrient management must be jointly considered to close maize yield gaps (Morris, 2007; Sommer *et al*., 2013; Obayelu *et al*., 2021; Kato & Greeley, 2016). The observed regional differences in yield outcomes reflect Tanzania Mainland's agro-ecological diversity. Zones such as the Eastern–Coastal and parts of the Central Zone exhibited weak yield responses across farming systems, even under improved input use. These patterns are consistent with documented constraints related to soil fertility, rainfall variability, and market access (Bekunda *et al*., 2002; Tittonell *et al*., 2013; Kimaro *et al*., 2016; Bongole *et al*., 2020). The results suggest that input intensification alone may be insufficient in such environments without complementary soil and water management interventions (Dahlin & Rusinamhodzi, 2019).

Additionally, the limited yield responsiveness observed in the Eastern–Coastal Zone suggests that, beyond input intensification, broader production strategies, including crop diversification aligned with agroecological comparative advantage, may warrant consideration. In livestock-rich zones, particularly the Northern Highlands and Lake Zone, farming systems using organic fertilizers exhibited relatively better performance compared to other regions. While organic inputs did not consistently outperform inorganic fertilizer systems, they contributed to moderate yield probabilities under certain conditions. This supports evidence that integrated crop–livestock systems can enhance nutrient recycling and support sustainable intensification, especially where access to inorganic fertilizers is constrained (Giller *et al*., 2011; Rufino *et al*., 2007; Mugwe & Otieno, 2020).

The study demonstrates the value of nonparametric stochastic simulation for agricultural policy analysis in data-constrained settings. Unlike biophysical crop models that require detailed climatic and edaphic parameters, the Monte Carlo Simulation framework captures observed yield variability and risk using historical data, making it well-suited to probabilistically evaluate yield outcomes under business-as-usual conditions (Richardson *et al*., 2007; Kadigi *et al*., 2020a, 2020b, 2025). The probabilistic approach allows assessment of both upside potential and downside risk, which is critical for smallholder-dominated systems facing climatic and market uncertainty (Sileshi *et al*., 2010; Snapp *et al*., 2018; Amondo *et al*., 2019). The findings of the study confirm that closing Tanzania's maize yield gap requires integrated seed and nutrient management strategies tailored to agro-ecological conditions. While improved seeds are necessary, they are insufficient on their own to achieve high yield. Complementary fertilizer use, particularly inorganic fertilizers in high-potential zones and organic inputs in livestock-rich systems, plays a central role in shifting yield distributions toward higher and more stable outcomes.

The probabilistic yield patterns observed in this study highlight the importance of assessing maize performance under uncertainty rather than relying solely on average outcomes. The results show that farming systems integrating improved seeds and fertilizer inputs consistently outperform other systems in terms of both higher yield potential and reduced downside risk. This pattern aligns with empirical evidence from similar smallholder contexts in Sub-Saharan Africa, where yield-enhancing technologies are most effective when evaluated in terms of risk reduction and resilience rather than mean yield gains alone (De Groote *et al*., 2002; Sanginga & Woomer, 2009; Rusinamhodzi *et al*., 2011; Vanlauwe *et al*., 2006; 2015; Worku *et al*., 2020). In like any other sub-Saharan country, Tanzania's smallholder systems, where climatic variability and resource constraints are pervasive, the observed distributional outcomes underscore the relevance of strategies that simultaneously raise expected yields and lower the probability of crop failure (Wortmann *et al*., 2020).

Conclusions and Recommendations

This study evaluated maize yield outcomes across Tanzania Mainland's agroecological zones by examining the likelihood that farms would achieve yields above a policy-relevant threshold of 3.5 t ha^{-1} under alternative seed and fertilizer combinations. Using a nonparametric Monte Carlo simulation framework applied to nationally representative NSCA 2019/20 data, the analysis quantified both yield potential and downside risk under different combinations of seed type and fertilizer use. By explicitly accounting for stochastic yield variability, the study provides an empirical basis for assessing maize yield outcomes under real-world smallholder farming conditions. The findings demonstrate substantial heterogeneity in yield performance and risk profiles across farming systems and regions. In particular, farming systems that combine improved seed varieties with inorganic fertilizers consistently exhibit a higher likelihood of achieving high yields and a lower probability of low-yield outcomes, highlighting their importance for strengthening maize production systems under variable climatic conditions. The results further show that yield responses are strongly conditioned by agroecological context, underscoring the need for region-specific strategies that align input use with local soil, climate, and farming system characteristics. By revealing differences in both upside yield potential and downside production risk, the study provides a robust empirical basis for designing targeted interventions that enhance maize system resilience, support smallholder livelihoods, and contribute to sustainable agricultural transformation in Tanzania.

The findings further demonstrate that the effectiveness of seed and fertilizer combinations is strongly mediated by agroecological context. Across zones with favorable rainfall regimes, soil fertility, and farming system characteristics, particularly the Southern Highlands and parts of the Northern Highlands, the combination of improved seeds and inorganic fertilizers (Farming_5) exhibits the highest probability of achieving yields above the 3.5 t ha^{-1} threshold and the lowest risk of low-yield outcomes. For example, in the Southern Highlands, this farming system attains a 21% probability of exceeding 3.5 t ha^{-1}, reflecting the zone's comparatively high yield potential. In contrast, in agroecological zones characterized by greater climatic variability and soil constraints, such as the Eastern–Coastal and Central zones, the same input combinations yield more modest improvements, underscoring the role of environmental conditions in shaping yield responses. These results indicate that while improved seeds and fertilizers are central to yield enhancement, their performance is inherently zone-specific, reinforcing the need for agroecologically tailored strategies rather than uniform input recommendations.

Additionally, the study indicates that organic fertilizer–based systems can contribute to improved maize yields in specific agroecological contexts, particularly in zones such as the Northern Highlands and Lake Zone. However, across all zones, systems combining improved seeds with inorganic fertilizers consistently exhibit the highest likelihood of achieving high yields and the lowest probability of poor outcomes. At the same time, substantial differences in yield performance persist across agroecological zones, reflecting underlying environmental and resource constraints that limit uniform yield responses. These findings underscore that maize yield enhancement in Tanzania is not driven solely by input use but is inherently shaped by the agroecological context, reinforcing the importance of location-specific strategies to close yield gaps.

Marked differences in yield probabilities across agro-ecological zones further highlight the importance of spatial context in maize yield outcomes. While some zones exhibited strong responsiveness to improved input combinations, others showed uniformly low probabilities of achieving high yields under all farming systems. These findings confirm that national yield targets cannot be met through uniform interventions alone and must account for agro-ecological heterogeneity.

Policy-relevant recommendations

Based on these findings, and directed explicitly to central government agricultural ministries, local government authorities (LGAs), public extension systems, and development partners, the study recommends the following:

- Strengthen access to improved seeds and fertilizers, particularly in zones where the analysis shows a high probability of yield gains under combined input use. This recommendation is grounded in Farming_5's consistently superior performance across agro-ecological zones.
- Enhance farmer capacity through extension and training, with emphasis on appropriate input combinations and management practices. This is supported by the finding that improved seeds alone do not reliably translate into high yield without complementary nutrient application.
- Implement location-specific interventions, whereby national strategies are adapted and operationalized by LGAs to reflect local soil, climatic, and farming system conditions, as evidenced by the strong variation in yield responses across zones.

Future research should build on the probabilistic framework developed in this study by examining the long-term effects of alternative seed–fertilizer combinations on soil health, yield stability, and smallholder resilience to climatic and market shocks. Extending the analysis beyond short-term yield probabilities to dynamic outcomes would strengthen the evidence base for sustainable agricultural intensification and inform strategies aimed at fostering more resilient maize production systems in Tanzania and similar agro-ecological contexts.

A notable limitation of this study concerns the classification of fertilizer use. While many smallholder households, particularly those operating integrated crop–livestock systems, apply both organic and inorganic fertilizers within the same production season, the 2019/20 National Sample Census of Agriculture (NSCA) does not consistently capture such combined practices. To meet the requirement of mutually exclusive farming system categories necessary for robust probabilistic simulation, fertilizer use was therefore grouped into three distinct classes: no fertilizer, organic fertilizer only, and inorganic fertilizer only. Consequently, mixed organic–inorganic fertilizer regimes could not be explicitly modeled. Future studies should address this limitation by utilizing datasets with more detailed input-use information, enabling the simultaneous modeling of combined fertilizer applications and a more comprehensive evaluation of integrated soil fertility management and its productivity effects across Tanzania's diverse agro-ecological zones.

Acknowledgments

The author sincerely appreciates the support and guidance provided by the Simetar team (www.simetar.com) in utilizing the Monte Carlo Simulation model via the Simetar Add-In. Their contributions have greatly enriched the quality and robustness of this manuscript.

Conflict of Interest

The author declares no conflicts of interest.

References

Adzawla, W., Setsoafia, E.D., Setsoafia, E.D., Amoabeng-Nimako, S., Atakora, W. K., Camara, O. ... & Bindraban, P.S. (2024). Fertilizer use efficiency and economic viability in maize production in the Savannah and transitional zones of Ghana. Frontiers in Sustainable Food Systems, 8, 1340927.

Alliance for a Green Revolution in Africa (AGRA), (2020a). Impact of Fertilizer Policy Reforms in Tanzania. Available at https://agra.org/wp-content/uploads/2021/02/Impact-of-Fertilizer-Policy-Reforms-in-Tanzania.pdf

Alliance for a Green Revolution in Africa (AGRA), (2020b). Fertilizer Systems Development Strategy Approach to increasing fertilizer use and adoption. https://agra.org/wp-content/uploads/2020/05/02-AGRA-Fertilizer-Systems-Development-Strategy0406201901.pdf

Ahmed, M.H. (2022). Impact of Improved seed and inorganic fertilizer on maize yield and welfare: Evidence from Eastern Ethiopia. Journal of Agriculture and Food Research, 7, 100266.

Amondo, E., Simtowe, F., Rahut, D.B., & Erenstein, O. (2019). Productivity and production risk effects of adopting drought-tolerant maize varieties in Zambia. *International Journal of Climate Change Strategies and Management*, 11(4), 570-591.

Ariga, J., & Jayne, T.S. (2011). Fertilizer in Kenya: Factors driving the increase in usage by smallholder farmers. Yes Africa can: Success stories from a dynamic continent, 269-288.

Badu-Apraku, B., Fakorede, M.A., Nelimor, C., Osuman, A.S., Bonkoungou, T.O., Muhyideen, O., & Akinwale, R.O. (2023). Recent advances in breeding maize for drought, heat and combined heat and drought stress tolerance in sub-saharan Africa. CABI Reviews, (2023).

Bayne, K., & Renwick, A. (2021). Beyond sustainable intensification: transitioning primary sectors through reconfiguring land-use. Sustainability, 13(6), 3225.

Bekunda, M.A., Nkonya, E., Mugendi, D., & Msaky, J.J. (2002). Soil fertility status, management, and research in East Africa. *East African Journal of Rural Development,* 20(1), 94-112.

Bongole, A.J., Kitundu, K.M.K., & Hella, J. (2020). Usage of climate smart agriculture practices: an analysis of farm households' decisions in southern highlands of Tanzania. *Tanzania Journal of Agricultural Sciences,* 19(2), 238-255.

Dahlin, A.S., & Rusinamhodzi, L. (2019). Yield and labor relations of sustainable intensification options for smallholder farmers in sub-Saharan Africa. A meta-analysis. Agronomy for Sustainable Development, 39(3), 32.

De Groote, H., Doss, C., Lyimo, S.D., Mwangi, W., & Alemu, D. (2002, December). Adoption of maize technologies in East Africa–what happened to Africa's emerging maize revolution. In FASID Forum V, "Green Revolution in Asia and its Transferability to Africa", Tokyo (pp. 8-10).

Gadanakis, Y. (2015). The sustainable intensification of farming systems: evaluating agricultural productivity, technical and economic efficiency (Doctoral dissertation, University of Reading).

Giller, K.E., Corbeels, M., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E., & Tittonell, P. (2011). A research agenda to explore the role of conservation agriculture in African smallholder farming systems. Field crops research, 124(3), 468-472.

Golla, B. (2021). Agricultural production system in arid and semi-arid regions. International *Journal of Agricultural Science and Food Technology*, 7(2), 234-244.

Habtewold, T.M., & Heshmati, A. (2023). Impacts of improved agricultural technology adoption on welfare in Africa: A meta-analysis. Heliyon, 9(7).

Hardaker, J.B., Lien, G., Anderson, J.R., & Huirne, R.B. (2015). Coping with risk in agriculture: Applied decision analysis. Cabi.

Heisse, C., & Morimoto, R. (2024). Climate vulnerability and fertilizer use–panel evidence from Tanzanian maize farmers. Climate and Development, 16(3), 242-254.

Holden, S.T. (2018). Fertilizer and sustainable intensification in Sub-Saharan Africa. Global food security, 18, 20-26.

Kadigi, I.L., Mkuna, E., & Sieber, S. (2025). Exploring the Impact of Improved Maize Seeds on Productivity of Tanzanian Family Farms: A Maize Seed Stochastic Simulation (MaizeSim) Approach. Agronomy, 15(5), 1167.

Kadigi, I.L., Mutabazi, K.D., Philip, D., Richardson, J.W., Bizimana, J.C., Mbungu, W., ... & Sieber, S. (2020a). An economic comparison between alternative rice farming systems in tanzania using a monte carlo simulation approach. Sustainability, 12(16), 6528.

Kadigi, I.L., Richardson, J.W., Mutabazi, K.D., Philip, D., Mourice, S.K., Mbungu, W., ... & Sieber, S. (2020b). The effect of nitrogen-fertilizer and optimal plant population on the profitability of maize plots in the Wami River sub-basin, Tanzania: A bio-economic simulation approach. Agricultural systems, 185, 102948.

Kalonga, J., Mtei, K., Massawe, B., Kimaro, A., & Winowiecki, L.A. (2024). Characterization of soil health and nutrient content status across the North-East Maasai Landscape, Arusha Tanzania. Environmental Challenges, 14, 100847.

Kato, T., & Greeley, M. (2016). Agricultural input subsidies in sub-Saharan Africa. IDS Bulletin, 47(2), 33-48.

Kimaro, A.A., Mpanda, M., Rioux, J., Aynekulu, E., Shaba, S., Thiong'o, M., ... & Rosenstock, T.S. (2016). Is conservation agriculture 'climate-smart'for maize farmers in the highlands of Tanzania?. Nutrient cycling in agroecosystems, 105, 217-228.

Mango, N., Zamasiya, B., Makate, C., Nyikahadzoi, K., & Siziba, S. (2014). Factors influencing household food security among smallholder farmers in the Mudzi district of Zimbabwe. Development Southern Africa, 31(4), 625-640.

Meredia, M., Nyange, D., & Yoyo, L. (2022). Fertilizer Sector Development Strategy for Tanzania (2022–2032). Feed the Future: The U.S. Government's Global Hunger & Food Security Initiative. https://www.aspires.or.tz/wp-content/uploads/2022/11/The-Fertilizer-Sector-Development-Strategy.pdf

Michelson, H., Magomba, C., & Maertens, A. (2024). Restoring Trust: Evidence from the Fertiliser Market in Tanzania. Working Paper. Available at https://www.povertyactionlab.org/sites/default/files/research-paper/Fertilizer_Tanzania.Nov2023.pdf

Minde, I.J., Silim, S.N., Nyange, D.A., Ijumba, C.K., Kadigi, I., & Ires, I. (2024). Tanzania Seed Sector Development Strategy: Inception Report.

Mkonda, M.Y. (2022). Awareness and adaptations to climate change among the rural farmers in different agroecological zones of Tanzania. Management of Environmental Quality: *An International Journal,* 33(6), 1502-1527.

Mkonda, M.Y., & He, X. (2018). Agricultural history nexus food security and policy framework in Tanzania. Agriculture & Food Security, 7, 1-11.

Morris, M.L. (2007). Fertilizer use in African agriculture: Lessons learned and good practice guidelines. World Bank Publications.

Mugwe, J., & Otieno, E.O. (2020). Integrated soil fertility management approaches for climate change adaptation, mitigation, and enhanced crop productivity. Handbook of Climate Change Management: Research, Leadership, Transformation, 1-22.

Mwakatwila, A. (2016). Adoption of improved maize varieties in northern and Eastern zones of Tanzania (Doctoral dissertation, Sokoine University of agriculture).

Obayelu, A.E., Arowolo, A.O., Oyawole, F.P., Aminu, R.O., & Ibrahim, S.B. (2021). The linkage between agricultural input subsidies, productivity, food security, and nutrition. In Food security and nutrition (pp. 107-124). Academic Press.

Prasanna, B.M., Bruce, A., Beyene, Y., Makumbi, D., Gowda, M., Asim, M., ... & Parimi, S. (2022). Host plant resistance for fall armyworm management in maize: relevance, status and prospects in Africa and Asia. Theoretical and Applied Genetics, 135(11), 3897-3916.

Richardson, J.W., Herbst, B.K., Outlaw, J. L., & Gill, R.C. (2007). Including risk in economic feasibility analyses: the case of ethanol production in Texas. *Journal of Agribusiness,* 25(2), 115-132.

Richardson, J.W., Klose, S.L., & Gray, A.W. (2000). An applied procedure for estimating and simulating multivariate empirical (MVE) probability distributions in farm-level risk assessment and policy analysis. *Journal of Agricultural and Applied Economics,* 32(2), 299-315.

Richardson J.W., Feldman P., and Schuemann K. (2003). Simetar™. Department of Agricultural Economics, Texas A&M University. College Station, TX.

Richardson, J.W., Schumann, K., & Feldman, P. (2006). Simetar: Simulation for excel to analyze risk. Department of Agricultural economics, Texas A&M University.

Ricker-Gilbert, J. (2020). Inorganic fertiliser use among smallholder farmers in sub-Saharan Africa: implications for input subsidy policies. The role of smallholder farms in food and nutrition security, 81-98.

Rufino, M.C., Tittonell, P., Van Wijk, M.T., Castellanos-Navarrete, A., Delve, R.J., De Ridder, N., & Giller, K.E. (2007). Manure as a key resource within smallholder farming systems: analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livestock Science, 112(3), 273-287.

Rusinamhodzi, L., Corbeels, M., Van Wijk, M. T., Rufino, M.C., Nyamangara, J., & Giller, K.E. (2011). A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agronomy for sustainable development, 31, 657-673.

Sanginga, N., & Woomer, P.L. (Eds.). (2009). Integrated soil fertility management in Africa: principles, practices, and developmental process. CIAT.

Sheahan, M., & Barrett, C.B. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. Food policy, 67, 12-25.

Sileshi, G., Akinnifesi, F.K., Debusho, L.K., Beedy, T., Ajayi, O.C., & Mong'omba, S. (2010). Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa. Field Crops Research, 116(1-2), 1-13.

Snapp, S.S., Grabowski, P., Chikowo, R., Smith, A., Anders, E., Sirrine, D., ... & Bekunda, M. (2018). Maize yield and profitability tradeoffs with social, human and environmental performance: Is sustainable intensification feasible?. Agricultural Systems, 162, 77-88.

Sommer, R., Bossio, D., Desta, L., Dimes, J., Kihara, J., Koala, S., ... & Winowiecki, L. (2013). Profitable and sustainable nutrient management systems for East and Southern African smallholder farming systems challenges and opportunities: A synthesis of the Eastern and Southern Africa situation in terms of past experiences, present and future opportunities in promoting nutrients use in Africa.

Tittonell, P., & Giller, K.E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. Field Crops Research, 143, 76-90.

Tittonell, P., Muriuki, A., Klapwijk, C.J., Shepherd, K.D., Coe, R., & Vanlauwe, B. (2013). Soil heterogeneity and soil fertility gradients in smallholder farms of the East African highlands. *Soil Science Society of America Journal,* 77(2), 525-538.

Tovihoudji, P.G., Akponikpè, P.I., Agbossou, E.K., Bertin, P., & Bielders, C.L. (2017). Fertilizer microdosing enhances maize yields but may exacerbate nutrient mining in maize cropping systems in northern Benin. Field crops research, 213, 130-142.

URT (United Republic of Tanzania) – (2021). National Sample Census of Agriculture 2019/20. https://www.fao.org/fileadmin/templates/ess/ess_test_folder/World_Census_Agriculture/WCA_2020/WCA_2020_new_doc/TZA_REP2_ENG_2020.pdf

URT (United Republic of Tanzania) (2016). Agricultural Sector Development Programme Phase Two (ASDP-II). Government Programme Document. https://faolex.fao.org/docs/pdf/tan169870.pdf

Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., ... & Van Asten, P. (2014). Sustainable intensification and the African smallholder farmer. Current Opinion in Environmental Sustainability, 8(0), 15-22.

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., ... & Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. Soil, 1(1), 491-508.

Vanlauwe, B., Ramisch, J.J., & Sanginga, N. (2006). Integrated soil fertility management in Africa: From knowledge to implementation. Biological approaches to sustainable soil systems, 113, 257-272.

Worku, M., De Groote, H., Munyua, B., Makumbi, D., Owino, F., Crossa, J., ... & Prasanna, B.M. (2020). On-farm performance and farmers' participatory assessment of new stress-tolerant maize hybrids in Eastern Africa. Field Crops Research, 246, 107693.

Wortmann, C., Amede, T., Bekunda, M., Ndung'u-Magiroi, K., Masikati, P., Snapp, S., ... & Kome, C.E. (2020). Improvement of smallholder farming systems in Africa. *Agronomy Journal,* 112(6), 5325-5333.

Zerssa, G., Feyssa, D., Kim, D.G., & Eichler-Löbermann, B. (2021). Challenges of smallholder farming in Ethiopia and opportunities by adopting climate-smart agriculture. *Agriculture*, 11(3), 192.