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Performance and Profitability of Released Climate-Smart Maize Varieties Under Increased Plant Densities

Wilber Wambi[1,2], Sylvester Dickson Baguma[3], Daniel Bomet Kwemoi[4], Ivan Abaho[1], Irene Bayiyana[4], Fred Ssekiwoko[5], Habtamu Zeleke[2] & Joseph Ekwangu[1]

[1] Bulindi Zonal Agricultural Research and Development Institute, National Agricultural Research Organization, Hoima, Uganda

[2] African Centre of Excellence for Climate-Smart Agriculture and Biodiversity Conservation, Haramaya University, Dire Dawa, Ethiopia

[3] The Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA), Entebbe, Uganda

[4] National Crops Resources Research Institute, National Agricultural Research Organization, Namulonge, Kampala, Uganda

[5] National Coffee Resources Research Institute, National Agricultural Research Organization, Kampala, Uganda

Correspondence: Wilber Wambi, Bulindi Zonal Agricultural Research and Development Institute, National Agricultural Research Organization, Hoima, Uganda. Tel: 256-774-648-306. E-mail: wambiwilber@gmail.com; wilber.wambi@naro.go.ug

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Abstract

The study was conducted to; validate the genotypic performance of the popular climate-smart released maize varieties under increased plant densities in the three sub-ecologies (Mid-altitude, semi-arid, and tropical rain forest zones), which are important maize crop production belts and testing sites for new hybrids, and estimate the profitability of growing the varieties under optimum plant density in the different sub-ecologies. Seven popular varieties; MM3, Longe 6H, Longe 9H, Longe 10H, Bazooka, WE 3106, and FH5160 were tested for two seasons at four different spacing levels: 0.75 × 0.6 M (44,444 plants ha^{-1}), 0.75 × 0.30 M (44,444 plants ha^{-1}), 0.75 × 0.25 M (53,333 plants ha^{-1}), and 0.5 × 0.3 M (66,667 plants ha^{-1}). The varieties varied significantly for grain yield (GY) and ear aspect (EA) traits across the spacings and environments. Using the closest spacing (0.50 × 0.30 M) resulted in higher GY productivity and net profit in the testing sites. At optimal spacing, FH5160 was the most stable genotype for cultivation across the three sub-ecologies. All varieties exhibited superior genotypic performance for GY (7-12 t ha^{-1}) and EA traits in the mid-altitude zone. Bazooka and Longe 10H were the best varieties for the tropical rainforest zone. While MM3, WE3106 and Bazooka were more suitable for semi-arid zone. Growing all the studied maize varieties in the mid-altitude sub-ecological zone is profitable, especially at optimal spacing.

Keywords: varietal performance, varietal stability, multi-environment trials (MET), genotype × environment interactions (GEI), GGE bioplots, plant density

1. Introduction

Maize, together with rice and wheat, constitutes the three major cereals projected to continue meeting global food demands for the rapidly growing population, as it is largely consumed by many people (Adiaha, 2017; Erenstein et al., 2022). In Africa, it occupies a large production area, particularly in sub-Saharan Africa (SSA), where over 37 million hectares (M ha) are harvested annually (Epule et al., 2022). In some African countries such as Uganda, without maize, the trajectory to a medium-status economy remains unclear, as the crop is widely grown for food and income security by almost every household (Badu-Apraku et al., 2017; Ekpa et al., 2018, 2019; Erenstein et al., 2022; Chune, 2022; Roberto et al., 2025). It has a range of industrial uses in pharmaceutical, livestock and poultry feeds, and local brew industries, making it the most traded food crop in Uganda, providing over US$ 52 million from annual exports (Daly et al., 2016; UBOS, 2022). Though maize is an anchor crop for income and food security, especially for the poor resource farmers in SSA, the average crop yields are still low (Epule et al., 2017). Hostile and exacerbating climate-induced stresses such as drought, heat, pest and diseases attributed to ongoing climate change cause variable unproductive effects on the maize yields as it is largely grown at the subsistence level (Adhikari et al., 2015; Ongoma et al., 2018; Parker et al., 2019; Bwambale & Mourad, 2022; Ocwa et al., 2023). The climate is rapidly warming, with temperature anomalies exceeding 1.4°C since 1950 in some countries (Ogwang et al., 2017; IPPC, 2018), thus making maize production more vulnerable to rising climatic stresses. It is reported that moisture stress could cause over 80% maize yield reduction and temperature extremes above 30 °C could cause decreased maize production (Lobell et al., 2011; Abebe et al., 2016; Epule et al., 2017). Additionally, the crop production is mostly under rain-fed conditions, but the rainfall patterns are erratic and vary over seasons, with growing occurrences of short-rainfall season windows (Epule et al., 2021). The effects of climate-induced stressors, therefore, severely impact large population of the rural poor farmers with limited adaptive capacities due to financial constraints (Udine et al., 2015; Kikoyo & Nobert, 2016; Parker et al., 2019).

In resource-limiting economies, using climate-smart varieties with increased resilience to multiple climate-induced stresses, especially rising heat and temperature, could play an important role in stabilizing maize yield (Lee, 2020; Prasanna et al., 2021). Progressively, for several years, breeding efforts involving national and international breeding programs resulted in the release of several multiple stress-tolerant maize varieties that could be used for climate-smart agriculture (CSA) (Asea et al., 2023; Prasanna et al., 2021). The climate-smart varieties harbor several resilience and adaptive traits, including drought tolerance, water and nitrogen-use efficiency, early maturity, and higher resistance to devastating pests and diseases such as maize lethal necrosis (MLN). These varieties include the currently cultivated open-pollinated varieties (OPVs) such as MM3 and several hybrids (Longe 6H, Longe 9H, Longe 10H, Bazooka, WE 3106, and FH5160), but some have been cultivated since 2002 in Uganda (Lee, 2020). At the time of release, the varieties were reported with consistent superior yield (6-10 t ha^{-1}) advantage compared to the local ones (2.4 t ha^{-1}) in testing sites for new hybrids (UBOS, 2017; MAAIF, 2010; Asea et al., 2023). These research sites not only represent unique climatic environments in which new hybrids are tested and released for commercial use but also farmers' production conditions. The sites primarily include three diverse sub-environments, namely the mid-altitude, tropical-rain forest and semi-arid zones, where maize is the most widely cultivated cereal crop at the subsistence level (Okonya et al., 2013). Under unpleasant climate change-induced production conditions, such as rising temperatures in the major production belts/testing sites, maize varietal performance could rapidly deteriorate and become outdated over years (Chivasa et al., 2022; Asea et al., 2023). Also, other factors, including variations over time in soil fertility and emerging pest and disease epidemics, could significantly contribute to genotype-by-environment interactions, which influence cultivar performance (IPPC Secretariat, 2021; Reddy et al., 2022; Wambi et al., 2025). Regular and reliable assessment of varietal stability and performance is thus vital to inform active deregistration of obsolete ones, selection of the adapted new varieties, and guiding future improvement programs.

Additionally, the released varieties are widely cultivated at a conventional wide spacing (0.75 × 0.60 M), but attaining the reported productivity (6-10 t ha^{-1}) at the farmer household level remains a myth. Amidst a worsening climate, promoting the varieties under increased seed-input intensification cropping systems could enhance maize yield, thus providing necessary adaptation for subsistence farmers. However, inadequate evidence on the response of the released varieties under higher seeding rate inputs is available. Several studies indicate that using increased plant density strategy can boost crop productivity and biomass production by enhancing radiation use efficiency (Zhang et al., 2021; Cui et al., 2022). In a certain range, it can lead to more efficient use of resources, especially water and nutrients in areas that experience dry and hot production conditions (Haarhoff & Swanepoel, 2022). On the other hand, higher plant densities can create a more favourable environment for the spread of diseases and pests, cause increased yield variability, especially in dryland environments when competition for water is intense (Maddonni & Martínez-Bercovich, 2014; Zhang et al., 2021). Economically, it can increase the production costs associated with higher seed requirements, increased water and fertilizer needs, and potentially more labor (Schmitz and Ransom, 2021). Thus, finding the optimal plant density that balances the economic benefits of adopting the popular released climate-smart varieties with minimal risks of reduced yield stability and increased production costs is necessary. This study was therefore carried out to (i) validate the genotypic performance of the popular climate-smart released maize varieties under increased plant densities in the three sub-ecologies (Mid-altitude, semi-arid, and tropical rain forest zones), and estimate the profitability of growing the varieties under optimum plant density in the different sub-ecologies.

2. Materials and Methods

2.1 Materials

Seven popular maize varieties that were released between 2002 and 2016 were used in the study. The varieties were voluntarily provided by the seed companies, including NASECO, FICA, Pearl Seeds Ltd., and Growmore Seeds, which were availed with the parental lines. The details of the maize varieties and their characteristics are indicated in Table 1 below.

Table 1. Characteristics of released maize varieties used in the study

Varieties	Year of release	Grain yield t ha^{-1}	Maturity date	Characteristics
WE3106	2016	8	120	Drought tolerant, intermediate maturity
Bazooka	2013	9-10	130	High yield, Drought and MLN tolerant
FH5160	2012	8-10	120-130	High-yield stability, Drought tolerant
MM3	2010	4-6	75-85	Resistant to MSV, NLB, GLS, early maturity
Longe 9H	2009	8	120	Resistant to MSV, NLB, GLS, drought tolerant
Longe 10H	2009	9	120	Resistant to MSV, NLB, GLS, drought tolerant
Longe 6H	2002	8	125	Resistant to MSV, NLB, GLS

Note. MLN: Maize lethal necrosis; MSV: Maize streak virus; NLB: Northern corn leaf blight; GLS: Gray leafspot.

2.2 Study Area

Rain-fed field experiments were conducted in 2017 for two seasons in the three sub-ecologies of Lake Albert Cresent Zone (LACZ), which are important maize crop production belts and testing sites for new hybrids. The sub-ecological zones included the mid-altitude zone that covers Masindi, Hoima, Kiryandongo, Kikuube, and Kagadi districts; the tropical rain forest zone covering areas near Kibaale and Budongo forests in Kibaale and Masindi districts, respectively; and the semi-arid zone that occupies the lower part of Bulisa district in the rift valley (Figure 1). The LACZ lies in the midwestern region of Uganda at 0.25810N latitude and 30.52790E longitude with an approximate area of 17471.9 km^2. Rainfall is bimodal, occurring in March to May and August to November main seasons. It ranges between 700 and 1000 mm annually, with seasonal variations and prolonged droughts. Annual daily minimum and maximum temperatures in the region range between 18°C and 35°C. The soil varies, but Plinthosols and ferralsols soils dominate with sand-clay-loam and loam soil profiles (Kaizzi et al., 2012; Kikoyo & Nobert, 2016).

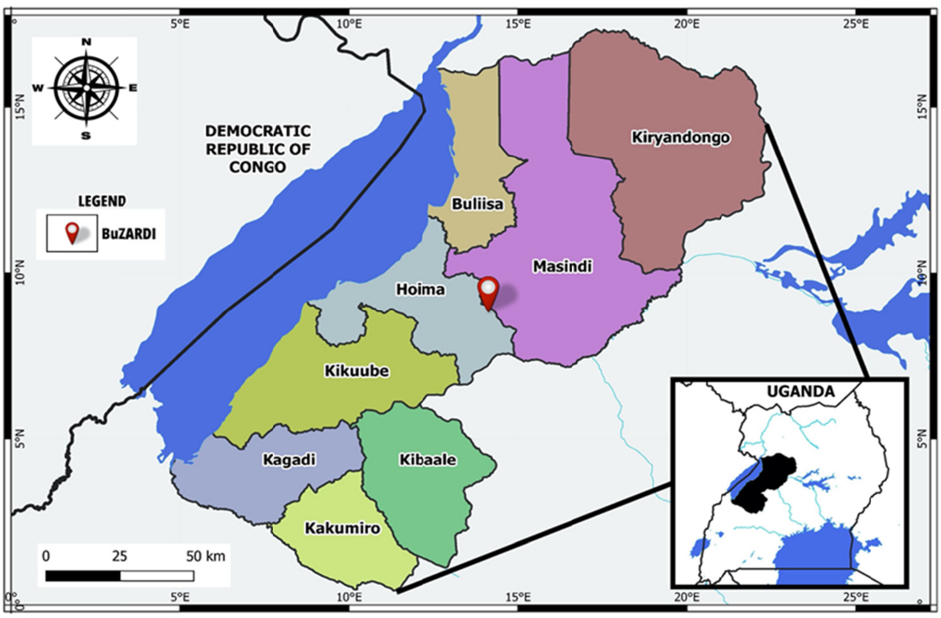


Figure 1. Map of operation areas of LACZ

2.3 Treatment Structure and Field Layout

A two-factor factorial experiment with seven varieties and a four-spacing-level treatment structure was established in a randomized complete block design (RCB). While the four different spacing levels included inter-row and intra-row spacing of 0.75 × 0.6 M, 0.75 × 0.30 M, 0.75 × 0.25 M, and 0.5 × 0.3 M. The traditional spacing of 0.75 × 0.6 M was used as a control. At planting, plots of 3 meters width by 5 meters length were used for each of the treatment combinations that were replicated three times in each sub-ecological zone. For all spacings, one plant per hole was left at thinning except for 0.75 × 0.6 M spacing where two plants were maintained. Consequently, this resulted in plant densities of 44,444, 44,444, 53,333, and 66,667 per hectare from spacings of 0.75 × 0.6 M, 0.75 × 0.30 M, 0.75 × 0.25 M, and 0.5 × 0.3 M, respectively.

2.4 Data Collection and Analysis

2.4.1 Data Collection

Data was collected on yield component traits, including plant number, ear number, field weight, and moisture content at harvest, that were used to compute grain yield (GY). All the harvested ears from the two middle rows of each plot were weighed to determine plot field weight data. Grain moisture content was measured using a moisture meter. Using an average shelling percentage of 80%, grain yield (GY t ha^{-1}) was calculated and adjusted to 12.5% moisture content (Worku et al., 2016). Ear aspect (EA) data was also collected using all the harvested ears following a scale of 1-5, where 1 represented large cobs with good EA and 5 represented small cobs with poor EA.

2.4.2 Data Analysis

(1) Analysis of Variance

During data analysis, the sub-ecological zones and seasons were grouped as a single environment, which resulted in five environments (Mid-altitude 2017A, TRF 2017A, TRF 2017B, Semi-arid 2017A, and Semi-arid 2017B). Analysis of variance for grain yield and ear aspect was performed for the combined environments with R software. The mean performance of the varieties based on GY at the four different spacing levels in each sub-ecology of LACZ was evaluated using the LSD test considering $p < 0.05$ probability level.

(2) GGE Bioplot Analysis

By using the genotype plus genotype environment interaction (GGE) bioplot analysis technique, breeders can easily examine how different varieties perform and remain stable across various environments (Olanrewaju et al., 2021; Reddy et al., 2022). It's one of the robust statistical methods used to analyze and visualize multi-environment data when studying genotype environment interaction (GEI) effects. Several applications of GGE bioplot analysis were reported, such as mean *vs.* stability genotype evaluation, identification of selective testing environments, and analysis of "which-won-where" patterns. In the current study, the GGE biplot analysis model was applied to assess the genotype and environmental performance and yield stability across the 5 environments using the GGE biplot R package version 0.1.3. The column metric SVP and tester-centered G+GE with no scaling method were used to generate graphics for the (i) which-won-where pattern, (ii) correlations among the five test environments that were based on angles between environmental vectors, and (iii) ranking discrimination and representativeness of test locations.

(3) Profitability Analysis

Several methods are utilized in determining the profitability of agricultural investments, such as net profit margin, return on equity (ROE), and profit growth (Handayani & Winarningsih, 2020), and return on investment (ROI) (Zalkuwi et al., 2010; Kaiira et al., 2014). Some of these methods require estimation of costs that are subjective, not easy to determine, and long-duration studies of at least three years and above (Handayani & Winarningsih, 2020). Gross margin analysis of profitability is possibly the most commonly used method in the determination of short-duration projects with less consideration of fixed costs in profitability analysis (Zalkuwi et al., 2010; Agbugba et al., 2020). It gives a quick, short-term outlook of the performance of enterprises considering their costs and returns. The method has been used in various investment studies to evaluate lucrative agricultural projects after paying off variable production expenses. In the current study, the profitability of cultivating maize under varying seeding rates in the three sub-ecologies of LACZ was evaluated using the gross margin analysis approach. The procedure for data collection was as follows: The production variable cost data collected included labor costs for various activities such as planting, weeding, fertilizer application, harvesting, and threshing. These labor activities were rated following the guidelines for National Agricultural Research Organization (NARO) labor rates that were developed and adapted in 2016. Consultations were further conducted at the trial sites with the farmers in the respective sub-ecologies to confirm the transaction costs associated with maize cultivation and maize grain market prices. The seed, pesticide, and fertilizer input price data were collected from reliable and registered seed and agro-input companies that promote the released maize varieties. The Total Variable Cost (TVC) was computed for each spacing and used for further analysis. Profitability analysis involved revenue from mean maize grain yield per plot of 5 × 3 M extrapolated per hectare. Gross Revenue (GFR) was determined by obtaining the product of the prevailing price of maize grain in 2017 and the mean grain yield per hectare. Finally, the net returns were computed by subtracting the TVCs from the gross return as detailed by Zalkuwi et al. (2010).

3. Result

3.1 Performance of the Seven Varieties at Different Spacing Under Sub-ecologies of LACZ

ANOVA revealed significant variety, spacing, variety × E, and spacing × E mean squares among the seven varieties for both grain yield and ear aspect traits (Table 2).

Table 2. Mean squares from combined ANOVA for grain yield and ear aspect of the varieties and spacing across five environments

Source of variation	Df	Grain yield	Ear aspect
Environment (E)	4	299.19***	14.46***
Rep	2	45.33***	3.08**
Spacing	3	146.94***	2.73**
Variety	6	15.42***	4.34***
Variety × E	24	4.97**	1.78***
Spacing × E	12	7.25**	1.49**
Residuals	198	2.52	0.56

Note. ** and *** = Significant at $P \leq 0.01$ and $P \leq 0.001$ probability level, respectively.

The performance of the seven varieties based on GY at the four different spacing levels in each of the sub-ecologies of LACZ was presented in Table 3. With the exception of the traditional widest spacing of 0.75 × 0.60 M, in the mid-altitude, productivity of all the varieties was either comparable to or above their expected yield (6-10 t ha^{-1}) potential under 0.50 × 30 M, 0.75 × 0.25 M, and 0.75 × 0.30 M spacing regimes. The top-yielding varieties included Bazooka (12 t ha^{-1}), Longe 6H (11.01 t ha^{-1}), Longe 10H (10.86 t ha^{-1}), and FH5160 (10 t ha^{-1}) at a spacing of 0.50 × 0.30 M; Longe 10H (10.97 t ha^{-1}), Bazooka (10.65 t ha^{-1}), and Longe 9H (10.14 t ha^{-1}) at a spacing of 0.75 × 0.25 M; and Longe 10H (10.75 t ha^{-1}) and Bazooka (9.71 t ha^{-1}) at a spacing of 0.75 × 0.30 M. The varieties that responded to the effect of spacing included Bazooka, Longe 10H, and WE3106. Increasing the plant densities to 53,333 and 66,667 plants ha^{-1}, respectively, resulted in a yield increment of 94.34% (5.17 t ha^{-1}) and 118.8% (6.5 t ha^{-1}), 121.62% (6.02 t ha^{-1}) and 119.4% (5.91 t ha^{-1}), and 193.5% (5.63 t ha^{-1}) and 104.5% (3.04 t ha^{-1}) over the widest spacing for Bazooka (5.48 t ha^{-1}), Longe 10H (4.95 t ha^{-1}), and WE3106 (2.91 t ha^{-1}). Overall, the varieties also exhibited excellent ear aspect (2-3.5) under reduced spacings that was comparable to the traditional spacing (0.75 × 0.60 M), except for MM3 in the mid-altitude (Figure 2).

The recorded grain yields for most varieties in the tropical rain forest (TRF) zone were below their yield potential, except for MM3, WE3106, and Longe 10H, which had a maximum of 4.85 t ha^{-1}, 5.18 t ha^{-1}, and 8.36 t ha^{-1}, respectively, under 0.50 × 0.30 M narrow spacing (Table 3). The varieties that responded significantly to the effect of spacing in the TRF zone included Bazooka and MM3. Using the narrow spacings of 0.50 × 0.3 M and 0.75 × 0.25 M, translated to GY productivity benefits, respectively, in a range of 1.7-130.6% and 107.1-134.7% over the wide traditional spacing of 0.75 × 0.60 M for MM3 (1.8 t ha^{-1}) and Bazooka (1.96 t ha^{-1}) varieties. All the varieties exhibited poor EA above 3.5 under reduced spacings, except Bazooka, Longe 6H, and Longe 9H at a spacing of 0.75 × 0.30 M (Figure 2).

In the semi-arid zone, the top-performing varieties included WE3106, which had a mean GY of 5.85 t ha^{-1} at 0.75 × 0.25 M spacing; Bazooka and WE3106, with a productivity of 5.68 t ha^{-1} and 5.39 t ha^{-1}, respectively, at 0.50 × 0.30 M spacing; and Bazooka, which recorded a productivity of 5.54 t ha^{-1} at 0.75 × 0.30 M (Table 3). The varieties that responded significantly to the effect of spacing in this zone included Bazooka, Longe 10H, and MM3. Narrowing the spacing to 0.50 × 0.30 M and 0.75 × 0.25 M for the varieties resulted in 29.88% and 26.90% yield advantages, respectively, over the traditional spacing (0.75 × 0.60 M).

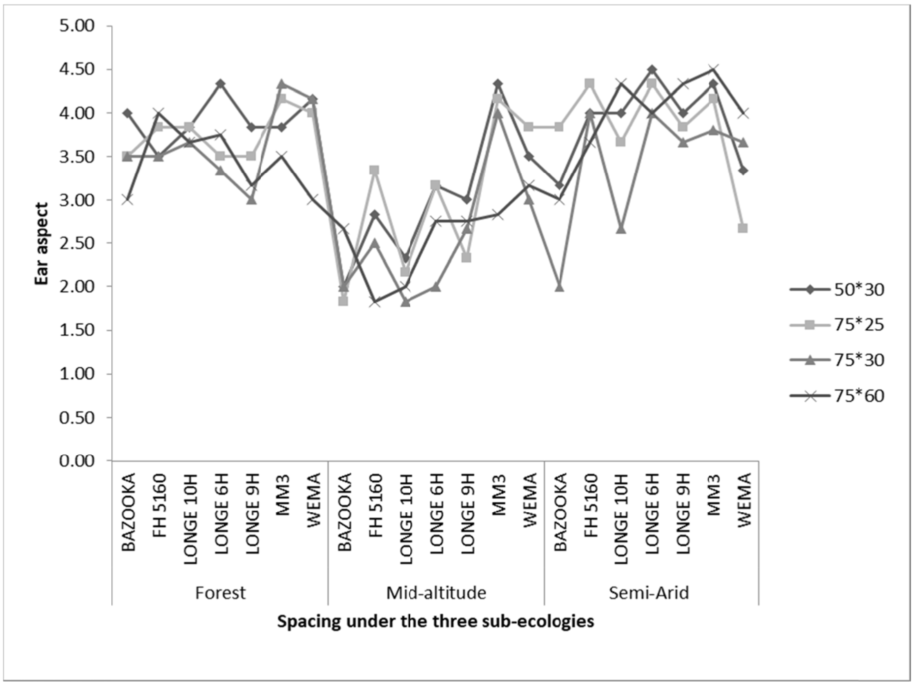


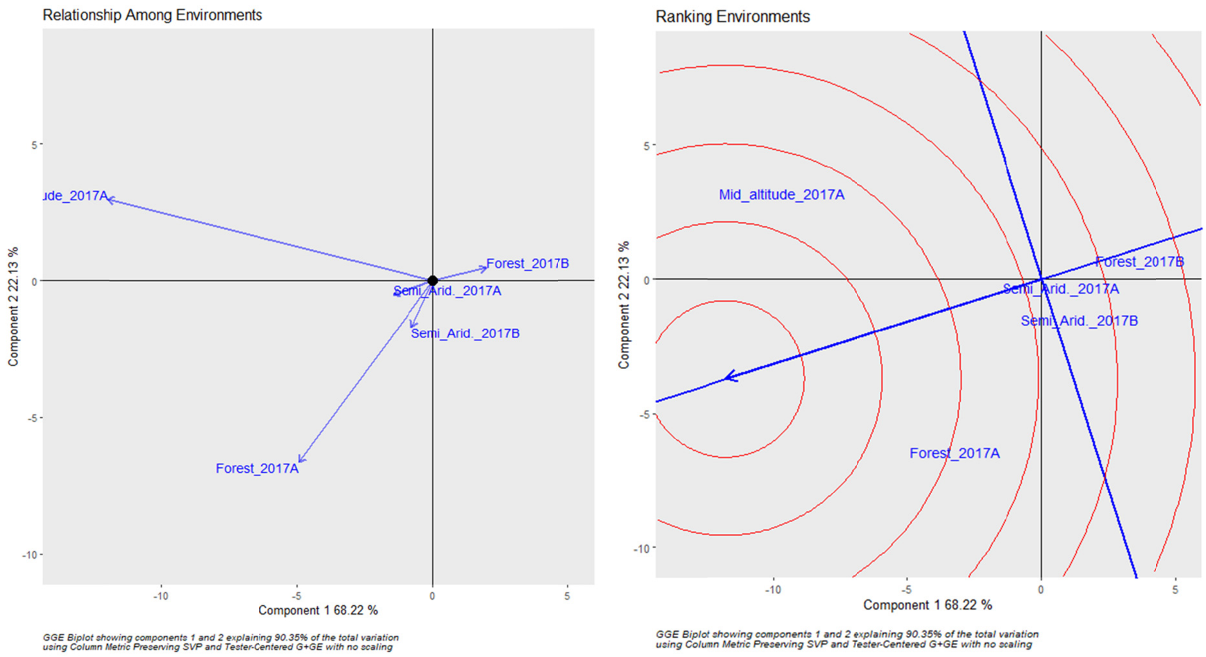
Figure 2. Variety performance-based ear aspect under different spacings

Table 3. Performance of the seven varieties based on grain yield at different spacing under sub-ecologies of LACZ

Spacing	Varieties						
	BAZOOKA	FH 5160	LONGE 6H	LONGE 9H	MM3	WE 3106	LONGE 10H
Tropical rain forest							
0.50*0.30	4.60±1.08	4.28±1.55	2.73±0.45	3.44±0.78	4.15±0.70	3.65±1.53	5.77±2.59
0.75*0.25	4.06±0.75	2.27±0.45	3.91±0.37	2.46±0.85	1.83±1.19	2.92±0.86	3.15±0.88
0.75*0.30	2.96±0.24	2.79±0.94	3.11±1.28	3.05±0.80	2.92±0.90	2.64±1.04	2.8±1.31
0.75*0.60	1.96±0.50	1.66±0.32	1.35±0.35	1.52±0.11	1.80±0.52	2.01±0.68	1.33±0.17
Mean	3.39 ±0.52	2.75±0.61	2.77 ±0.53	2.62±0.59	2.68±0.14	2.81±0.73	3.26±1.46
$LSD_{0.05}$	1.8±0.74	ns	ns	ns	1.43±0.59	ns	ns
CV	26.5	38.6	32.8	39	26.8	44.8	41.2
Mid-altitude							
0.50*0.30	11.99±1.39	10.00±1.84	11.01±2.55	9.45±2.30	7.01±1.16	8.54±0.41	10.86±1.40
0.75*0.25	10.65±0.18	8.76±0.94	9.01±0.79	10.14±0.58	5.71±2.23	5.95±1.22	10.97±0.93
0.75*0.30	9.71±1.62	8.65±2.33	7.1±0.85	7.78±0.93	6.13±2.53	7.78±1.02	10.75±0.86
0.75*0.60	5.48±0.83	4.01±0.33	4.12±0.30	5.3±1.90	3.92±0.93	2.91±0.42	4.95±0.50
Mean	9.46±0.66	7.86±1,80	7.81±1.39	8.17±1.27	5.69±0.94	6.29±0.75	9.38±1.12
$LSD_{0.05}$	2.27±0.93	ns	ns	ns	ns	2.59±1.06	3.86±1.57
CV	12	39.6	30.8	27	28.6	20.6	20.6
Semi-Arid							
0.50*0.30	5.68±1.32	4.06±0.52	3.40±0.89	4.55±0.92	3.76±0.28	5.39±0.53	4.73±0.99
0.75*0.25	4.81±0.66	3.36±1.34	4.49±`1.08	3.85±0.51	3.54±0.62	5.85± 1.44	4.05±1.30
0.75*0.30	5.54±0.74	3.01±0.65	3.97±0.98	3.47±0.42	3.25±0.14	4.79±1.50	5.32±1.53
0.75*0.60	2.71±0.38	1.67±0.33	1.63±0.31	1.27±0.28	1.61±0.20	1.24±0.63	1.41±0.22
Mean	4.69±0.43	3.03±0.47	3.37±0.68	3.29±0.53	3.04±0.38	4.31±1.00	3.88±0.77
$LSD_{0.05}$	1.47±0.60	ns	ns	ns	1.31±0.54	ns	2.68±1.09
CV	15.7	26.8	35.2	27.9	21.6	40.4	34.6

3.2 GGE Bioplot and Stability Analysis

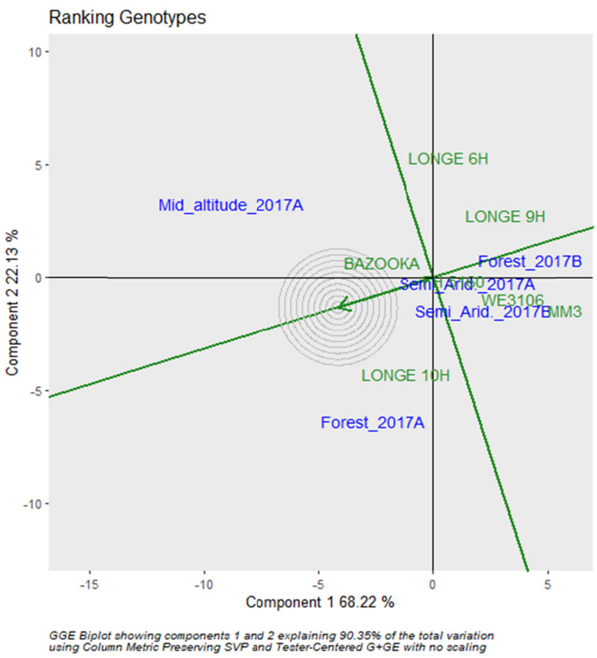
We used the GGE biplot analysis to identify the best varieties for each environment and their stabilities across the test environments, considering their grain yield performance at a narrow spacing (0.50 × 0.30 M). The biplot explained 90.35% of the total variation observed, generated by the first principal component (68.22%) and second principal component (22.13%). The five environments were separated into three groups (Figure 3A). Group one included the mid-altitude environment. Group two involved semi-arid 2017A, semi-arid 2017B, and TRF2017A environments that exhibited acute vector angles and were positively correlated. While group three included the TRF2017B environment that was negatively correlated with other test environments.



3A 3B

Figures 3A and 3B. Bioplots displaying relationship and ranking among environment, respectively

Ranking of environments was displayed in Figure 3B. The mid-altitude environment was the most productive environment, followed by the TRF 2017A. While the worst environment was the TRF 2017B. Ranking of genotypes and “which-won-where” patterns results were displayed in Figures 3C and 3D, respectively. The top productive varieties included Bazooka and Longe 10H in the mid-altitude and TRF2017A environments, respectively (Figure 3C). While in the semi-arid 2017A and B environments, MM3 and WE3106 were ranked as top-performing varieties.



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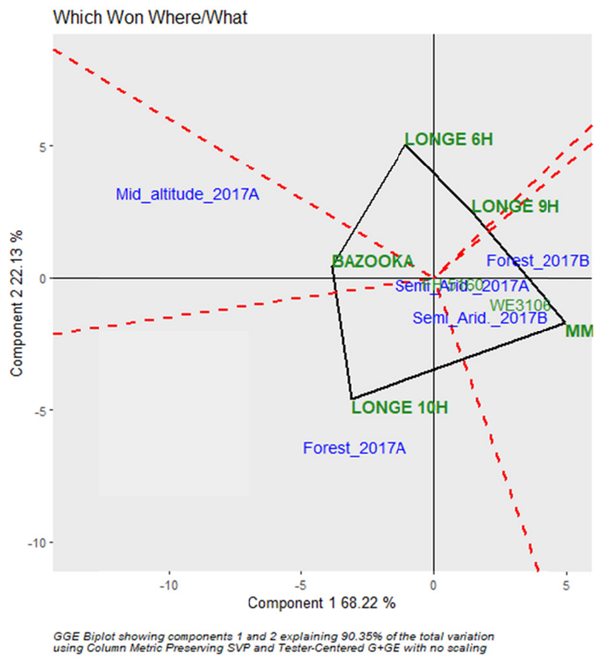
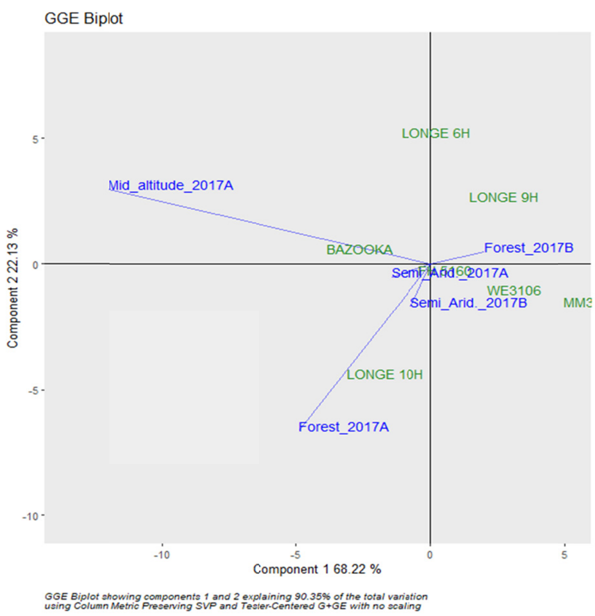


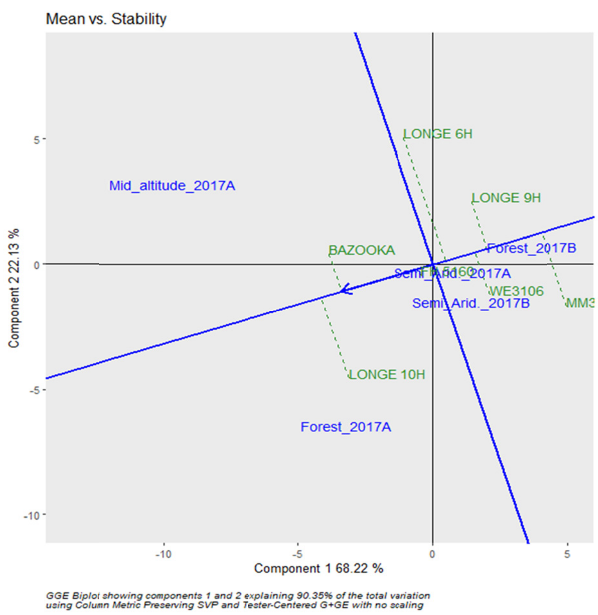
3D

Figures 3C and 3D. Bioplots displaying genotypes ranking and their which won where patterns, respectively

FH5160 was the highest stable genotype across the environments, but with moderate GY (Figures 3E and 4F). The highest productive genotype was Longe 10H, but it was unstable compared to FH5160 and Bazooka. While Bazooka had higher GY and stronger stability. Overall, Bazooka was ranked as the best variety across the test environments, and Longe 6H was the worst variety for cultivation.



3E



3F

Figures 3E and 3F. Bioplots displaying means *vs.* stability and performance of genotypes

3.3 Effect of Spacing on Production Cost and Net Returns in Three Sub-ecological Zones of LACZ

Table 4 shows that spacing influenced production costs and profitability of maize across zones. The highest production costs and profit return were obtained from the closure spacing of 0.50 × 0.3M, and the lowest from the widest spacing of 0.75 × 0.60 M. The profit margin was highest in the mid-altitude zone, followed by the semi-arid. Planting under optimal spacing (0.75 × 0.30 M) resulted in profit returns ranging from 4,229,500 UGX (USD 1143) to 10,005,500 UGX (USD 2704) in the mid-altitude zone. In the TRF zone, no profit returns were realized for most varieties, except for a few that were planted under the closest spacing.

Table 4. Effect of spacing on production cost, gross and net returns in three sub-ecological zones of LACZ (1USD = 3700UGX)

Variety	Spacing	Plant density	Tropical rain forest zone				Mid-altitude zone				Semi-arid zone			
			GY	Gross return	Total variable cost	Net return	GY	Gross return	Total variable cost	Net return	GY	Gross return	Total variable cost	Net return
BAZOOKA	0.50*0.30	66667	4.60	5520000	4308500	1211500	11.99	14388000	4382500	10005500	5.68	6816000	4322500	2493500
	0.75*0.25	53333	4.06	4872000	4242500	629500	10.65	12780000	4312500	8467500	4.81	5772000	4251500	1520500
	0.75*0.30	44444	2.96	3552000	4192500	-640500	9.71	11652000	4262500	7389500	5.54	6648000	4218500	2429500
	0.75*0.60	44444	1.96	2352000	4182500	-1830500	5.48	6576000	4222500	2353500	2.71	3252000	4190500	-938500
FH 5160	0.50*0.30	66667	4.28	5136000	4207500	928500	10.0	12000000	4287500	7712500	4.06	4872000	4227500	644500
	0.75*0.25	53333	2.27	2724000	4165500	-1441500	8.76	10512000	4232500	6279500	3.36	4032000	4176500	-144500
	0.75*0.30	44444	2.79	3348000	4140500	-792500	8.65	10380000	4202500	6177500	3.01	3612000	4142500	-530500
	0.75*0.60	44444	1.66	1992000	4129500	-2137500	4.01	4812000	4152500	659500	1.67	2004000	4129500	-2125500
LONGE 6H	0.50*0.30	66667	2.73	3276000	4215500	-939500	11.01	13212000	4297500	8914500	3.40	4080000	4221500	-141500
	0.75*0.25	53333	3.91	4692000	4181500	510500	9.01	10812000	4232500	6579500	4.49	5388000	4187500	1200500
	0.75*0.30	44444	3.11	3732000	4142500	-410500	7.10	8520000	4182500	4337500	3.97	4764000	4152500	611500
	0.75*0.60	44444	1.35	1620000	4126500	-2506500	4.12	4944000	4152500	791500	1.63	1956000	4129500	-2173500
LONGE 9H	0.50*0.30	66667	3.44	4128000	4221500	-93500	9.45	11340000	4277500	7062500	4.55	5460000	4233500	1226500
	0.75*0.25	53333	2.46	2952000	4167500	-1215500	10.14	12168000	4242500	7925500	3.85	4620000	4181500	438500
	0.75*0.30	44444	3.05	3660000	4142500	-482500	7.78	9336000	4192500	5143500	3.47	4164000	4147500	16500
	0.75*0.60	44444	1.52	1824000	4127500	-2303500	5.30	6360000	4162500	2197500	1.27	1524000	4125500	-2601500
MM3	0.50*0.30	66667	4.15	4980000	4152500	827500	7.01	8412000	4182500	4229500	3.76	4512000	4150500	361500
	0.75*0.25	53333	1.83	2196000	4100500	-1904500	5.71	6852000	4142500	2709500	3.54	4248000	4117500	130500
	0.75*0.30	44444	2.92	3504000	4091500	-587500	6.13	7356000	4122500	3233500	3.25	3900000	4095500	-195500
	0.75*0.60	44444	1.80	2160000	4080500	-1920500	3.92	4704000	4102500	601500	1.61	1932000	4079500	-2147500
WE 3106	0.50*0.30	66667	3.65	4380000	4224500	155500	8.54	10248000	4277500	5970500	5.39	6468000	4241500	2226500
	0.75*0.25	53333	2.92	3504000	4171500	-667500	5.95	7140000	4202500	2937500	5.85	7020000	4202500	2817500
	0.75*0.30	44444	2.64	3168000	4138500	-970500	7.78	9336000	4192500	5143500	4.79	5748000	4160500	1587500
	0.75*0.60	44444	2.01	2412000	4132500	-1720500	2.91	3492000	4141500	-649500	1.24	1488000	4125500	-2637500
LONGE 10H	0.50*0.30	66667	5.77	6924000	4264250	2659750	10.86	13032000	4314250	8717750	4.73	5676000	4254250	1421750
	0.75*0.25	53333	3.15	3780000	4188500	-408500	10.97	13164000	4267200	8896800	4.05	4860000	4197500	662500
	0.75*0.30	44444	2.80	3360000	4153000	-793000	10.75	12900000	4233000	8667000	5.32	6384000	4179000	2205000
	0.75*0.60	44444	1.33	1596000	4138000	-2542000	4.95	5940000	4175000	1765000	1.41	1692000	4140000	-2448000

4. Discussion

In the current study, we investigated the performance of released varieties under varied planting densities that could balance the economic benefits of adopting the climate-smart varieties with minimal risks of reduced yield stability and increased production costs. ANOVA revealed significant genotype and spacing mean squares for the tested varieties for both grain yield and ear aspect traits. Suggesting that the yield potential of tested varieties was not the same across the three sub-ecological environments. It also indicated that the tested spacings influenced the varieties' performance throughout the five environments for GY and EA traits. Significant interactions existed for the spacing × E and variety × E. It should be noted that all the varieties used in the current study were released for their known superior GY performance as well as stable genotypes for wider cultivation. Probably, environmental changes over time experienced in the zone, such as variation in soil fertility (Aigbe et al., 2023), shifts in rainfall and temperature patterns (Chisanga et al, 2017; Parker et al., 2019), and new emerging pest and disease epidemics (Otim et al., 2018; Wambi et al., 2025) could have significantly contributed to genotype-by-environment interactions, thus influencing cultivar performance. The interactions identified thus highlighted the importance of growing each tested variety at a unique spacing in a suitable sub-ecology.

Planting under increased plant density (closer spacing) consistently increased maize productivity in the three sub-ecologies of LACZ. The result conforms to that of Worku et al. (2016), which indicated higher productivity of over 16 t ha^{-1} under higher plant density. Also, Hasan et al. (2018) and Akther et al. (2024) observed maximum maize GY at closer spacings of 0.75 × 0.25 M (9.04 t ha^{-1}) and 0.45 × 0.20 M (8.43 t ha^{-1}), respectively. Probably, narrowing the spacing modulated the canopy formation, which could have improved interception of photosynthetically active radiations (Haarhoff and Swanepoel, 2022). With narrow spacing, chlorophyll degradation is slow, antioxidant system enzyme activity increases, and the functional leaf ages more slowly, thus leading to increased grain filling even in environmental extremes (Tian et al., 2019; Zheng et al., 2022). Additionally, because of the large open canopy associated with wider spacing, the soils experience increased incoming radiation. A situation that could cause moisture stress through evaporation, triggering weed seed germination, thus affecting overall performance of the crop.

The mid-altitude zone generally registered the highest maize grain yield across all varieties and seeding rates/plant densities. This thus confirm that the tested varieties were developed for wider adaptation to mid-altitude production conditions (Asea et al., 2023). Additionally, the zone received more uniform rainfall distribution that could have influenced excellent maize crop growth and development (Seasonal rainfall outlook over Uganda, 2017). In general, maize productivity was low in the tropical rain forest and semi-arid sub-ecologies. In TRF zone, maize productivity is frequently limited by low soil fertility, especially N deficiency, where N is lost through erratic rainfall, extreme runoffs, and leaching (Aigbe et al., 2023). Investigating the optimal fertilizer application regimes and rates with the tested maize varieties that will result in increased yields is crucial. During experimentation, we also observed symptoms of emerging maize dwarf virus disease in the TRF zone, thus requiring extended research attention. The top productive varieties in this zone were mainly intermediate and late-maturing varieties (Longe 10H, Bazooka, and WE3106). According to Aigbe et al. (2023), late maturing varieties offer better utilization of the extended rainfall window and could out-yield the extra-early and early-maturing varieties. Therefore, for optimum yield in the TRF zone, it is recommended to breed and promote intermediate and late-maturing climate-resilient maize varieties. The low productivity in the semi-arid zone, which lies under the rift valley area, could be attributed to increasing and extreme heat stress and prolonged dry spells exacerbated by climate change (Macauley & Ramadjita, 2015; Ogwang et al., 2017). A reduction in GY was reported by Banaj et al. (2023), in drier maize production conditions, which validates the current findings that the abiotic stresses highlighted above influenced the genotypic performance of the varieties. Increases in temperature result in more demand for water as an input and can lower yield, depending on the level of the increase. For several crops, the preferred optimal number of growing degree days ranges between 8°C and 32°C, and above 34°C degree days are always injurious to maize crop (Schlenker et al., 2005). According to Lobell et al. (2011), each degree day spent above 30°C could cause a final yield penalty equivalent to 1% under optimal rain-fed conditions and 1.7% with drought conditions. Under raised temperature, Abebe et al. (2016) also reported decreased maize grain and stover yield (4.9% and 37.0%, respectively) compared to ambient temperature. Therefore, breeding for improved varieties should focus on introgressing moisture and heat stress tolerance traits to enhance maize resilience in the semi-arid conditions in the future. Interestingly, two varieties, namely WE3106 and MM3, exhibited maximum grain yield comparable to their yield potential under narrow spacing in the semi-arid environment experience short rainfall window and severe moisture stress. The superior performance of the varieties in the semi-arid zone could be attributed to the breeding breakthroughs that resulted in the release of water-efficient use varieties that harbor moisture stress tolerance traits (NARO, 2015; Asea et al., 2023). Further, the MM3 variety was improved for early maturity (75-85 days) and matches well with the short growing season rainfall window in the zone.

Following ANOVA, we performed the GGE biplot analysis considering the variety performance at the optimal spacing (0.50 × 0.30 M) to explore the GEI that were identified. The extended analysis aimed at identifying the best sub-ecology and variety for each sub-ecology and those that were stable across the three sub-ecologies. The genotypes found at the corners of the polygons in a "which-won-where" polygon are the outstanding genotypes in the respective environments, according to Olanrewaju et al. (2021). The varieties Bazooka, Longe 10H, and MM3 were all situated at the corners of the polygon (Figure 3D), toward the mid-altitude, TRF2017A, and semi-arid environments, respectively. At the closest and optimal spacing (0.5 × 0.30 M), we thus recommend cultivation of the varieties, as they outperformed others in terms of GY performance in the respective environments. The variety FH5160 was located close to the center of the GGE biplot. Use of such a variety for climate-smart farming could guarantee a stable yield performance for maize across the sub-ecologies of LACZ. Based on the angles of environment vectors, the five environments were separated into three groups (Figure 3B). This grouping coincides partly with the traditional grouping of the three broader sub-ecologies of LACZ. In the future, the highlighted test locations can further be used as mega-environments for screening and selecting reliable climate-smart genotypes by the breeding programs. The mid-altitude environment had a longer environmental vector but also showed narrow angles with other test environments (semi-arid 2017A and B and TRF 2017A). These observations suggested its high differentiating power for the GY trait among the genotypes and a more representative environment that can be used in the initial multi-location screening of maize genotypes with limited resources, even when other related environments are not considered. The mid-altitude sub-ecology thus is considered to be a superior environment due to its discriminating power and representativeness. Furthermore, this sub-ecology registered the highest maize productivity across the tested spacings, which confirms that most varieties were well adapted for mid-altitude conditions.

4.1 Profitability Analysis

Profitability is the ability of a given business to earn returns (Toshniwal, 2016). Profitability was assessed using gross margin analysis, which accounts for variable costs (seed, labor, and inputs) against gross revenue. While suitable for short-term evaluation, this approach excludes fixed costs such as equipment and storage facilities, and thus may represent an optimistic estimate of net returns. This analysis showed how efficiently the farmers could make a profit by cultivating maize under varying plant densities with necessary variable costs. The highest production costs were obtained from the closest spacings, probably due to increased costs associated with increased seed input and number of storage bags. However, production of the released maize varieties at the optimal closest spacing of 0.50 × 0.3 M resulted in maximum economic benefits, emerging from increased yields. Previous reports consistently indicate that closer spacing raised production costs but also increased yields and revenues (Ho et al., 2024). Though the seed cost for the OPV variety MM3 was low compared to hybrid varieties, it produced a low yield, which had a negative bearing on profit returns. The yield potential of MM3 is generally low compared to hybrids, but could provide beneficial copping option when used food security in semi-arid environments that experience short rainfall windows, as it matures faster and can escape the dry growing spell. The profitability analysis revealed that producing all varieties under the three LACZ sub-ecologies is more profitable in mid-altitude, with the profit margin returns depending on the variety and spacing. Overall, high-density planting enhances profitability mainly in mid-altitude areas and with hybrid varieties, while returns in marginal zones are conditional and risk-prone. If farmers don't use family labor, low or no considerable profit could be realized from maize enterprise except with the use of varieties WE3106 and Bazooka in the semi-arid areas and Bazooka and Longe 10H in the TRF under narrow spacings. WE3106 and Bazooka were recently released water-efficient use hybrids with better yield performance under moisture stressed conditions. In the semi-arid areas, using these hybrids could offset yield losses and increase the profitability of maize production for the resource-poor farmers. Though increases in yield could influence the maize enterprise profitability, also a large increase in price could be necessary to make maize production lucrative in the semi-arid and TRF areas based on the current production cost variables.

4.2 Broader and Future Perspective of the Research

Generally, research findings generated showed solid evidence that the use of high seed input generates higher GY productivity and profit returns compared to the low-density traditional seeding rates. To this end, the intervention has the potential to significantly increase the resource-poor farming households' and other stakeholders' income and resilience to changing climate as well as maize export revenues. Unfortunately, under intensifying climate-induced heat and moisture stressors, especially in the semi-arid zone, the intervention may not be successful if used alone. Farmers will have to think about entering into irrigation use campaigns to further increase maize crop resilience and yield. We also recommend extended research on radiation use efficiency of the crop at optimal spacing.

5. Conclusion and Recommendation

The results indicated that the tested spacings influenced the varieties' performance for GY and EA traits across the three sub-ecologies of LACZ. Using increased plant density across the three sub-ecologies of LACZ from 44,444 to 53,333 and 66,667 plants ha^{-1} under reduced spacings (0.75 × 0.25 M and 0.50 × 0.30 M) translated to over 20% GY increment for most of the varieties. At optimal spacing (0.50 × 0.30 M), FH5160 was the most stable genotype for cultivation across the three sub-ecologies. All the varieties evaluated consistently exhibited superior genotypic performance for GY and EA traits in the mid-altitude zone under different plant densities. The intermediate and late-maturing varieties, Bazooka and Longe 10H were the best for the tropical rainforest zone. In addition to MM3, an early-maturing variety, the drought-tolerant hybrid varieties WE3106 and Bazooka (released water-efficient use hybrid varieties) were suitable for semi-arid zones. Farming the climate-smart varieties in the sub-ecologies of LACZ can be a financially profitable enterprise, especially under closer spacings (0.50 × 0.30 M and 0.75 × 0.25 M). The profitability was influenced by prevailing climatic conditions of sub-ecologies, and it is more profitable to grow the varieties in the mid-altitude sub-ecological zone. Under the spacing of 0.50 × 0.30 M that gave high yields, optimizing other agronomic practices, such as fertilization and irrigation application regimes in TRF and semi-arid areas, could further help to improve maize yields. Thus, high-density planting of the climate-smart maize varieties is economically viable primarily in mid-altitude areas with responsive hybrids, while profitability in semi-arid and tropical rainforest areas will require complementary investments and supportive policies to mitigate costs and risks. Breeding for new varieties should focus on new emerging challenges for maize production in the zone, such as increasing heat stress, fall armyworm and maize dwarf virus disease.

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Authors Contributions

W.W.—writing—review and editing, investigation, writing—original draft preparation, methodology, conceptualization, visualization; S.D.B.—writing—review and editing; D.B.K.—writing—review and editing; I.A.—writing—review and editing; I.B.—writing—review and editing; F.K.—writing—review and editing, investigation and supervision; H.Z—writing—review, editing and supervision, and J.E.—methodology, writing—review and editing

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