

RE: Comparative Evaluation of Carrot Growth and Yield under Zero, Minimum, Mulch, and Double Dig Tillage Systems in Eastern of Rwanda

Manzi Steven^{1*}, Eric Derric Bugenimana², Hussein Bizizmana³, Athanase Mukuralinda⁴, Nzamurambaho Etienne⁵

Rwanda Polytechnic (Rp)-Gishari College, Agricultural Engineering Department, Rwanda

Corresponding Author: stevenmanzi1@gmail.com

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Abstract

Background: Soil degradation, rainfall variability, and pressure to increase productivity create challenges for crop production in Rwanda. Tillage and surface-cover management can modify soil physical conditions, moisture conservation, root-zone development, and crop performance.

Objective: This study evaluated carrot growth and marketable yield under four tillage systems: Zero Tillage (ZT), Minimum Tillage (MT), Mulch Tillage (MuT), and Double-Dig Tillage (DDT) in Eastern Rwanda.

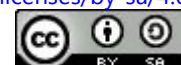
Method: A Randomized Complete Block Design (RCBD) with four replications was used during two growing seasons. Plant height was measured at different growth stages; root depth and marketable yield were assessed at harvest.

Results: At harvest, the plant-height ranking was DDT (39.5 cm) > MuT (36.9 cm) > MT (34.7 cm) > ZT (31.5 cm). MuT had the greatest mean root depth (19.85 cm), but the treatment effect was not statistically significant ($P = 0.0548$). The marketable-yield ranking was MuT (20.21 t ha^{-1}) > DDT (18.75 t ha^{-1}) > MT (16.69 t ha^{-1}) > ZT (14.54 t ha^{-1}); yield means are presented descriptively pending verification of the plot-level records.

Conclusion: MuT appears promising for local validation, but the findings should not be generalized beyond the study conditions. Multi-site, multi-season trials measuring soil moisture, bulk density, penetration resistance, infiltration, and economic returns are recommended.

Keywords: conservation tillage; carrot growth and yield; soil moisture and structure; semi-arid agriculture; sustainable land management

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INTRODUCTION

Agriculture is central to rural livelihoods, employment, and food security, but productivity is increasingly constrained by soil degradation, climate variability, water stress, and declining soil quality. Tillage is one of the management practices through which farmers modify the soil environment available to crops. Depending on its intensity, duration, soil type, and interaction with residue management, tillage can alter soil structure, aggregate stability, penetration resistance, water movement, evaporation, and root-zone conditions (Aziz et al., 2013; Blanco-Canqui, 2020; Nunes et al., 2020). These effects are especially important for root crops such as carrot because the marketable product develops below the soil surface and is sensitive to soil physical conditions.

Reduced or zero tillage is frequently promoted as part of conservation agriculture, particularly when combined with permanent soil cover and crop diversification. However, conservation agriculture should not be treated as a universal yield-enhancing technology. Evidence from sub-Saharan Africa shows substantial variation in crop responses according to rainfall, soil conditions, crop, residue availability, nutrient management, and farmer circumstances (Corbeels et al., 2020; Giller et al., 2009; Thierfelder et al., 2017; Vanlauwe et al., 2014). Importantly, Double-Dig Tillage in the present study is an intensive soil-disturbance practice and is therefore considered separately from reduced-disturbance and mulch-based approaches rather than being classified as conservation-oriented.

These issues are particularly relevant to Rwanda. According to the National Institute of Statistics of Rwanda (NISR), 1.372 million ha approximately 58% of the country's 2.376 million ha land area were used for agriculture in Season A of 2024, while 1.350 million ha were used in Season B. In the same survey, only 7.5% of farmers reported irrigation in Season A, compared with 12.1% in Season B and 58.2% in Season C, whereas 90.6%, 89.2%, and 92.9% reported anti-erosion activities in Seasons A, B, and C, respectively (National Institute of Statistics of Rwanda [NISR], 2024). These figures illustrate the simultaneous importance of soil conservation and limited access to irrigation. Recent Rwanda studies also show that soil-erosion-control adoption, conservation-agriculture adoption, and the sustainability of erosion-control measures vary with biophysical and socioeconomic conditions (Majoro et al., 2023; Murindangabo et al., 2021; Twumasi & Ng'ombe, 2025).

The problem is particularly relevant in Eastern Rwanda, where agricultural production is exposed to seasonal water stress and where maintaining soil moisture can be important for crop establishment and productivity. The present study site is in Gatsibo District in Eastern Province, an area described in the original study as having approximately 800–1,200 mm annual rainfall and predominantly sandy-loam soils. Under such conditions, tillage and surface-cover practices may influence infiltration, evaporation, soil resistance, and the availability of water in the crop root zone. Evidence from semi-arid East Africa indicates that tillage and mulching can affect soil moisture and crop productivity, especially in seasons with below-normal rainfall (Lenga et al., 2024).

Carrot (*Daucus carota* subsp. *sativus*) is an appropriate crop for evaluating these effects because the harvested product is a storage root whose shape, length, and marketability depend partly on the physical environment of the soil. Soil compaction can restrict carrot root development and may contribute to economic losses (Johansen et al., 2015). Mulch can also modify the soil microclimate and has been associated with improved carrot root development and yield in several production environments (Olfati et al., 2008; Rahman et al., 2018; Biswas et al., 2019; Akand et al., 2023). These relationships make carrot useful for testing whether

different combinations of soil disturbance and surface protection produce contrasting growth and marketable-yield responses.

Previous experimental evidence indicates that carrot responses to tillage are strongly context dependent. Agbede, (2021) evaluated tillage combined with biochar, poultry manure, and NPK fertilizer under tropical conditions in Nigeria. Reduced tillage was associated with lower soil bulk density and penetration resistance, higher aggregate stability and soil water content, and approximately 11% higher fresh-root yield than conventional tillage in each of two seasons. These findings suggest that reduced disturbance can improve the soil environment and carrot productivity when supported by appropriate fertility and management. However, the study involved additional soil amendments and therefore does not isolate tillage effects in the same way as the present four-treatment comparison.

Evidence from a long-term European experiment points in a different direction. Van Balen et al. (2023) evaluated ten years of reduced tillage on sandy-loam soil across 13 crops. Overall marketable crop yield was similar between reduced and deep-inversion tillage, but marketable carrot yield was significantly lower under reduced tillage, by 13.4% with sub-soiling and 15.2% without sub-soiling. The authors highlighted seedbed and residue-management effects as possible explanations. The contrast with the Nigerian results demonstrates that reduced tillage should not be assumed to increase carrot yield in all environments.

Taken together, these studies indicate that tillage responses depend on the interaction among soil properties, climate, residue or mulch management, depth and intensity of disturbance, nutrient availability, and crop requirements. Similar caution is warranted in sub-Saharan Africa, where conservation-agriculture yield responses are generally modest on average and vary considerably among environments (Corbeels et al., 2020). The evidence therefore supports location-specific testing rather than transferring recommendations directly from Nigeria, Europe, or other production environments to Rwanda.

Mulch management provides an additional mechanism through which soil conditions may be modified. Surface mulch can reduce direct exposure of soil to solar radiation and rainfall, moderate soil temperature, reduce evaporation, and protect the soil surface. Carrot studies have reported positive responses to organic or other mulch materials, although the magnitude of the response varies with mulch material, nutrient management, irrigation, sowing time, and environment (Olfati et al., 2008; Rahman et al., 2018; Hussen & Muhie, 2025). Long-term studies also show that the effects of tillage and mulch on soil water and yield are dependent on precipitation conditions rather than being uniformly positive (Wang et al., 2026).

Despite the importance of soil and water conservation in Rwanda, experimental evidence directly comparing zero tillage, minimum tillage, mulch tillage, and double-dig tillage for carrot production under Eastern Rwandan conditions remains limited. Rwanda-specific studies have largely focused on conservation-agriculture adoption or erosion-control practices rather than carrot growth and marketable yield under contrasting tillage intensities (Majoro et al., 2023; Murindangabo et al., 2021; Twumasi & Ng'ombe, 2025). The gap is therefore both agronomic and geographic: locally generated evidence is needed on how contrasting levels of soil disturbance and surface mulch affect carrot vegetative growth, root development, and marketable yield under the soil and climatic conditions of Eastern Rwanda.

The novelty of this study is the direct comparison of four contrasting management systems zero tillage, minimum tillage, mulch tillage, and double-dig tillage in a common RCBD experiment for carrot production in Eastern Rwanda. Reduced disturbance is not treated as a single category; instead, different degrees of soil disturbance are distinguished, while surface mulch is represented as a specific management treatment. This design provides a practical

comparison of management options that differ in both soil disturbance and surface protection. The study does not include a separate conventional mouldboard/plough treatment, and no conventional-tillage control should therefore be inferred from the title or abstract.

The study has potential scientific and practical benefits. Scientifically, it provides locally generated evidence on relationships among tillage intensity, carrot vegetative growth, root development, and marketable yield in a semi-arid Rwandan environment. It also identifies measurements needed in future work, including soil moisture, bulk density, penetration resistance, organic matter, infiltration, soil temperature, and economic costs. Practically, the findings can help farmers, extension personnel, and researchers identify candidate soil-management options for local validation rather than relying on universal assumptions about reduced tillage.

The implications extend beyond yield. Mulch-based or reduced-disturbance systems that maintain competitive carrot productivity while protecting the soil surface could complement Rwanda's existing emphasis on erosion control. However, the benefits of a treatment should be evaluated together with labour requirements, mulch availability, soil conditions, and profitability. Evidence from Rwanda indicates that adoption of soil-conservation practices is shaped by farm and institutional conditions as well as environmental vulnerability (Majoro et al., 2023; Twumasi & Ng'ombe, 2025). Thus, agronomic performance alone is insufficient for a final recommendation.

The overall objective of this study was to evaluate the effects of zero tillage, minimum tillage, mulch tillage, and double-dig tillage on carrot growth and marketable yield under the conditions of Eastern Rwanda. Specifically, the study aimed to: (i) describe the effects of the four tillage systems on carrot plant height during crop development; (ii) compare carrot root depth at maturity among tillage treatments; and (iii) compare the reported marketable yield among the four tillage systems. A further objective was to identify the treatment showing the most favourable combination of vegetative growth, root development, and reported marketable productivity under the experimental conditions.

The first hypothesis was that carrot growth and marketable yield would differ among tillage systems because soil disturbance and surface cover can modify the physical and moisture environment of the root zone. The second hypothesis was that mulch tillage would improve root development and marketable yield relative to systems without surface mulch because surface cover can reduce evaporation and moderate soil conditions. These hypotheses were treated as site-specific and were evaluated under the soil, climate, and management conditions of the Eastern Rwanda experimental site.

RESEARCH METHO

Quantitative field experiment was conducted to compare carrot growth and. reported saleable yield under four tillage systems: zero tillage (ZT),. minimal tillage (MT), mulch tillage (MuT), and double dig tillage (DDT). The. experiment used a Randomized Complete Block Design (RCBD) with four treatments. and four replications in four blocks. Each trial plot measured 3 m × 4 m. (12 m²), with 1 m alleys between plots. The experiment covered two growing. seasons: July– October 2025 and November 2025– February 2026.

The study site was. Gakenke Cell, Kiramuruzi Sector, Gatsibo District, Eastern Province, Rwanda, at. roughly 1°47'48.54" S and 30°24'28.00" E and 1,576 m above sea level. The treatments were defined as follows: ZT involved no general soil disturbance; MT involved shallow cultivation; MuT involved light cultivation plus surface mulch; and DDT involved deep soil loosening to approximately 30-40 cm. All other crop-management practices were intended to be applied uniformly across treatments. No soil sampling or laboratory soil-property analysis was reported in the original study; therefore, soil physical and chemical properties are not presented as measured outcomes in this manuscript.

The weighing scale manufacturer and model were not recorded in the submitted methods and should be added from the original field records if available. Plant height was measured in centimeters (cm) from the soil surface at the plant base to the tip of the longest leaf using a measuring tape at 14, 30, 45, 60, and 90 days after establishment. At harvest, representative carrot plants were carefully uprooted and root depth was measured in centimeters from the crown to the tip of the primary root using a measuring tape. For yield determination, marketable carrot roots were hand-harvested at physiological maturity, cleaned to remove adhering soil, graded according to physical condition, and weighed separately from non-marketable roots.

A digital platform weighing scale with a maximum capacity of 300 kg and stated accuracy of 0.01 kg was used. Marketable yield was recorded as kg plot⁻¹ and converted to t ha⁻¹ using the 12 m² plot area. Leaf number was not included as a final response variable because no corresponding leaf-number dataset is reported in the manuscript. Statistical analyses were performed using Microsoft Excel 2021 Data Analysis ToolPak. ANOVA was conducted under RCBD at a 5% significance level. For the present revision, root-depth data were evaluated using the RCBD structure reported in the original analysis, with treatment and block effects assessed at $\alpha = 0.05$.

Tukey's HSD was specified for mean separation only when the overall treatment effect was statistically significant. Root-depth means are reported as mean $\pm$ standard error (SE), and all means share the same letter where the overall treatment effect is non-significant. Yield analysis was not finalized because the reported plot-level observations are internally implausibly similar. The original yield ANOVA is therefore treated as a provisional diagnostic rather than inferential result.

RESULT AND DISCUSSION

Carrot growth parameters including, plant height and root depth at different stages provided insights into physiological responses to soil management practices.

Carrot height

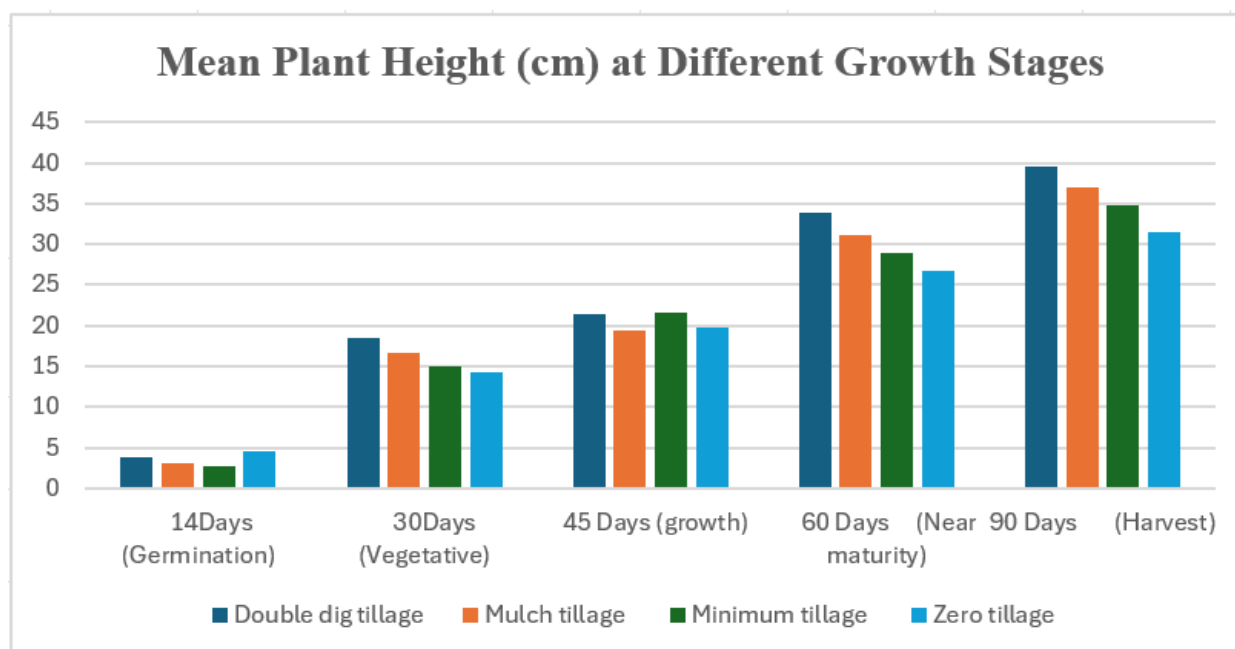
Table 1 presents the reported plant-height values at five developmental stages. Because plot-level replicate data for plant height are not provided in the manuscript, these values are presented descriptively rather than as statistically separated treatment means.

Table 1. Mean Plant Height (cm) at Different Growth Stages

Tillage practice	14Days (Germination)	30Days (Vegetative)	45 Days (growth)	60 Days (Near maturity)	90 Days (Harvest)
Double dig tillage	3.8	18.5	21.5	33.8	39.5
Mulch tillage	3.2	16.7	19.4	31.2	36.9
Minimum tillage	2.8	15.1	21.6	28.9	34.7
Zero tillage	4.5	14.3	19.8	26.7	31.5

At harvest, DDT had the greatest reported plant height (39.5 cm), followed by MuT (36.9 cm), MT (34.7 cm), and ZT (31.5 cm). The greater height under DDT may be consistent with its deeper soil loosening, but the experiment did not directly measure soil compaction, moisture, or nutrient availability; therefore, the proposed mechanism cannot be established from the present data. An important descriptive reversal occurred under ZT: it had the greatest reported height at 14 days (4.5 cm) but the lowest reported height at harvest (31.5 cm). The early advantage therefore was not maintained through crop development.

This pattern is observational and should not be interpreted as evidence of a causal soil mechanism because the relevant soil variables were not measured. MuT showed relatively steady reported growth across the measurement dates, while MT showed an intermediate final height. The possible contribution of mulch to soil-temperature or soil-moisture moderation is supported by previous research, but these variables were not measured in the present experiment; accordingly, the discussion remains explanatory rather than causal (Hussen & Muhie, 2025; Olfati et al., 2008).

**Figure 1.** Plant height under different growth stages

Carrots root depth

The carrot roots measurements were measured at maturity stage using measuring tape. The data are presented in Table 2.

Table 2. Carrot root depth at harvest (mean $\pm$ SE) with mean-separation letters

Statistic	Zero tillage	Minimum tillage	Mulch tillage	Double-dig tillage
Mean $\pm$ SE (cm)	17.93 $\pm$ 0.42	17.73 $\pm$ 0.77	19.85 $\pm$ 0.46	17.54 $\pm$ 0.22
Mean-separation letter	a	a	a	a

Note: Means are based on the four reported replications. Because the treatment effect was not significant at $\alpha = 0.05$ ($P = 0.0548$), all means share the same letter (a).

The reported mean root depth was 17.93 $\pm$ 0.42 cm for ZT, 17.73 $\pm$ 0.77 cm for MT, 19.85 $\pm$ 0.46 cm for MuT, and 17.54 $\pm$ 0.22 cm for DDT. MuT therefore had the greatest descriptive mean, but the treatment effect was not statistically significant at the 5% level ($F = 3.714$, $P = 0.0548$). The observed difference should consequently be described as a near-significant trend rather than as a confirmed treatment effect.

The relatively modest within-treatment variation in the root-depth measurements does not by itself establish that treatment effects are responsible for the observed differences. Possible variation may arise from differences in soil structure, moisture distribution, plant-to-plant variation, or measurement error. The figure below presents the treatment means with their standard errors.

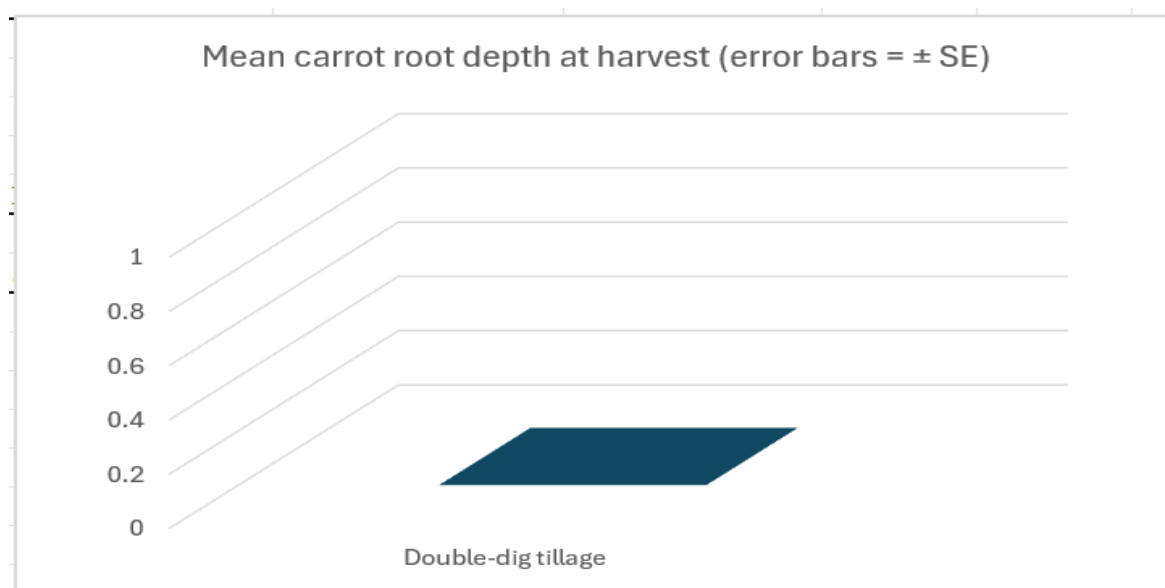
**Figure 2.** Mean carrot root depth at harvest (error bars = $\pm$ SE)

Table 3. Statistical analysis for root depth

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	1.32941875	3	0.44313958	0.35868012	0.78434779	3.86254835
			3	8	3	8
Columns	13.7654187	3	4.58847291	3.71394051	0.05483078	3.86254835
	5		7	2	4	8
Error	11.1192562	9	1.23547291			
	5		7			
Total	26.2140937	15				
	5					

The block effect was not statistically significant ($F = 0.359$, $P = 0.784$). This indicates that the reported block-to-block variation in root depth was small relative to the residual variation in the analysis. It should not, however, be interpreted as proof that the experimental field was completely homogeneous.

For the tillage treatments, the reported treatment effect was not statistically significant at the 5% level ($F = 3.714$; $P = 0.0548$). Because $P > 0.05$, the null hypothesis of equal treatment means is not rejected at the prespecified significance level. The descriptive ranking of root depth should therefore not be presented as statistically confirmed treatment differences.

The P-value of 0.0548 is close to 0.05 and may be described as a borderline or near-significant result. This does not make the result statistically significant at $\alpha = 0.05$. Additional replication or trials under different environmental conditions could determine whether the observed pattern is reproducible.

The residual mean square in the reported root-depth ANOVA was 1.235. Given the treatment P-value of 0.0548, the appropriate interpretation is that the data provide suggestive but insufficient evidence of a treatment effect at the 5% significance level.

Carrot marketable yield

Table 4. Marketable carrot yield (t ha^{-1} ; mean $\pm$ SE)

Statistic	Zero tillage	Minimum tillage	Mulch tillage	Double-dig tillage
Reported mean (t ha^{-1})	14.54	16.69	20.21	18.75
SE / Tukey letter	Pending verification	Pending verification	Pending verification	Pending verification
Reported range (kg plot^{-1})	17.44–17.46	20.02–20.04	24.24–24.26	22.49–22.51
Conversion to t ha^{-1}	$\times 0.8333$	$\times 0.8333$	$\times 0.8333$	$\times 0.8333$

Note. The reported yield means are descriptive only. Standard errors and Tukey mean-separation letters are intentionally withheld because the original plot-level yield records have

not been verified. Final mean $\pm$ SE values and mean-separation letters should be calculated from the genuine independent plot observations after data verification.

The reported marketable-yield means were highest under MuT (20.21 t ha⁻¹), followed by DDT (18.75 t ha⁻¹), MT (16.69 t ha⁻¹), and ZT (14.54 t ha⁻¹). The descriptive ranking was therefore MuT > DDT > MT > ZT. The reported MuT mean was approximately 39.0% higher than the reported ZT mean. Because the four within-treatment replicate values were almost identical, these differences should not currently be interpreted as statistically confirmed treatment effects.

The narrow reported within-treatment ranges (17.44–17.46 kg plot⁻¹ for ZT; 20.02–20.04 kg plot⁻¹ for MT; 24.24–24.26 kg plot⁻¹ for MuT; and 22.49–22.51 kg plot⁻¹ for DDT) produce an exceptionally small residual error term. This is a data-quality warning rather than evidence of unusually stable field yield. The original weighing sheets and data-entry records must be checked to confirm that every value corresponds to an independent plot, that no values were duplicated or rounded before analysis, and that the same yield definition was applied in both seasons.

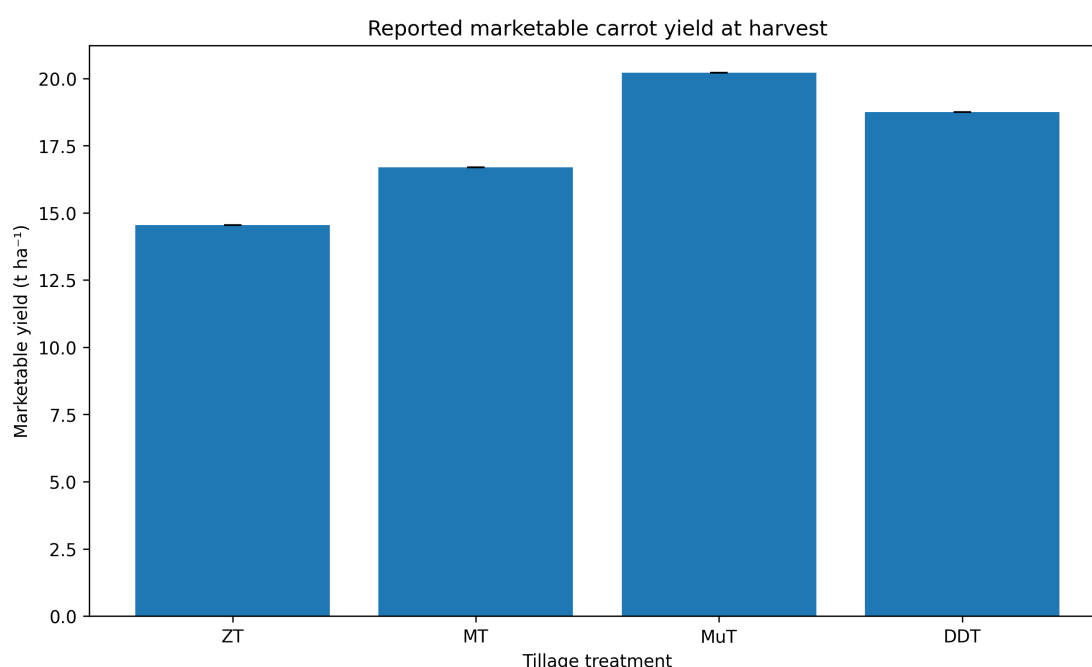


Figure 3. Reported marketable carrot yield at harvest (error bars = $\pm$ SE).

The original yield ANOVA generated an implausibly extreme F-value because the reported replicate values had almost zero within-treatment variance. This diagnostic result is not retained as a valid inferential result in this revision. The yield ANOVA should be rerun from the original independent plot-level observations after verification. Until that step is completed, the manuscript reports the yield ranking only descriptively and makes no claim of statistically significant yield differences.

CONCLUSION

Carrot growth and marketable yield responded differently to the four tillage systems in Eastern Rwanda. At harvest, plant height was greatest under Double-Dig Tillage (39.5 cm),

followed by Mulch Tillage (36.9 cm), Minimum Tillage (34.7 cm), and Zero Tillage (31.5 cm). Mulch Tillage had the greatest mean root depth (19.85 cm), but the treatment effect was not statistically significant. The reported marketable-yield means were highest under Mulch Tillage (20.21 t ha⁻¹), approximately 39% higher than Zero Tillage (14.54 t ha⁻¹), but this comparison is descriptive rather than a statistically verified treatment effect. Subject to verification of the original plot-level records, Mulch Tillage appears promising for local validation. The results support further testing of mulch-based management, while avoiding a universal recommendation until the yield records and statistical analysis have been verified.

ACKNOWLEDGEMENT

An acknowledgement section may be presented after the conclusion, if desired.

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