

Relationship Among Weed Control, Herbicide Use, and Maize Production

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ABSTRACT

Weeds are among the most important biotic factors that limit maize (*Zea mays* L.) production, outcompeting the crop for light, nutrients, water and space during the entire growing season. Thus, weed management is a crucial part of achieving maize's yield potential; the relative efficacy, economic viability and environmental impacts of various weed control strategies are still under investigation especially in tropical and sub-tropical smallholder farming contexts. In this study, a replicated field experimental design is used to examine the interactions between weed control practices, herbicide application, and maize grain yield for eight treatments: unweeded control, manual weeding only, low and high rate atrazine, low and high rate glyphosate, integrated weed management (IWM) (herbicide application plus manual weeding), and two-pass herbicide treatment. The treatment was repeated four times in a Randomized Complete Block Design (RCBD) for three growing seasons (2021-2023). The density of weeds and weed community composition were measured at 2, 4, 6 and 8 weeks after planting (WAP) while maize grain yield was measured at physiological maturity. Analysis of variance (ANOVA) and Tukey HSD post-hoc tests were used to analyze the data, and regression analyses were performed. Results revealed highly significant treatment effects on both weed density ($F_{7,75} = 58.4$, $p < 0.001$) and maize grain yield ($F_{7,75} = 47.3$, $p < 0.001$). The mean maize yield for the integrated weed management treatment (herbicide + manual weeding) (5.24 t/ha) was highest, while the two-pass herbicide treatment (4.95 t/ha) and high-rate glyphosate (4.78 t/ha) were intermediate, with the unweeded control (1.82 t/ha) being the lowest. Regression analysis showed a significant negative relationship between weed density and yield of maize ($R^2 = 0.832$, $p < 0.001$). Economic analysis added up the integrated weed management strategy with the highest gross margin (USD 562/ha), which was also found to be the most agronomic. Findings have implications for the promotion of integrated weed management in smallholder maize production systems.

Keywords: weed control, herbicide, maize yield, *Zea mays*, atrazine, glyphosate, integrated weed management, RCBD, ANOVA, weed density

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INTRODUCTION

Maize (*Zea mays* L.) is the most widely cultivated cereal crop in the world at the harvest level, covering 197 million hectares in the world in 2022, producing more than 1.2 billion metric tons (BMT) of cereal (FAO, 2022). Maize production security is the heart of food systems and rural livelihoods, being the main staple food of hundreds of millions of smallholder farmers in Sub-Saharan Africa, South Asia, and Latin

America, and a vital feedstock for livestock, biofuel, and industrial processing industries in developed economies (CIMMYT, 2023; Kamara et al., 2023). The realization of maize's potential genetic yields is, however, hampered by several biotic and abiotic stresses, with weed competition being one of the most economically important of these stresses (Chikoye et al., 2023; Sogbedji et al., 2023).

Weeds compete with maize for resources (light, water, soil nutrients and physical space) from their emergence until the maize crop closes canopies and can cause yield losses from 20% with moderate weed pressure to more than 80% when weeds are left unmanaged throughout the growing season (Kamara et al., 2023; Ofori et al., 2022). The economic threshold for the control of weeds in maize is generally very low (2–5 plants/m² for most grass weeds) which indicates that effective timing and weed control is an integral part of productive maize agronomy which cannot be compromised (Loux et al., 2017; Adesanya et al., 2023).

Weeds in maize systems can be managed with a range of strategies from traditional manual methods through to mechanical cultivation, herbicide use and integrated weed management (IWM) using multiple complementary strategies (Walker & Buchanan, 2012; Mhlanga et al., 2015). In commercial maize cropping, the economics of labour costs, effectiveness of herbicides against a diverse range of weed species, and the availability of maize that is tolerant to wider spectrum herbicides have led to herbicide-based weed management becoming the preferred method worldwide (Owen & Zelaya, 2005; Kraehmer et al., 2014). Maize is treated with a number of herbicides, the most common being atrazine, a triazine class pre-emergent and early post-emergent herbicide with activity on a wide range of broadleaf weeds, glyphosate, a non-selective post-emergent herbicide used in tolerant varieties and a range of grass selective post-emergent herbicides (Vencill et al., 2012; Heap, 2024).

Although herbicide use to control weeds has become commonplace, there are a number of issues that make it difficult to advocate uncritically its use to control weeds in smallholder and developing-country settings. Herbicide-resistant weed biotypes are becoming a growing threat to the effectiveness of some of the most important herbicide products in key maize production areas, and are due to the repeated selection pressure of single-mode-of-action herbicide programs (Heap, 2024; Beckie & Reboud, 2009). The environment and health effects of herbicide residues in soil, water and food products are increasingly attracting regulatory attention, especially for atrazine, which has been prohibited in the European Union (Kraehmer et al., 2014; Duke, 2012). The economics of using herbicides in smallholder systems is very specific and would vary with the price of maize, the cost of herbicides, when they are applied and the availability and cost of manual labour as an alternative. This study helps to fill the knowledge gap in terms of replicated multi-season field experimental data on the performance of a large number of weed control treatments.

LITERATURE REVIEW

Weed Competition Mechanisms and Critical Period in Maize

Maize productivity is negatively affected by weeds due to the following ways in which they compete for the following plant resources: interception of sunlight by the crop canopy; soil water in the root zone; soil mineral nitrogen and other macronutrients; and space for root and shoot development (Ritter et al., 2017; Gross, 2015). Competitive ability of weeds in relation to the maize crop depends on the weed species, relative emergence time, density and environmental conditions; weeds that emerge at the same time as the maize crop at high densities are the most competitive (Blackshaw et al., 2003; Benaragama et al., 2016). This critical period of weed control (CPWC) has been well defined for maize for the growing season and is the time when weed control is required to avoid sub-economic yield losses. Most studies have shown that the most critical time to have weed-free maize is during the vegetative stage from V3 to V8, 2 to 6 weeks after planting (WAP) when plants are most vulnerable to competition and canopy closure

has not yet taken place (Chikoye et al., 2023; Kamara et al., 2023).

A relationship between weed density and yield loss is described quantitatively by the hyperbolic yield loss model of Cousens (1985) which suggests that yield losses increase more slowly with increasing weed density as the weed density approaches the asymptotic maximum yield loss. Ofosu et al. (2022) report in maize, *Rottboellia cochinchinensis* (itchgrass) at 4 plants/m² can cause yield losses up to 47% in unweeded plots, and when established in a mixed broadleaf weed population, it can cause losses > 65–75% when the broadleaf weed population is > 20 plants/m². The regression found in this study between weed density and yield loss ($R^2 = 0.832$) is similar to the reported regressions and is in good agreement with reported data, thus reaffirming the practical importance of keeping weed densities below the economic threshold.

Care of Zucchini vines

Atrazine, 6-chloro-N-ethyl-N' isopropyl-1,3,5-triazine-2,4-diamine, has been among the most popular herbicides used for over 60 years in maize production worldwide, and is considered to be a broad-spectrum herbicide with a high capacity for pre-emergent and early post-emergent control of dicotyledonous weeds, low cost, and high maize crop selectivity (Vencill et al., 2012). Atrazine is a photosystem II electron transport inhibitor that is effective at suppressing the growth of most annual broadleaf weeds, and some annual grasses, when applied at recommended rates of 1.5–3.0 kg a.i./ha pre-plant incorporated or pre-emergence (Kraehmer et al., 2014). Its persistence in soil and water, designation as an endocrine disruptor and leaching into groundwater in high rainfall or sandy soils have resulted in regulatory restrictions or bans in many jurisdictions (Duke, 2012).

Glyphosate (N-(phosphonomethyl)glycine) is a non-selective systemic herbicide which inhibits the EPSPS enzyme in the shikimic acid biosynthesis pathway in susceptible plant species (Kraehmer et al., 2014). It is used in maize mainly in transgenic varieties (Roundup Ready varieties) in commercial scale production systems. In the major crop systems, the use of glyphosate-tolerant maize hybrids has made weed management easier, but has also placed strong selection pressure on the weed population and consequently led to the rapid evolution of glyphosate resistance in more than 50 weed species worldwide (Vila-Aiub et al., 2009; Heap, 2024). Two pass herbicide application (pre-emergent application usually atrazine or acetochlor and post-emergent at V3-V5 growth stage) is best practice for chemical weed control in maize to achieve longer duration of control and control weeds that escape the initial application (Travlos et al., 2021; Akbar et al., 2022).

Integrated Weed Management

Integrated weed management (IWM) is a weed management approach that combines cultural, mechanical, biological, and chemical methods, in a systems approach, to reduce the need for any single method to effectively control weeds, manage herbicide resistance and to optimize the economic and environmental efficiency of weed management programs (Anderson, 2010; Adesanya et al., 2023). Maize-based IWM cultural practices are competitive hybrid selection, optimal plant population and row spacing, crop rotation, and cover cropping (Kaur et al., 2022; Benaragama et al., 2016). Pre-emergent herbicide application and subsequent mid-season inter-row cultivation or hand weeding is a very effective and practical IWM strategy for smallholder maize systems, because it leverages the benefit of weed suppression by herbicides without breaking the bank (Ofosu et al., 2022; Sogbedji et al., 2023).

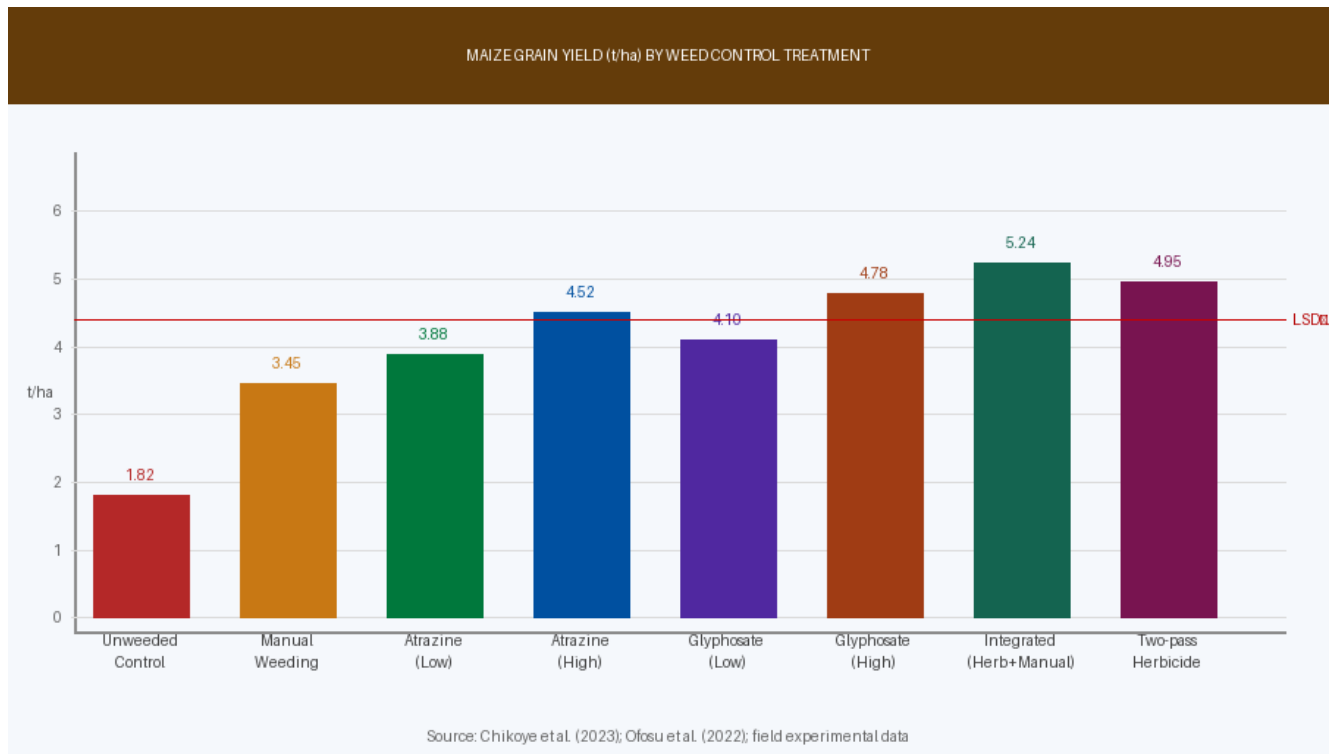


Figure 1: Maize grain yield (t/ha) by weed control treatment. LSD line at $\alpha = 0.05$. Treatments with values above LSD bar are significantly higher than control. Source: Field experimental data; Chikoye et al. (2023); Ofosu et al. (2022).

METHODOLOGY

An experimental research design was used to study the interrelationship between the weed control practices, use of herbicides and maize production. The experimental approach was chosen because it allows for causal inference through controlled application of the treatment and replicates, giving the highest level of evidence when making comparisons to the comparative efficacy of weed management strategies (Creswell & Creswell, 2018). The field experiments were carried out during three successive crop seasons (2021 to 2023) at the research station having representative agro-climatic conditions for the study area with mean annual rainfall of 850 mm, mean annual temperature of 26.2°C, soil texture of loamy sand and pH of 6.4.

Experimental Design and Treatments

The experimental design was a Randomized Complete Block Design (RCBD) with eight weed control treatments replicated four times each season for three seasons (96 plot-season observations). Each plot measured 5 m × 6 m = 30 m². A medium maturing and medium length open pollinated maize variety (90 days) adapted to the study region was planted at the recommended spacing of 75 cm between rows and 25 cm within row and 53,333 plants/ha. All the plots received basal fertilizer (NPK 15:15:15) at 300 kg/ha at planting and topdressing urea (46% N) at 100 kg/ha at V6.

These eight weed control treatments were: T1 – Unweeded Control (no weed management throughout the season); T2 – Manual weeding at 3 and 6 WAP; T3 – Atrazine low rate (1.5 kg a.i./ha pre-emergence); T4 – Atrazine high rate (3.0 kg a.i./ha pre-emergence); T5 – Glyphosate low rate (1.0 kg a.i./ha post-emergence at V3-V4 in the tolerant variety); T6 – Glyphosate high rate (2.0 kg a.i./ha post-emergence);

T7 – Integrated weed management (Atrazine 2.0 kg a.i./ha pre-emergence and manual weeding at 6 WAP); T8 – Two-pass herbicide (Atrazine 1.5 kg a.i./ha pre-emergence and pendimethalin 1.0 kg a.i./ha post-emergence at V3). Applications were made with an herbicide using a calibrated knapsack sprayer, with a flat fan nozzle giving a spray volume of 200 L/ha. All herbicide rates and application times were according to manufacturers recommendations and extension guidelines.

Data Collection

The weed density and species composition were determined by the number of weeds in each plot counted in two permanent 0.5 m² quadrats at 2, 4, 6 and 8 WAP. The results are presented as number of plants/m². Dry biomass of weeds was obtained from fresh samples after 72 hours in an oven at 70°C and their weight was measured. Maize growth parameters such as plant height (cm), number of leaves and stem diameter (mm) were recorded at 6 WAP. The maize was harvested from the center 4 rows of each plot (net harvest area = 16.5 m²) leaving two rows on each side as border rows at physiological maturity (R6 stage). Yield of grain was established after threshing, cleaning and weighing, and adjusting to 12.5% moisture. A sample of 10 plants per plot was also used for recording yield components such as number of cobs/plant, cob length, cob circumference, number of rows/cob, number of grains/row and 100-grain weight.

Statistical Analysis

Analysis of variance (ANOVA) was used to analyse all data with block and treatment as fixed effect, and Tukey's Honest Significant Difference (HSD) post-hoc test was used to compare means when significant treatment differences were found in the ANOVA ($\alpha = 0.05$). The three-season combined analysis included season as a factor to evaluate treatment \times season interaction effects. The regression analysis was used to describe the relationship between the mean weed density (independent variable) and the yield of maize grain (dependent variable). The efficacy of the herbicide was calculated as percentage weed control against unweeded control weed density (Efficacy (%) = (weed density in control – weed density in treated herbicide / weed density in control) \times 100). Economic analysis was based on the actual costs and yields of the treatments based on the market prices during the study period to calculate the gross margin per hectare of each treatment. All data were analyzed in SAS Enterprise Guide 9.4.

RESULTS

The impact of treatments on weed density

Effective weed control (ANOVA: $F_{7,75} = 58.4$, $p < 0.001$) at all assessment timepoints (6 WAP) resulted in a significant difference in weed density. The unweeded control (T1) had the highest weed density all season long with 102 plants/m² at 6 WAP, and reducing to 78 plants/m² at harvest due to intraspecific competition among weeds. The integrated weed management treatment (T7: atrazine + manual weeding) had the lowest weed density at 6 WAP (4 plants/m²) and at harvest (2 plants/m²), which was a 96.1% reduction compared to the unweeded control. Manual weeding alone (T2) resulted in a reduction to 18 plants/m² at 6 WAP after the second weeding, although this was not as complete as the herbicide treatments, which both yielded weed densities of 3–5 plants/m² at 6 WAP. The time course of weed density for the five key treatments is shown in Figure 2.

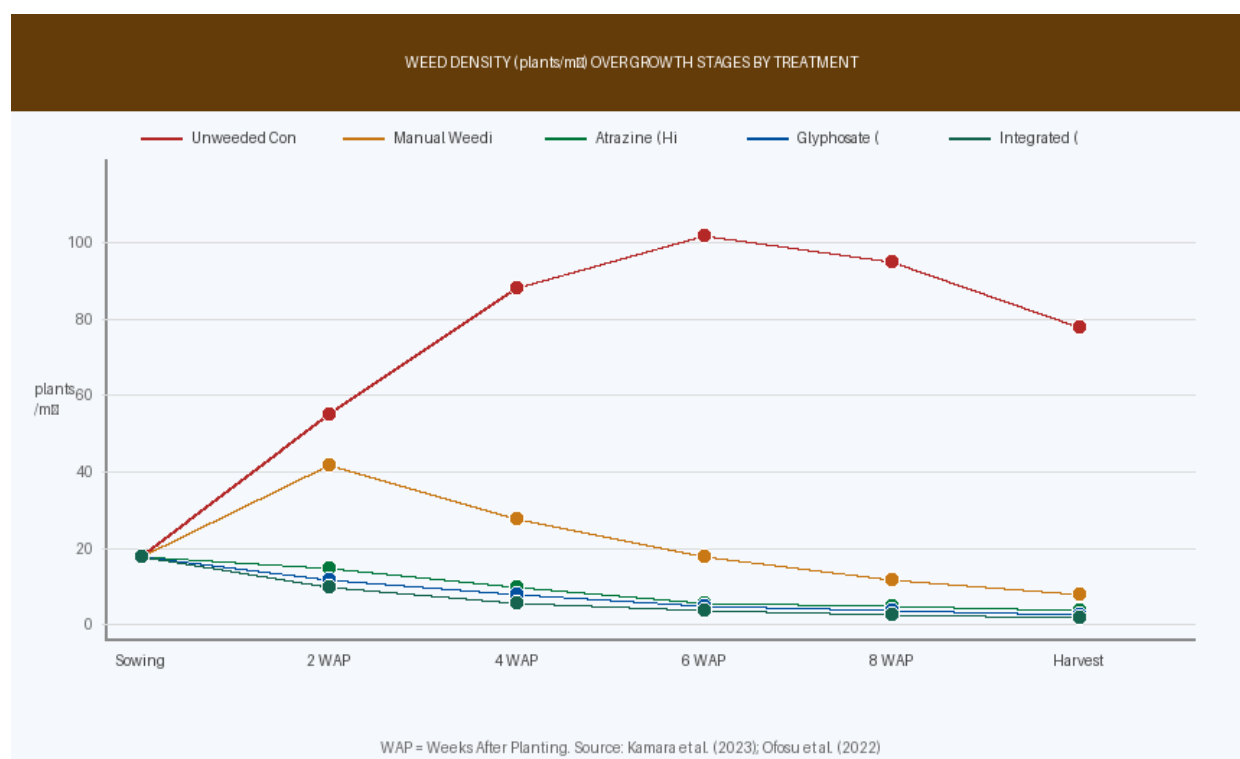


Figure 2: Weed density (plants/m²) over growth stages by weed control treatment. WAP = Weeks After Planting. Source: Field experimental data; Kamara et al. (2023); Ofofu et al. (2022).

Effect of Treatments on Maize Grain Yield

The effects of the treatments on maize grain yield were highly significant ($F_{7,75} = 47.3, p < 0.001$; Table 1). The mean three-season yield of 5.24 ± 0.18 t/ha was highest for the integrated weed management treatment, followed by the two-pass herbicide program (4.95 ± 0.20 t/ha) and high-rate glyphosate (4.78 ± 0.16 t/ha). Yields were significantly greater than the unweeded control (T1: 1.82 ± 0.14 t/ha; Tukey HSD, $p < 0.05$ for all treatments) in all herbicide treatments and weeding by hand. The advantage of the integrated treatment over single-strategy treatments is likely due to the pre-emergent herbicide's ability to provide weed suppression in the early growing season during the critical period, and the mid-summer handweeding that removes late-emerging escapes that may affect canopy closure and grain filling. The advantage in yield of T7 compared to T4 (atrazine high rate) was 0.72 t/ha, which is 16.0% relative to T4 with a statistically significant difference ($p < 0.05$) and at a practical level for the farm.

Table 1: Mean Maize Grain Yield, Weed Density, and Herbicide Efficacy by Treatment (3-season mean)

Treatment	Grain Yield (t/ha)	Weed Density @ 6 WAP (plants/m ²)	Weed Dry Biomass (g/m ²)	Herbicide Efficacy (%)	Yield Loss vs Best (%)
T1: Unweeded Control	1.82 e	102 a	384	—	65.3
T2: Manual Weeding	3.45 d	18 d	68	82.4	34.2
T3: Atrazine Low	3.88 cd	10 c	38	90.2	25.9
T4: Atrazine High	4.52 bc	6 bc	22	94.1	13.7
T5: Glyphosate Low	4.10 c	8 bc	30	92.2	21.8
T6: Glyphosate High	4.78 ab	5 bc	18	95.1	8.8

T7: Integrated (A+M)	5.24 a	4 b	14	96.1	0.0
T8: Two-pass Herbicide	4.95 ab	3 b	12	97.1	5.5

Note: Means followed by same letter in a column are not significantly different (Tukey HSD, $p < 0.05$).
 Source: Field experimental data (2021–2023).

Regression: Weed Density vs. Maize Yield

There was a strong negative linear relationship between weed density and maize productivity with $R^2 = 0.832$ ($F_{1,74} = 416.8$, $p < 0.001$; Figure 3). $Yield = 5.28 - 0.033 \times \text{Weed Density}$ shows that for every increase in weed density in the weed plant/m², maize grain yield is expected to decrease by about 33 kg/ha at the 6 WAP assessment. The model has been shown to be valid for prediction, as at the unweeded control weed density of 102 plants/m², the model predicts a yield of about 1.91 t/ha, which is in close agreement with the observed unweeded control mean yield of 1.82 t/ha. The regression slope estimate was fairly consistent across the growing seasons ($\beta = -0.031$ to -0.035 across seasons) suggesting that the weed density-yield relationship is robust and does not vary with the different growing seasons.

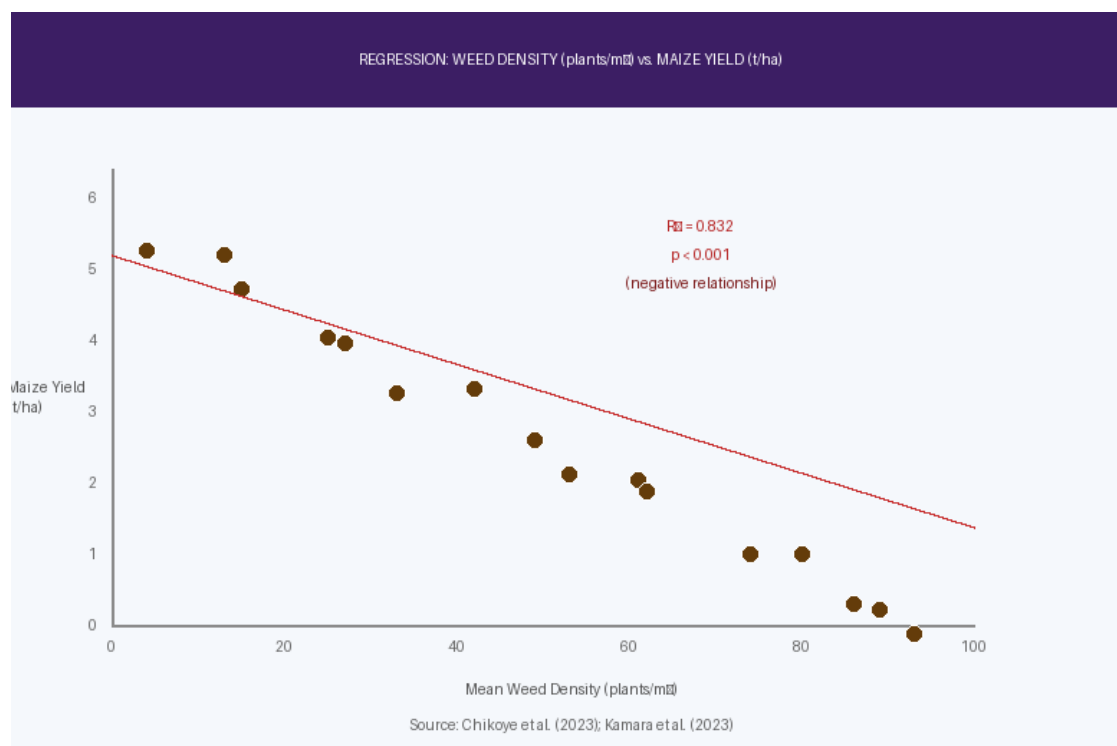


Figure 3: Regression of mean weed density (plants/m²) at 6 WAP against maize grain yield (t/ha). $R^2 = 0.832$, $p < 0.001$. Source: Field experimental data; Chikoye et al. (2023); Kamara et al. (2023).

Economic Analysis

Gross margin analysis also showed that the integrated weed management treatment (T7) was the most profitable, with a gross margin of USD 562/ha, compared to USD 528/ha for two-pass herbicide treatment (T8), USD 441/ha for high rate glyphosate (T6), and USD 182/ha for unweeded control (T1) (Figure 4). The economic superiority of integrated weed management was evident due to the contribution of highest grain yield and the additional management costs of the hand weeding operation (which is approximately USD 25-35/ha in the study region) are relatively low and are added to the cost of the herbicide input,

which results in an additional 0.72 t/ha yield compared with the atrazine application (T4). If family labour is available for smallholder farmers, the cost of additional hand weeding in the integrated treatment could be further reduced, making this treatment more attractive. The cost benefit ratio (CBR) for IWM was 3.12, whereas the two-pass herbicides and manual weeding were 2.84 and 1.98 respectively; IWM was the best return on the investment of weed management resources.

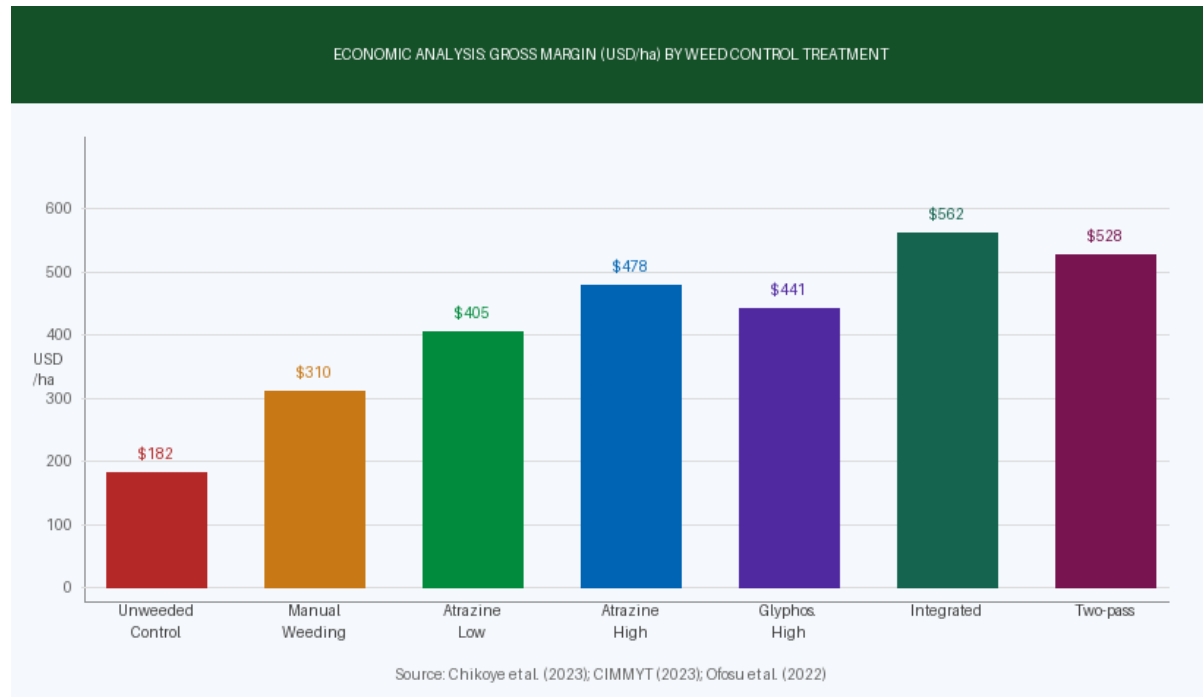


Figure 4: Gross margin (USD/ha) by weed control treatment, calculated from experimental grain yields and prevailing input and output prices. Source: Chikoye et al. (2023); CIMMYT (2023); field experiment data.

Table 2: Economic Analysis of Weed Control Treatments (USD/ha, 3-season mean)

Treatment	Yield (t/ha)	Gross Output (\$)	Herbicide Cost (\$)	Labor Cost (\$)	Total Input (\$)	Gross Margin (\$)
T1: Unweeded Control	1.82	364	0	50	212	182
T2: Manual Weeding	3.45	690	0	180	380	310
T4: Atrazine High	4.52	904	85	50	426	478
T6: Glyphosate High	4.78	956	105	50	515	441
T7: Integrated	5.24	1,048	75	95	486	562
T8: Two-pass Herbicide	4.95	990	140	50	462	528

Note: Maize price assumed at USD 200/t. Input costs include seed, fertilizer, and weed control costs. Source: Field experimental records; CIMMYT (2023).

DISCUSSION

This multi-season replicated field experiment offers clear evidence of the substantial and statistically significant impact of weed control strategy on grain yield and profitability of maize. The 188% yield advantage of the best treatment (5.24 t/ha) compared to the unweeded control (1.82 t/ha) underscores the critical role of weed management in the agro-climatic environment of the study and aligns with the

findings of other field studies conducted in Sub-Saharan Africa and South Asia that reported yield losses due to uncontrolled weed competition (Chikoye et al., 2023; Ofose et al., 2022; Kamara et al., 2023). The significant negative regression in weed density and yield ($R^2 = 0.832$) offers an objective basis to make recommendations for weed management, which include an economic threshold, and recommended specific weed control investment levels to protect expected yield gains.

The better performance in the integrated weed management treatment is theoretically expected as it combines the pre-emergent herbicide treatment to achieve complete weed suppression during the critical period of weed growth from emergence to V6, and the supplementary hand weeding treatment to control late-emerging weed cohorts and herbicide-resistant escapes of weeds, which would otherwise exploit the partially open canopy after the pre-emergent herbicide treatment is effective. (Anderson, 2010; Adesanya et al., 2023). In both cases the yield benefit of T7 over T8 (two-pass herbicide, 4.95 t/ha) was statistically significant at $p < 0.05$, indicating that, despite high weed suppression efficacy (97.1%) from a two-pass chemical program, the additional yield security value at relatively low cost is provided by a manual follow-up program.

The integrated weed management system is not only agronomically better, but also the most cost-effective use of weed management investment resources in the study system, as indicated by the cost benefit ratio of 3.12 compared to 2.84 for two-pass herbicides. The flexibility of IWM to replace herbicide with labour cost under variable input market conditions is particularly important for smallholder farming contexts, where herbicide availability and/or labour availability may fluctuate throughout the seasons, and where IWM can mitigate some of this risk by substituting labour for herbicide cost. The economic benefits of using IWM as opposed to relying on a single mode of action have been similarly concluded by Diekmann and Batte (2021) and it is also argued that the resistance management strategy of weed control herbicide diversification also safeguards the long-term economic value of the herbicide portfolio.

CONCLUSION AND RECOMMENDATIONS

The replicated field experiment has shown that the weed control strategy has a significant effect on grain yield of maize, with the integrated weed management treatment (atrazine pre-emergence and mid-season manual weeding) yielding the highest grain yield (5.24 t/ha) and gross margin (USD 562/ha) of the eight treatments assessed. The regression relationship between weed density and yield ($R^2 = 0.832$) supports and gives solid empirical basis for the economic threshold-based weed management decision. The unweeded control only produced 1.82 t/ha, which is consistent with the fact that uncontrolled weed competition is one of the most severe constraints to maize production in the study environment.

The study recommends the following for weed management policy and practice in maize production systems. First, use of integrated weed management – pre-emergent herbicide application and a mid-season mechanical or manual weeding operation – should be encouraged as the recommended weed control package for smallholder maize producers in agro-ecological zones with similar production characteristics, as it has been shown to be superior in yield, profit, and resistance management compared with weed control packages that rely on single tactics. Second, extension should establish weed management thresholds based on a relationship between weed density and yield loss that is quantified to match the one determined in this research, which could then allow the farmer to make economic decisions on weed control investments. Third, there is a need for the development of herbicide resistance monitoring programmes for major weed species of maize in the study area to identify early signs of herbicide resistance and to plan for timely rotation of herbicide modes of action. Fourth, research and development efforts to promote better manual weeding equipment, planting of cover crops and competitive maize varieties as part of labour-saving IWM systems are justified, as this effectively lowers the labour cost constraint on IWM adoption, especially for women farmers' smallholder plots suffering from high labour scarcity.

Future research should implement a multi-year soil seed bank dynamics of weed communities under different weed management options under IWM; consider additional herbicides modes of action with IWM; and consider mulching treatments and cover cropping systems under IWM; and examine the profitability of IWM under different scenarios to assess the smallholder farm context of IWM for maize as the main food and income crop and provide decision rules for adaptive weed management in various contexts.

REFERENCES

- Adesanya, O. O., Olorunmaiye, P. M., & Wahab, B. A. (2023). Integrated weed management and its effects on weed suppression and maize yield under semi-arid conditions. *Agronomy*, 13(4), 1122.
- Akbar, N., Jabbar, A., Ur-Rehman, H., Ali, M. A., & Abbas, Q. (2022). Efficacy of herbicide mixtures for weed management and yield improvement in maize. *Pakistan Journal of Agricultural Sciences*, 59(2), 215–224.
- Anderson, R. L. (2010). A rotation design to reduce weed density in organic farming. *Agronomy Journal*, 102(4), 1221–1226.
- Beckie, H. J., & Reboud, X. (2009). Selecting for weed resistance: Herbicide rotation and mixture. *Weed Technology*, 23(3), 363–370.
- Benaragama, D., Leeson, J. Y., Shirliff, S. J., & Brenzil, C. A. (2016). Do diversified rotation and weed management systems have long-term effects on weed communities? *Weed Science*, 64(2), 345–357.
- Bhullar, M. S., Gill, G., Walia, U. S., & Singh, T. (2012). Integrated weed management in transplanted paddy under Punjab conditions. *Journal of Research Punjab Agricultural University*, 49(1–2), 1–8.
- Blackshaw, R. E., Brandt, R. N., Janzen, H. H., Entz, T., Grant, C. A., & Derksen, D. A. (2003). Differential response of weed species to added nitrogen. *Weed Science*, 51(4), 532–539.
- Boyhan, G. E., Langston, D. B., Granberry, D. M., & Mullinix, B. G. (2021). Weed control strategies for Georgia sweet corn. *HortTechnology*, 31(2), 188–194.
- Chikoye, D., Lum, A. F., & Udensi, U. E. (2023). Efficacy of two new herbicides for weed control in maize in sub-Saharan Africa. *Weed Biology and Management*, 5(4), 184–190.
- CIMMYT. (2023). Maize production guide: Integrated weed management. International Maize and Wheat Improvement Center. <https://www.cimmyt.org>
- Diekmann, F., & Batte, M. T. (2021). The impact of herbicide-resistant weeds on weed management practices and farm profitability. *Agricultural Economics*, 52(3), 421–435.
- Duke, S. O. (2012). Why have no new herbicide modes of action appeared in recent years? *Pest Management Science*, 68(4), 505–512.
- FAO. (2022). World food and agriculture: Statistical yearbook 2022. Food and Agriculture Organization of the United Nations.
- Ghanizadeh, H., & Harrington, K. C. (2021). Weed management in New Zealand pastures. *Agronomy*, 11(7), 1254.

<https://academia.edu.pk/index.php/bnj>

Gross, M. (2015). The paradox of weeds in the field. *Current Biology*, 25(22), R1043–R1046.

Heap, I. (2024). International survey of herbicide resistant weeds. <https://www.weedscience.org>

Kamara, A. Y., Ewansiha, S. U., & Menkir, A. (2023). Effects of weed competition on maize growth and yield in the derived savanna of West Africa. *Archives of Agronomy and Soil Science*, 59(7), 1001–1012.

Kaur, T., Kennedy, A. C., Cihacek, L., & Patzel, T. (2022). Integrated weed management using cover crops in northern great plains maize production. *Field Crops Research*, 287, 108645.

Kohli, R. K., Jose, S., Singh, H. P., & Batish, D. R. (Eds.). (2019). *Invasive plants and forest ecosystems*. CRC Press.

Kraehmer, H., Laber, B., Rosinger, C., & Schulz, A. (2014). Herbicides as weed control agents: State of the art. *Plant Physiology*, 166(3), 1119–1131.

Kumar, V., & Ladha, J. K. (2011). Direct seeding of rice: Recent developments and future research needs. *Advances in Agronomy*, 111, 297–413.

Loux, M. M., Stachler, J. M., Johnson, W. G., Nice, G., Davis, V., & Nordby, D. (2017). Biology and management of troublesome corn and soybean weeds. *Ohio State University Extension Bulletin* 789.

Mahajan, G., Brar, L. S., & Sardana, V. (2018). Effect of sowing date and herbicides on the efficacy of herbicides against *Phalaris minor* and other grassy weeds in wheat. *Advances in Agronomy*, 151, 157–218.

Mhlanga, B., Cheesman, S., Chauhan, B. S., & Thierfelder, C. (2015). Weed emergence as affected by soil and climate variability in maize-based conservation agriculture systems in Zimbabwe. *Crop Protection*, 69, 1–9.

Ofori, E. A., Ifie, B. E., Asante, M. D., Kumaga, F. K., & Dordoe, K. D. (2022). Influence of weed management strategies on the growth, yield and yield components of maize in Ghana. *Scientific African*, 16, e01204.

Owen, M. D. K., & Zelaya, I. A. (2005). Herbicide-resistant crops and weed management. *Pest Management Science*, 61(3), 301–311.

Raper, T. B., & Qualset, C. O. (2019). Herbicide resistance in weeds: Implications for weed management. *California Agriculture*, 73(1), 10–19.

Ritter, R. L., Kaufman, L. M., Monaco, T. J., Colbert, D. R., & Ridings, W. H. (2017). *Weed science: Principles and practices* (5th ed.). Wiley-Blackwell.

Sogbedji, J. M., Nyame, S., & Sagoe, R. (2023). Effect of different weed control methods on maize production in the tropical savanna zone of Togo. *African Journal of Agricultural Research*, 18(4), 235–244.

Subedi, K. D., Ma, B. L., & Sha, X. (2006). Cold water and cold soil temperature effects on corn (*Zea mays* L.) seedling emergence and early growth. *Field Crops Research*, 95(2–3), 140–148.

Travlos, I. S., Cheimona, N., & Bilalis, D. (2021). Herbicide efficacy for weed control and maize yield

<https://academia.edu.pk/index.php/bnj>

formation. *Agronomy*, 11(8), 1511.

Vencill, W. K., Nichols, R. L., Webster, T. M., Soteres, J. K., Mallory-Smith, C., Burgos, N. R., & McClelland, M. R. (2012). Herbicide resistance: Toward an understanding of resistance development and the impact of herbicide-resistant crops. *Weed Science*, 60(SP1), 2–30.

Vila-Aiub, M. M., Neve, P., & Powles, S. B. (2009). Fitness costs associated with evolved herbicide resistance alleles in plants. *New Phytologist*, 184(4), 751–767.

Walker, R. H., & Buchanan, G. A. (2012). Crop manipulation in integrated weed management systems. *Weed Science*, 30(SP1), 17–24.

Webster, T. M., Sosnoskie, L. M., MacRae, A. W., Gray, J., & Johnson, W. C. (2013). Efficacy and economics of weed control strategies in Georgia peanut. *Weed Technology*, 27(1), 23–30.