Soil physical properties and maize productivity under different tillage methods in the Central Highlands of Kenya †

[Propiedades físicas del suelo y productividad del maíz bajo diferentes métodos de labranza en las Tierras Altas Centrales de Kenia]

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SUMMARY

Background. Inappropriate tillage methods are one of the leading causes of land degradation which threatens food security in most sub-Saharan countries, especially given that most agriculture is rain-fed. Thus, production approaches to address this challenge need to be holistic, not only to improve crop production but also to enhance soil health and conserve water sustainably. **Objective.** To evaluate the effects of different tillage methods on soil properties and thus the impact on crop performance using maize as the test crop. **Methodology.** The study was done at the Upper Kabete Campus, University of Nairobi, during the 2021 long and short rainy seasons. The soils at the study site are Humic Nitisols. The trial used a Randomized Complete Block Design (RCBD) with four replicates and four treatments: Disc Ploughing and Harrowing (DPH), Ripping (R), Jab Planting (JP), and Hand-Hoeing (HH). Soil physical properties and crop performance indicators were monitored throughout the seasons. **Results.** Results indicated that tillage significantly ($p<0.05$) influenced soil moisture and grain yields in both seasons. Average moisture levels (%) were 46.91 (R)>31.41 (DPH)>29.60 (JP)>29.55 (HH) during long-rains and 41.59 (R)>28.38 (JP)>28.32 (HH)>26.95 (DPH) during short-rains. Soil surface roughness was significantly affected by tillage during SR, with average values (%) of 3.11 (HH), 2.96 (DPH), 2.13 (R), and 1.68 (JP). Crust strength trends were consistent across seasons, JP>R>DPH>HH, and values ranged from 0.5 to 2.8 MPa. Bulk density (Mg m^{-3}) during SR averaged 1.11 (JP)>1.03 (HH)>1.02 (R)>0.97 (DPH), with tillage significantly influencing the values. Porosity, inversely related to bulk density, average values (%) were 63.45(DPH)>61.61 (R)>61.31 (HH)>58.11 (JP)) in SR. Tillage did not significantly affect saturated hydraulic conductivity. Tillage also had no significant effects on maize height, leaf area, leaf area index, and biomass yields. Average grain yield (Mg/ha) trends during long-rains were 5.69 (R)>5.32 (DPH)>4.19 (JP)>3.96 (HH), and during short-rains, 12.73 (R)>10.04 (DPH)>9.78 (HH)>8.73 (JP). **Implications.** The findings of this study establish that minimum tillage can improve soil quality and crop production. **Conclusion.** Ripping yielded the most positive effects on soil properties and crop yields and is recommended for sustainable soil management and maize productivity in the Central Highlands of Kenya and similar agroecological zones.
Key words: soil health; water conservation; conservation agriculture; crop productivity; small-scale farming

RESUMEN

Antecedentes. Los métodos de labranza inadecuados son una de las principales causas de la degradación del suelo, lo que amenaza la seguridad alimentaria en la mayoría de los países subsaharianos, especialmente dado que la mayor parte de la agricultura es de secano. Por lo tanto, los enfoques de producción adoptados para abordar este desafío deben ser holísticos, no solo para mejorar la producción agrícola, sino también para mejorar la salud del suelo y la conservación del agua de forma sostenible. **Objetivo**. Evaluar los efectos de diferentes métodos de labranza en las

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propiedades del suelo y, por consiguiente, su impacto en el rendimiento del cultivo, utilizando el maíz como cultivo de prueba. **Metodología.** El estudio se realizó en el Campus Upper Kabete de la Universidad de Nairobi, durante las temporadas de lluvias largas y cortas de 2021. Los suelos del sitio de estudio son nitisoles húmicos. El ensayo utilizó un Diseño de Bloques Completos Aleatorizados (DBC) con cuatro réplicas y cuatro tratamientos: Arado y Rastra de Discos (DPH), subsolado (R), Siembra directa (JP) y Escardado Manual (HH). Se monitorearon las propiedades físicas del suelo y los indicadores de rendimiento del cultivo a lo largo de las temporadas. **Resultados.** Los resultados indicaron que la labranza influyó significativamente ($p<0.05$) en la humedad del suelo y el rendimiento de grano en ambas estaciones. Los niveles promedio de humedad (%) fueron 46.91 (R) > 31.41 (DPH) > 29.60 (JP) > 29.55 (HH) durante las lluvias largas y 41.59 (R) > 28.38 (JP) > 28.32 (HH) > 26.95 (DPH) durante las lluvias cortas. La rugosidad de la superficie del suelo se vio afectada significativamente por la labranza durante SR, con valores promedio (%) de 3.11 (HH), 2.96 (DPH), 2.13 (R) y 1.68 (JP). Las tendencias de resistencia de la corteza del suelo fueron consistentes en todas las estaciones: JP > R > DPH > HH, y los valores variaron entre 0.5 y 2.8 MPa. La densidad aparente (Mg m^{-3}) durante SR promedió 1.11 (JP) > 1.03 (HH) > 1.02 (R) > 0.97 (DPH), con la labranza influyendo significativamente en los valores. La porosidad, inversamente relacionada con la densidad aparente, presentó valores promedio (%): 63.45 (DPH) > 61.61 (R) > 61.31 (HH) > 58.11 (JP) en SR. La labranza no afectó significativamente la conductividad hidráulica saturada. La labranza tampoco tuvo efectos significativos en la altura del maíz, el área foliar, el índice de área foliar ni el rendimiento de biomasa. Las tendencias del rendimiento promedio de grano (Mg/ha) durante las lluvias largas fueron 5.69 (R) > 5.32 (DPH) > 4.19 (JP) > 3.96 (HH), y durante las lluvias cortas, 12.73 (R) > 10.04 (DPH) > 9.78 (HH) > 8.73 (JP). **Implicaciones.** Los hallazgos de este estudio indican que la labranza mínima tiene el potencial de mejorar la calidad del suelo y la producción agrícola. **Conclusión.** El desgarramiento tuvo los efectos más positivos en las propiedades del suelo y en el rendimiento agrícola, y se recomienda para la gestión sostenible del suelo y la productividad del maíz en las Tierras Altas Centrales de Kenia y en zonas agroecológicas similares.

Palabras clave: Salud del suelo; Conservación del suelo; Conservación del agua, Agricultura de conservación; productividad de cultivos; Agricultura de pequeña escala.

INTRODUCTION

Agriculture in Sub-Saharan Africa (SSA) is a key driver of socio-economic development, supporting over 60 % of the population (Gashu, Demment and Stoecker, 2019; FAO, 2021). The region's agricultural sector is primarily rain-fed and characterised by small-scale, family-owned farming. The industry faces significant challenges, including land degradation and climate change (Gashu, Demment and Stoecker, 2019; Sakho-Jimbira and Hathie, 2020). Soil degradation is a major concern as it threatens the sustainability of agricultural production, necessitating the adoption of improved land management practices.

Maize is a staple crop in SSA, covering over 40 million hectares of land in the region (Cairns *et al*., 2021). Its production in Kenya occurs across diverse climatic zones, with smallholder farmers contributing approximately 70% of the total output (Kang'ethe *et al*., 2020). Despite the advantages associated with its cultivation, maize production per hectare in Kenya has shown a decline and continues to remain relatively low, estimated at 1,440 kg to 1,836 kg per hectare compared to the global average of 5,751 kg per hectare and an average of 2,070 kg per hectare in Africa (FAOSTAT, 2019; Kang'ethe *et al*., 2020). This diminished productivity is linked to moisture stress, loss of soil fertility and soil degradation (Otieno *et al*., 2019; 2020a). Declining rainfall, coupled with extended drought periods (Otieno *et al*., 2020a; Marenya *et al*., 2022) or delayed rainfall, which are part of the moisture stress, present major challenges for maize production in the country, and this limits crop production in many cropping zones (Kumar *et al*., 2022). Additionally, suboptimal agronomic practices such as poor soil management by farmers further contribute to low productivity (Kipkulei *et al*., 2022). Therefore, the need to investigate ways to improve maize productivity in the face of these challenges cannot be overstated.

Soil and water resources are the most critical constraints in achieving sustainable maize production and soil conservation in Kenya (Munialo *et al*., 2019). Optimizing the use of limited rainfall by improving water use efficiency (Kumar *et al*., 2022) and promoting soil health and water conservation are essential for enhancing crop productivity. Soil and water management factors are integral to crop production, having direct impacts on soil and water resources. One significant factor is tillage, which affects soil properties (Alam *et al*., 2014), as well as crop performance and productivity (Khan, 2019). Inefficient tillage and cultivation are associated with soil degradation and declining agricultural productivity (MoALFC, 2021). The effects of tillage on the soil properties, and hence crop performance, can vary from beneficial to detrimental depending on the tillage method being used and the frequency of tillage operations, soil type, and other management practices (Liu *et al*., 2021).

Traditionally, most farmers have adhered to conventional farming methods without considering the long-term impact. In the Central Highlands of Kenya, smallholder maize farms are characterized by intensive soil use, a common practice in conventional tillage systems (Templer, Lelei and Onwonga, 2017). Due to the limited adoption of sustainable land management practices in Kenya (Birch, 2018), farmers have not widely adopted conservation tillage, despite its potential to address soil degradation (MoALFC, 2021). Additionally, with the reliance on rainfed production, farmers are vulnerable to changing climate patterns, considering the shifts in rainfall patterns in many parts of the world. To improve soil health and sustain crop productivity, it is imperative to encourage efficient tillage methods. Hence, the objective of this study was to evaluate the effects of different tillage methods on soil moisture, surface roughness, crust strength, saturated hydraulic conductivity, bulk density, and porosity, as well as maize height, leaf area, leaf area index, and yields under rainfed conditions in Kabete, Kenya.

MATERIALS AND METHODS

Study site

The study site is located at Upper Kabete Campus Field Station, University of Nairobi. The study site lies at 1°15′S, 36°44′ E with an elevation of 1876 meters above sea level (m.a.s.l.). The site is in agro-climatic Zone III (Sombroek, Braun and Pouw, 1982; Gachene *et al*., 1997), classified as sub-humid (Jaetzold *et al*., 2007) and has a bimodal rainfall pattern; the first season, referred to locally as 'long rains', falls between mid-March and May, while the second season, or 'short rains', falls between mid-October and December. The soils of the study area are well-drained, very deep (> 180 cm), dark red to dark reddish brown, friable clay, and are classified as Humic Nitisols (Gachene *et al*., 1997). The soil and climatic conditions of the area are representative of areas in the Central Highlands of Kenya. The geology of Kabete comprises grey-green porphyritic trachyte that is indistinguishable from the Ruiru Dam trachyte (GSA, 2014).

Field experimentation and design

Land preparation was done before the onset of the rains. As the land had been fallow, the land clearing was first done using machetes and cutlasses, followed by cleaning through raking. Baseline soil data were collected, and laboratory analyses were done using standard methods as outlined by Okalebo *et al*. (2002). Analysis was done for selected chemical and physical properties outlined in Table 1. The soil had medium levels of nitrogen (N), potassium, phosphorus, and organic carbon quantities. The soil had low bulk density, implying possible low resistance to root penetration (Karuku *et al*., 2012).

Table 1. Baseline soil physical and chemical properties of the study site.

Soil property	Values	
	0-20cm	0-40cm
pH	6.43	5.92
%N	0.32	0.31
%O.C	3.13	2.96
Ca (Cmol/kg)	6.6	5.85
Mg (Cmol/kg)	2.62	3.01
K (Cmol/kg)	1.16	1.08
Na (Cmol/kg)	0.25	0.25
P (ppm)	54.6	28.39
Mn (ppm)	79.1	65.7
Zn (ppm)	9.3	11.4
Fe (ppm)	71.2	68.2
Cu (ppm)	1.75	1.52
Bulk density (g/cm^3)	1.08	
Porosity (%)	59.38	
Saturated hydraulic conductivity Ksat (cm/h)	19.41	

The trials were conducted in 2021 during long and short rainy seasons. The treatments were tillage methods, which included: (i) disc ploughing and harrowing (DPH), (ii) ripping (R), (iii) jab planting (JP), and (iv) hand-hoeing (HH, control). The experiment was set up in a randomized complete block design (RCBD) with four replications of each treatment. Sole maize was planted in plots of 25 m^2.

A tractor-drawn disc plough was employed for the plots designated for DPH, facilitating both ploughing and harrowing processes. The disc blade plates had a diameter of 65 cm, enabling the plough to cultivate the soil to a depth of 35 cm. A ripper was utilized during land preparation for the plots designated as R. This tractor-drawn ripper featured two tines that created furrows 30 cm deep and 9 cm wide. Clean slashing was performed for the JP plots, while a hand hoe, commonly referred to as a jembe, was used for the HH plots. Hybrid maize, SC Duma 43 (SC 403), was planted in the two seasons, as it is the maize commonly grown by farmers in the local area. Fertilization was done during planting using Di-ammonium phosphate (DAP, 18:46:0) at a rate of 123.55 kg/ha. Different planting methods were used depending on the tillage treatment: a hand hoe for DPH and HH plots, a jab planter for JP, and machetes for R along the ripped lines. A uniform spacing of 75 cm × 30 cm was maintained across all plots.

For weed management, a pre-emergence herbicide (Primagram Gold 660c: S-metolachlor and Atrazine) was applied to the R and JP plots at a rate of 3 litres/ha after planting. Weeding was done 3 weeks after emergence (WAE) in the first season and 5 WAE in the second season. Hand-hoeing was used for DPH and HH plots, while a cutlass was used for weeding in the R and JP treatments. A post-emergence herbicide (Innovate 240 SC: Nicosulfuron) was applied to the JP and R plots at a rate of 2 litres/ha. Top dressing was done only during the SR 2021 season using CAN at a rate of 60 kg N/ha. Maize was harvested at physiological maturity.

Measurements of selected soil properties

Selected soil properties (moisture, surface roughness, crust strength, saturated hydraulic conductivity, bulk density, and porosity) were monitored at different weeks after planting (WAP). Soil moisture content was monitored from crop emergence to harvesting at depths of 0-20 cm and 20-40 cm. As observed by Karuma *et al*. (2014), most of the active consequences are concentrated at a depth of 0-40 cm; therefore, soil sampling was carried out within this depth, where most of the active maize roots are concentrated. Two random samples were taken from each plot at the two depths, and composite samples were prepared. The disturbed soil samples were subjected to the gravimetric method for moisture analysis (Black, 1995).

Soil surface roughness (SSR) was monitored after tillage operations, before weeding, and at harvest. A relief meter (Kuipers, 1957; Miriti *et al*., 2013) was used to measure soil surface roughness, and the determination was made using Eq. 1. The relief meter was a pinboard consisting of a 1 m by 0.4 m horizontal wooden board with a scale calibrated in centimetres. Attached to the pinboard were 20 perpendicular metallic pins 5 cm apart. The pins were slid down till they touched the soil surface. Three randomly selected samples were taken from each plot. The equation used for the calculation of SSR was as follows:

$$\mathrm{SR}\ (\%) = \mathrm{LOG(STDEV)} \times 100 \quad (1)$$

Where SR is the surface roughness, LOG is the logarithm, and STDEV is the standard deviation of the pin height measurements.

Crust strength was measured at the soil surface of 0-10cm using a handheld penetrometer (Miriti *et al*., 2013; Karuma *et al*., 2014). The type 1B penetrometer (Eijkelkamp equipment) consisted of cones and springs that were adjusted according to the strength of the soil. Ten randomly selected samples were taken per plot, and the average was computed. Cone resistance, which is an indicator of crust strength, was calculated using Eq. 2:

$$\mathrm{CR} = \mathrm{I} \times \frac{\mathrm{Cs}}{\mathrm{AC}} \quad (2)$$

Where CR is the resistance (N cm^{-2}), I is the impression on the scale (cm), Cs is the spring constant (N cm^{-1}), and AC is the area of the cone (cm^2).

Sampling for saturated hydraulic conductivity (K_{sat}), bulk density, and porosity was done at the beginning of the season and harvest. Undisturbed soil samples were collected at two depths 0-20 cm and 20-40 cm. The constant head method (Klute and Dirksen, 1986) was used in the measurement of K_{sat}. Log-transformed K_{sat} values were utilized in the subsequent statistical analysis. Afterwards, the Ksat soil samples were used to analyse bulk density using the core sample method (Blake and Hartge, 1986). Samples were oven-dried at 105 °C overnight and weighed. The weight of dry soil was divided by the soil volume. Porosity was then derived from bulk density in Eq. 3:

$$\mathrm{Porosity}\ (\%) = 1 - \frac{\mathrm{BD}}{\mathrm{PD}} \times 100 \quad (3)$$

Where BD is the soil BD (Mg m^{-3}), and PD is the average particle density (2.65 Mg m^{-3}).

Measurement of crop growth and yield parameters

Several maize parameters were considered to assess crop growth: maize height, leaf area, leaf area index, maize stover, and maize grain yield. Maize height (cm) was measured using a measuring tape, from the base of the plant to the top-most extended leaf, and also to the uppermost part of the tassel once the tasselling process began (Karuma *et al*., 2016). To determine the leaf area, the leaf length and the width at the widest part of the leaf were measured using a measuring tape. The area (Eq. 6) was then multiplied by a factor of 0.75, which is set as the maize calibration factor (Musa and Usman, 2016). The formula used was:

$$\text{Single leaf area} = \mathrm{L} \times \mathrm{W} \times \mathrm{K} \quad (4)$$

Where, L = Leaf length (cm), W = Maximum leaf width (cm), K = Coefficient

To establish the leaf area index (LAI) (Eq. 5), the total leaf area of a plant was taken, divided by the ground area of the plant. The parameters were assessed throughout the growing seasons. Three randomly selected plants per plot were monitored for plant height, leaf area, and leaf area index throughout the season.

$$\mathrm{LAI} = \frac{\text{Leaf area}\ (m^2)}{\text{Ground area}\ (m^2)} \quad (5)$$

Sampling for above-ground biomass (AGB) and grain yield was done from 3 rows by 3 m (4.5 m^2) at the centre of each plot during harvest. The sampled plants were harvested by cutting them at ground level. Maize ears were manually separated from their husks, and samples were weighed in the field. Subsamples for stover were then collected, weighed, and taken to the laboratory for dry weight analysis. The subsamples placed in labelled khaki bags were oven dried to a constant weight at 60 °C for 72 hours (Muigai *et al*., 2021). Dry weight was determined upon drying. Grain yield was determined at a moisture content of 12% and a shelling percentage of 80% (Tandzi and Mutengwa, 2019). Biomass and grain yields were calculated (Eq. 6-8) according to the net experimental plot and later adjusted to metric tons per hectare (tonnes per hectare = Mg ha^{-1}) (Bell and Fischer, 1994):

$$\text{DWS} = \text{DWSS} + \frac{\text{FWS}}{\text{FWSS}} \quad (6)$$

Where DWS = Total dry weight (g), DWSS = Subsample dry weight (g), FWS = total sample fresh weight (g), FWSS = subsample fresh weight (g).

$$\text{TDW} = \frac{\text{DWS}}{\text{A}} \quad (7)$$

Where, TDW = Standing biomass (g) and A = plot area m^{-2}

Grain yield was calculated as follows (Tandzi and Mutengwa, 2019):

$$\text{GY} = \frac{\text{Fwt x } (100 - \text{MC}) \text{ x } 0.8 \text{ x } 10}{100 - \text{adjusted MC x Plot area}} \quad (8)$$

Where GY is grain yield (t/ha), Fwt is fresh ear weight in Kg, MC is the moisture content of grains at harvest, and adjusted MC is adjusted moisture content of 12.5% (Karuma *et al*., 2016; Kebede, 2019) and 0.8 is the shelling coefficient (Tandzi and Mutengwa, 2019).

Statistical analysis

The soil and crop data were analyzed using analysis of variance (ANOVA) using the R statistical software (version 4.2.1, R Core Team, 2023) at the different weeks after planting (WAP). Mean differences were assessed using Tukey's Honestly Significant Difference (Tukey's HSD) test, with statistical significance determined at $p \leq 0.05$.

RESULTS AND DISCUSSION

Effect of tillage methods on soil properties

Soil moisture was significantly affected by tillage and time in both seasons, with significant interactions between tillage and time ($p < 0.001$). Compared to DPH and JP, R resulted in higher soil moisture content by 15.5% and 17.31% during LR 2021; and 14.64% and 13.31% during SR 2021, respectively. The average observed trends in soil moisture were R > DPH > JP > HH during the long rains and R > JP > HH > DPH during the short rains (Figure 1). Significant interactions were also observed between tillage, time, and depth ($p < 0.001$). Soil moisture under R treatment was significantly higher than DPH, JP, and HH across both seasons.

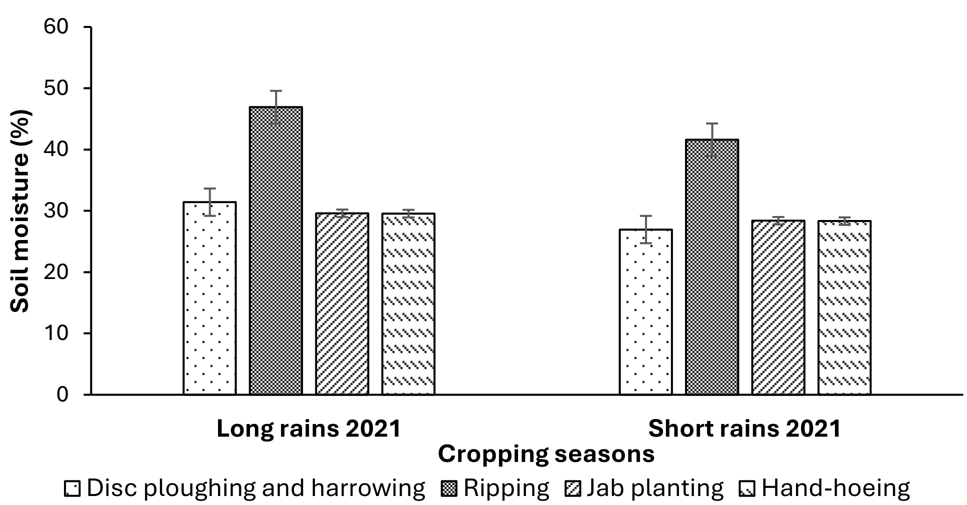

Figure 1. Average soil moisture (%) as affected by tillage during the long rains and short rains of 2021.

The high moisture values under ripping could be attributed to less exposure to evaporation and increased infiltration through the ripped lines, enhancing water storage. This concurs with the study by Zapata *et al*. (2021) who observed higher moisture content in conservation tillage compared to conventional cultivation under soybeans and wheat production. Tillage is a key factor that can lead to the creation of spatiotemporal microclimates induced by the differences in soil moisture (Hatfield and Prueger, 1996; Zapata *et al*., 2021). Similarly, a study by Bekele *et al*. (2022) conducted in Ethiopia for 3 years found that conservation tillage methods were more advantageous in soil moisture conservation. In their study, conservation tillage methods, including one-time tillage, two-time tillage, and no-tillage, had 57%, 46.6%, and 41.1% more soil moisture, respectively, compared to conventional tillage (three-time tillage), due to higher water infiltration. Conservation tillage methods that create slots improve rainwater harvesting and storage. They also reduce evaporation and steam transfer near the soil surface due to thermal insulation provided by crop residues.

While JP exhibited the lowest moisture content relative to R and DPH in the LR 2021 in this study, a study by Omondi (2013) in Rarieda, Western Kenya recorded higher values under no-tillage relative to conventional tillage. The sandy loam texture resulted in higher water losses under conventional tillage through evaporation and deep percolation due to soil disturbance. In a study by Karuma *et al*. (2014) in the Mwala District of Kenya, they observed that ox-ploughing had higher moisture content (14.1%) compared to subsoiling-ripping (13.43%). While both tillage methods improved water penetration into deeper soil layers, ox-ploughing facilitated greater infiltration due to its deeper ploughing depth.

The low moisture content under JP may be a result of limited water infiltration Zero and minimum tillage methods may result in soil compaction in the first years of introduction. This compaction diminishes over time, depending on soil type and its extent of degradation (Rusu *et al*., 2011). The compaction reduces water infiltration, leading to low moisture levels. DPH exhibited variations in soil moisture conservation across the two seasons, recording relatively high values during the long rains and lowest values during the short rains. This could be due to the reapplication of DPH during the short rains, which further enhances soil exposure to evaporative soil moisture losses.

Soil surface roughness (SSR) measurements show that the time of measurement significantly affected the results, while tillage had a significant impact only during SR 2021 ($p < 0.001$). The average observed trend in SSR was DPH > R > HH > JP during the LR 2021, and HH > DPH > R > JP during the SR 2021 (Figure 2). The high values under DPH could be attributed to the high degree of soil disturbance to a depth of 35 cm. da Rocha Junior *et al*. (2016) observed that SSR) increases with tillage methods causing greater soil disturbance. The deeper ploughing depth in the DPH treatment further contributed to higher SSR values (Karuma *et al*., 2014). Consistently, SSR was highest immediately after tillage in both seasons, aligning with findings by da Rocha Junior *et al*. (2016), Karuma *et al*. (2014), and Miriti *et al*. (2013).

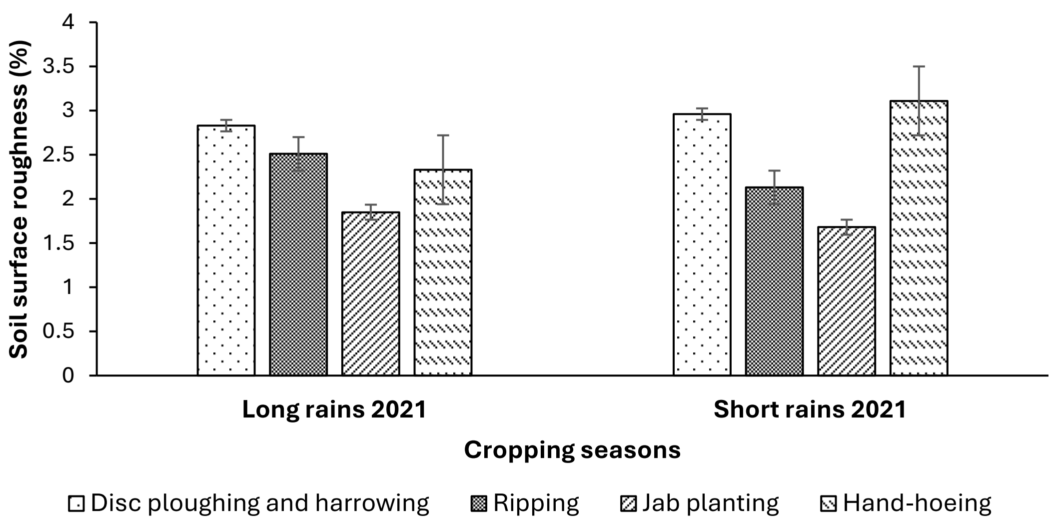

Figure 2. Average soil surface roughness (%) under different tillage methods during the long rains and short rains of 2021.

The jab planter (JP), in contrast, had the lowest SSR values during both the long rains (LR) and short rains (SR) periods of 2021. This low SSR may be attributed to minimal soil disturbance, as only the seed and fertilizer slots were opened during planting. Generally, tilled soils tend to have higher SSR values compared to non-tilled soils because of the disturbance caused by tilling (Adimassu *et al*., 2019; Zhao *et al*., 2014). Conversely, R exhibited higher SSR values compared to JP, likely due to the formation of furrows created by the ripped lines.

The highest decline in SSR was observed under DPH during LR 2021, with a decrease of 2.71%. This may be due to the kinetic energy from raindrops during the rainy season impacting soil micro-elevations and aggregates, leading to decreased SSR, with the most disturbed soils settling in more rapidly (da Rocha Junior *et al*., 2016). During the short rains, however, R had the highest decline of 2.46%, possibly due to the decomposition of crop residues.

Crust strength trends during the LR 2021 and SR 2021 seasons were similar, with tillage effects showing no significant impact ($p < 0.5$). The overall trend in decreasing order was JP > R > DPH > HH at $p < 0.05$ (Figures 3 and 4). The lack of significant tillage effects in this study could be attributed to the short production period of two seasons, as supported by findings from Miriti *et al*. (2013) and Nyambo, Chiduza and Araya, (2022). A short-term study conducted in the Eastern Cape Province of South Africa revealed significant differences in crust strength based on tillage practices. The findings indicated that conventional tillage led to higher crust strength values compared to no-tillage systems, which was attributed to soil crusting (Nebo *et al*., 2020). The differing impacts of tillage on crust strength can be attributed to the specific characteristics of the study sites.

During both the long and short rains, penetration resistance was significantly affected by time ($p < 0.001$) and showed significant interactions between tillage and time ($p < 0.001$ and $p < 0.0464$, respectively). These are likely due to changes and/or the extent of soil disturbance, as well as crop growth and development. At the start of production, primary cultivation weakens the crust's strength. This is followed by the first and second weeding, which further disturbs the soil and affects the crust strength. All tillage methods in this study exhibited the lowest penetration resistance values during both seasons after weeding, due to soil loosening during land preparation combined with weeding. Additionally, Miriti *et al*. (2013) note that tillage methods with hand-hoe weeding tend to have the weakest crust strength, as was the case with DPH and HH in this study.

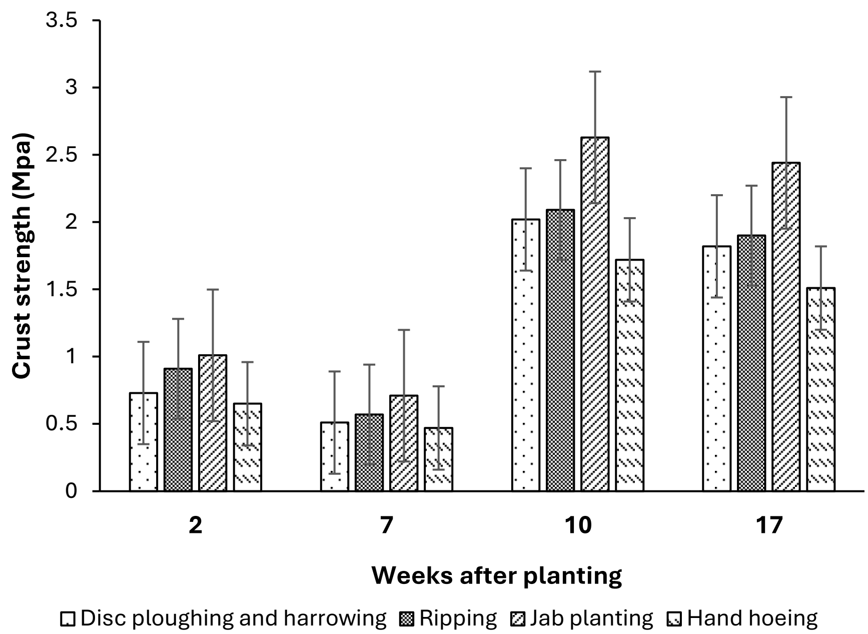

Figure 3. Crust strength (MPa) as influenced by tillage and time of measurement during the long rains of 2021.

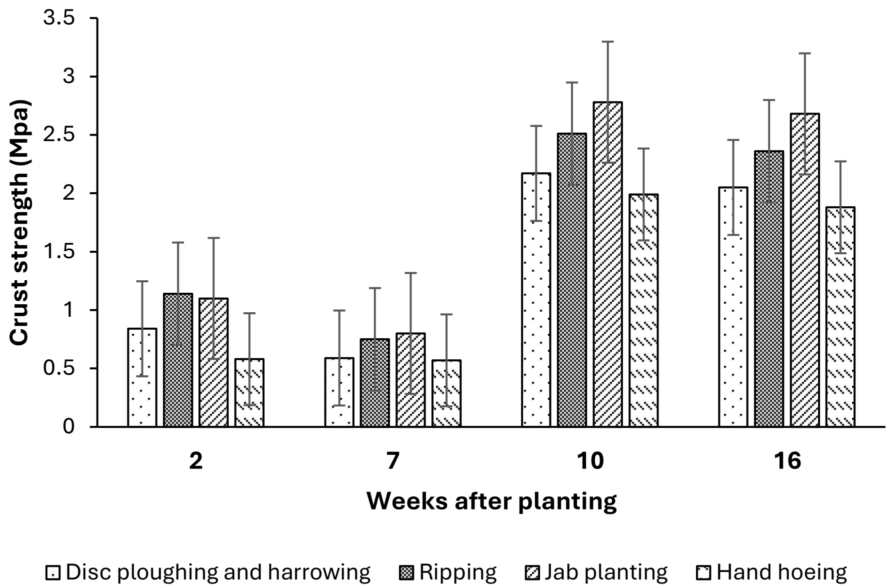

Figure 4. Crust strength (MPa) as influenced by tillage and time of measurement during the short rains of 2021.

Tillage had no significant influence on K_{sat} during the two seasons. This outcome may be attributed to the short study duration, as changes in soil structure and pore distribution often require extended periods to become evident. Studies by Miriti *et al*. (2013) and Nebo *et al*. (2020) also reported negligible effects of tillage on K_{sat} in the short term, suggesting that immediate impacts may be minimal in some soils. Conversely, a short-term study in Mozambique found significant impacts of tillage on Ksat, with lower values under conventional tillage compared to conservation tillage, attributed to the destruction of aggregates and reduction of macroporosity in tilled soils (Chichongue *et al*., 2020). Such variations are not uncommon and may be due to the presence of roots, faunal channels, and stones in the soil (Mwendwa, 2021). Moreover, soil physical properties are affected by multiple factors, including soil type, climate, and machinery in the short term (Nebo *et al*., 2020). Such disparities indicate the need for site-specific studies.

Despite the lack of significant tillage effects, the average trend in K_{sat} (Figure 5) during LR 2021 in decreasing order was R > HH > JP > DPH ($p < 0.05$). Time and the interaction between tillage and time significantly influenced K_{sat}. During SR 2021, the average trend of K_{sat} in decreasing order was DPH > JP > R > HH (Figure 5). K_{sat} was significantly affected by time of measurement and depth ($p < 0.001$). Generally, K_{sat} decreased as the seasons progressed across all tillage methods, with 0-20 cm recording higher values.

The effect of tillage on bulk density (BD) varied across the two seasons, LR 2021 and SR 2021, within the range of 0.85 Mg m^{-3} and 1.14 Mg m^{-3} as shown in Figure 5. During LR 2021, tillage (p=0.3144), time of sampling (p=0.1053), and depth (p=0.3144) did not significantly affect BD. The average trend of BD was JP > DPH > HH > R (Figure 6). The observations indicated significant interactions between tillage*time ($p < 0.001$), tillage*depth (p=0.0388) as well as tillage*time*depth (p=0.0488).

As was the case in Eastern Kenya (Miriti *et al*., 2013), tillage only significantly influenced bulk density (BD) during SR 2021 (p=0.0047), coupled with significant effects of time of measurement and interactions between tillage*time ($p < 0.001$). The average overall trend in BD (Mg m^{-3}) in decreasing order was JP > HH > R > DPH (Figure 6). High bulk density under JP is likely due to the total non-inversion of soil in the treatment, which enhanced soil compaction. A study in El Canós, Spain recorded the highest BD under no-tillage contrary to the minimum and subsoiling (Lampurlanés Castel and Cantero-Martínez, 2003).

The study further noted that BD increases in no-tillage systems after the first years of introduction with no great limitations to root growth and expansion of well-structured soils. Supporting these findings, Chichongue *et al*. (2020) noted that the absence of tillage increases BD through increased soil compaction.

The results indicated variations in total porosity during LR 2021 and SR 2021, ranging from 57% to 68% shown in Figure 7. During LR 2021, tillage (p = 0.3192) had no significant effect on total porosity. The average trend in total porosity (%) was R > HH > DPH > JP. The study indicated significant interactions between tillage*time ($p < 0.001$) and tillage*depth ($p = 0.0373$) that influenced total porosity. During SR 2021, tillage ($p = 0.0049$) and time of measurement ($p < 0.001$) significantly influenced total porosity. The average trend of total porosity (%) established in decreasing order was DPH > R > HH > JP (Figure 7). The observations also indicated a significant interaction between tillage and time ($p < 0.001$).

Porosity is significantly affected by the soil's bulk density (BD), as it is calculated based on the relationship between BD and the particle density of the soil. While agricultural manipulations may not greatly alter the particle density of soil, they can greatly affect the bulk density, thereby changing the porosity of the soil (Karuma *et al*., 2014). Additionally, interactions between soil management, climate, and physical and mineral soil properties influence porosity (Mateo-Marín *et al*., 2021).

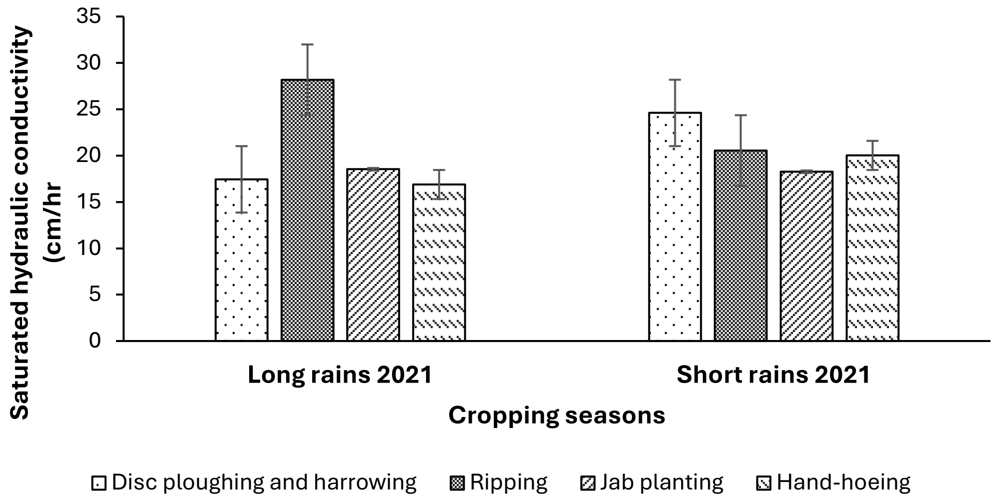

Figure 5. Average saturated hydraulic conductivity (cm/hr) under different tillage methods during the long rains and short rains of 2021.

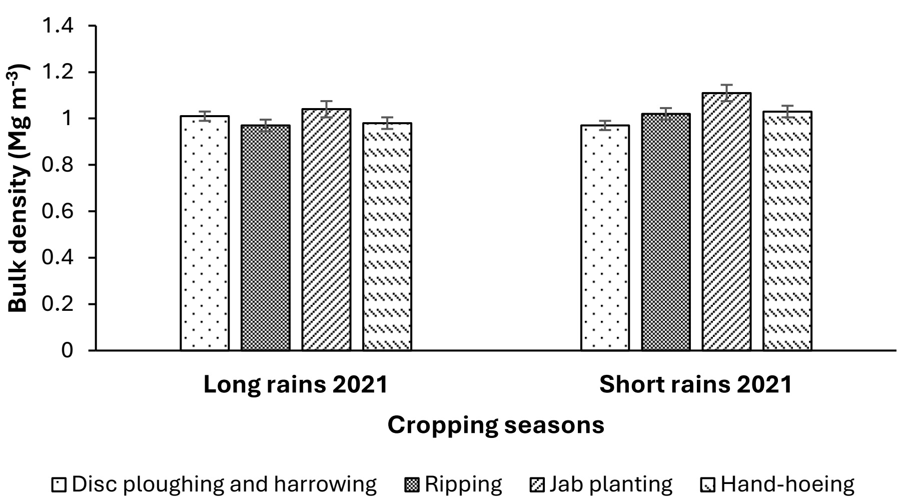

Figure 6. Average soil bulk density (Mg m⁻³) under different tillage methods during the long rains and short rains of 2021.

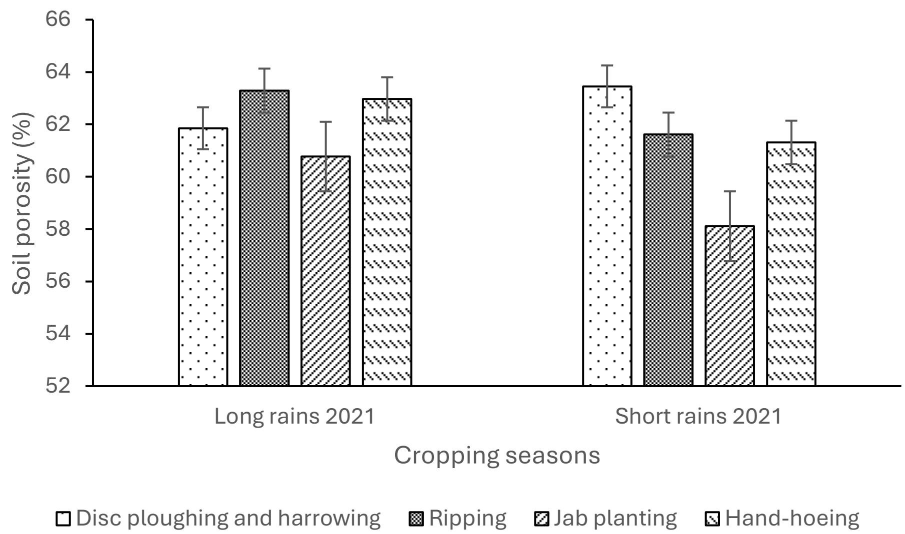

Figure 7. Average soil porosity (%) under different tillage methods during the long rains and short rains of 2021.

Effect of tillage on crop growth and yield parameters

Tillage had no significant effects on the crop height. The average observed trend of the parameter during the LR 2021 in decreasing order was R > DPH > JP > HH (Figure 8); during the SR 2021, the trend was R > DPH > HH > JP (Figure 9). High moisture values under R (LR and SR) and DPH (LR) could have contributed to the observed crop heights. During the SR 2021, the tall plant heights under DPH could be due to low bulk density and high Ksat values, which enhanced water availability for root uptake. The lack of significant effects of tillage on maize height has also been reported in Alupe, Kirinyaga, and Embu areas in Kenya (Otieno *et al*., 2020a). In other studies, Karuma *et al*. (2016) and Mas-Ud *et al*. (2024) have reported tillage significance on maize height, attributed to water conservation as influenced by different tillage methods.

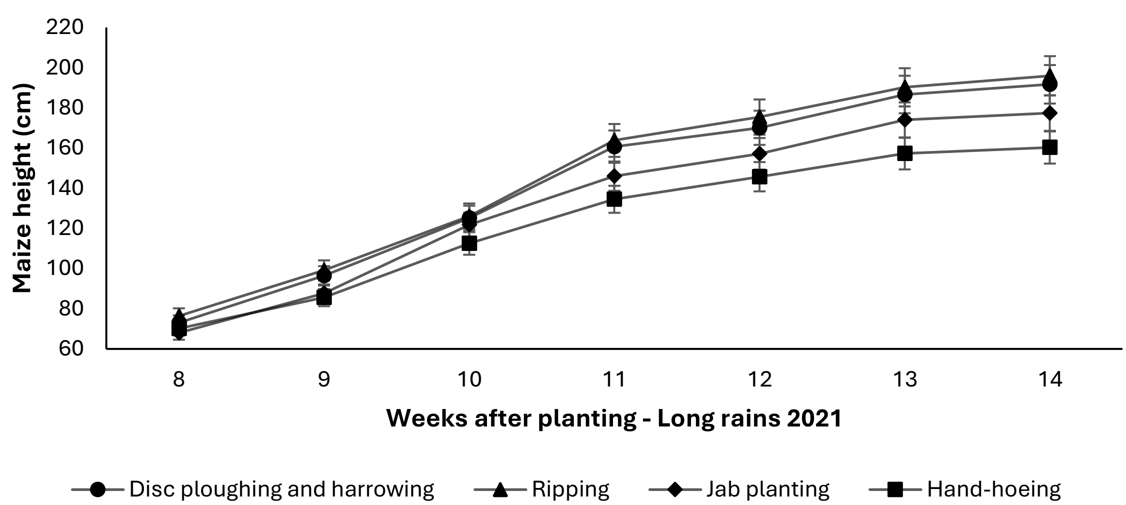

Figure 8. Maize height (cm) as influenced by tillage and time of measurement during the long rains of 2021.

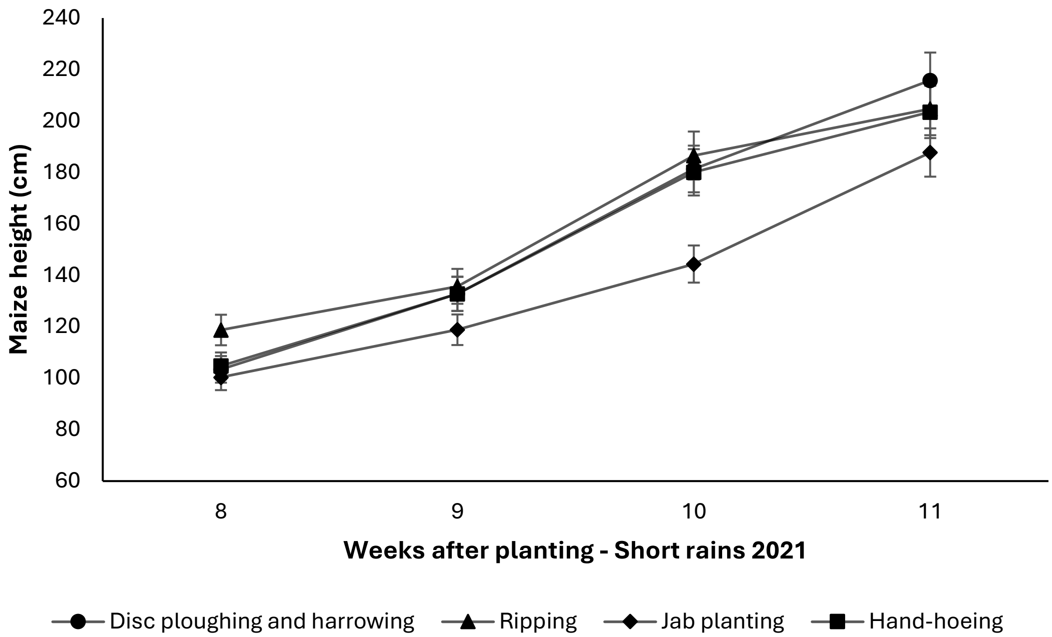

Figure 9. Maize height (cm) as influenced by tillage and time of measurement during the short rains of 2021.

As expected, plant height increased with time, which was a significant factor ($p < 0.001$) in both seasons. Although in most cases crops get taller with time, there are instances where crops may experience stunted growth for various reasons, including nutritional reasons. When all other factors remain constant, time is of the essence as it enables a farmer to keep their records and know when to expect to carry out various agronomic practices, such as first weeding and other activities at different times of the season.

Tillage had no significant effect on LA and LAI, while measurement times ($p < 0.001$) showed significant effects during both the LR 2021 and SR 2021 seasons. These findings may be attributed to seasonal variations during production. The average observed trend for both parameters in the LR 2021 was DPH > JP > HH > R, while in SR 2021, the trend was HH > DPH > R > JP (Figures 10 and 11).

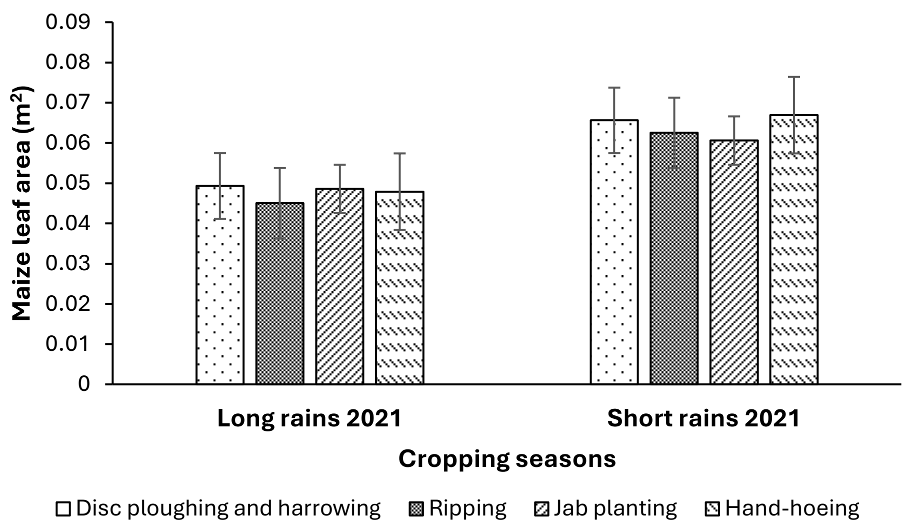

Figure 10. Maize leaf area (m^2) as influenced by tillage during the long and short rains of 2021.

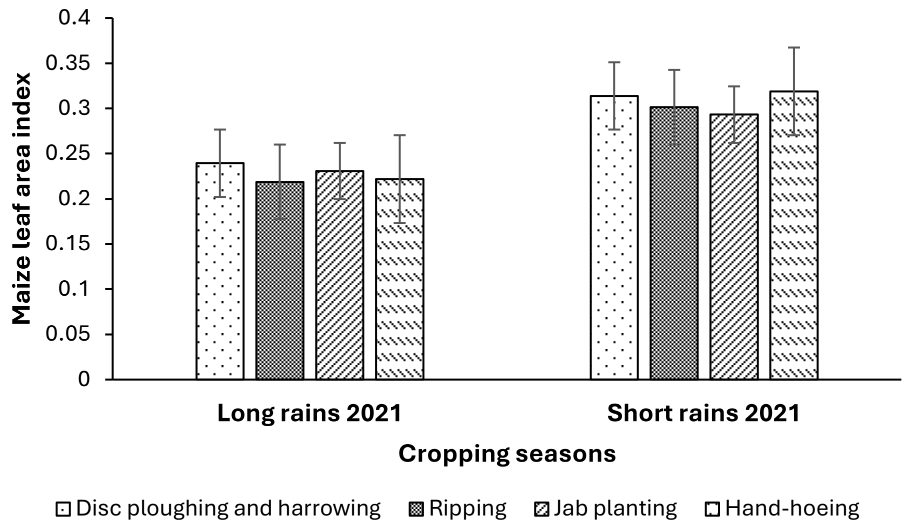

Figure 11. Maize leaf area index as influenced by tillage during the long and short rains of 2021.

The lack of significance of tillage on maize LA or LAI has also been reported in Alupe, Kenya (Otieno *et al*., 2020b), and the Eastern DRC (Zirimwabagabo *et al*., 2022). However, other studies in Eastern Kenya and the Savannah zone in Ghana have shown significant tillage effects, attributed to root spread and the ability to access soil moisture, nutrients, and improve soil aeration (Karuma *et al*., 2016; Mas-Ud, Seidu and Dokurugu, 2024).

Tillage significantly affected maize grain yields, $p < 0.0284$ and $p < 0.01$, during the LR 2021 and SR 2021, respectively. The average observed trend during LR 2021 was R > DPH > JP > HH, whereas in SR 2021, the trend was R > DPH > HH > JP (Figure 12). The high yields under R could be attributed to the high soil moisture content during both seasons. The lowest yields in JP have also been reported in other studies. For example, a study at Jabal al Akhdar in Libya recorded the lowest maize grain yields under zero tillage compared with ridge and conventional tillage methods (Abagandura, Nasr and Moumen, 2017).This was attributed to a lack of loosening of the soil, limiting favourable conditions for crop growth and yields. In this study, while JP had sufficient moisture during the second season, it exhibited high bulk density values, potentially limiting available water capacity, soil porosity, nutrient availability for plant use, and soil microbial activity, which are essential for nutrient release. For this reason, farmers' common practice of HH (9.8 Mg/ha) recorded better yields than JP (8.7 Mg/ha).

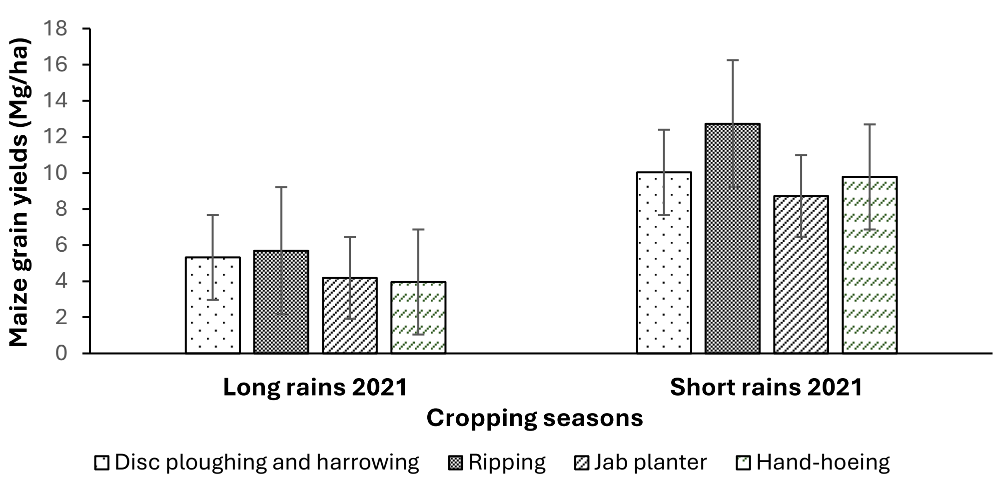

Figure 12. Maize grain yields as influenced by tillage during the long and short rains of 2021.

Maize biomass yields in this study were not significantly affected by tillage: LR 2021 p = 0.1593 and SR 2021 p = 0.7928. The average observed trend of biomass yields according to tillage treatments was R > DPH > JP > HH during the LR 2021 and HH > R > DPH > JP during the SR 2021 (Figure 13). The lack of significant differences in biomass due to tillage could be attributed to factors beyond soil conditions, such as nutrient distribution and crop genotype, which contribute to biomass accumulation. Similar findings were reported in Guinea savanna zone of Ghana (Buah *et al*., 2017). However, other studies, including those by Mas-Ud *et al*. (2024) and Karuma *et al*. (2016) showed significant tillage effects on biomass yields, attributed to changes in soil moisture and nutrient status.

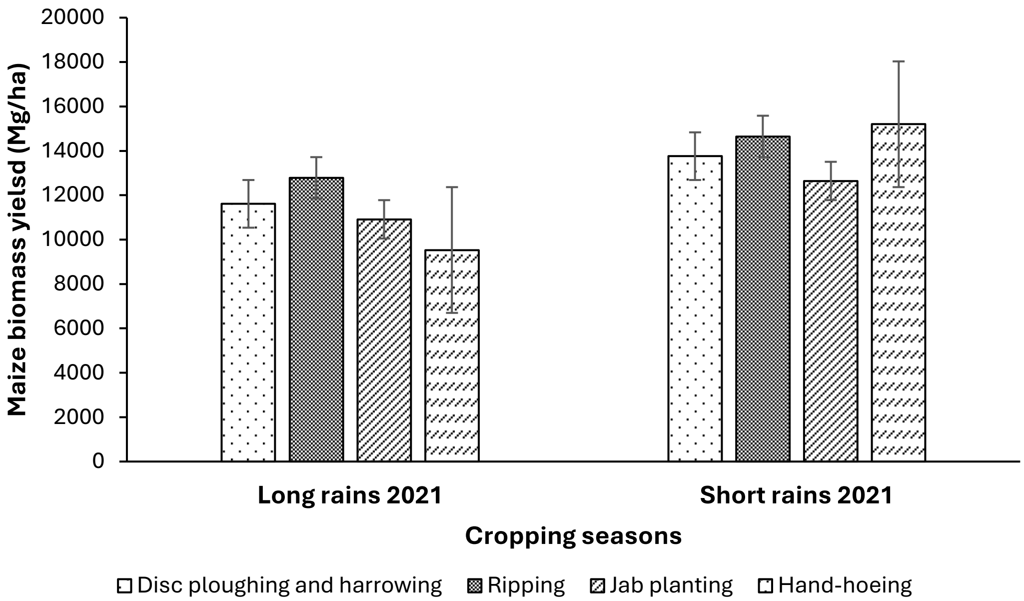

Figure 13. Maize biomass yields as influenced by tillage during the long and short rains of 2021.

CONCLUSIONS

Tillage had a significant impact on soil moisture during both the long and short rainy seasons, with notable effects on SSR and bulk density particularly observed during the short rains. Ripping resulted in the highest soil moisture content. While disc ploughing and harrowing, along with the farmer's common practice of hand, exhibited increased SSR values, they also recorded the lowest moisture levels during the short rains. Jab planting demonstrated the highest bulk density and crust strength values across both seasons.

The tillage methods used only minimally affected crop height, leaf area, and leaf area index. Ripping recorded the plant with the highest height, whereas disc ploughing and harrowing recorded the greatest leaf area and leaf area index throughout the two cropping seasons. Tillage methods also significantly influenced grain yields, with ripping recording the highest yields during both seasons.

Overall, ripping yielded better results in terms of improving soil moisture. Therefore, it is recommended as the preferred method for enhancing soil moisture conservation in the study area. Additionally, it is advisable to evaluate the long-term effects of different tillage methods on soil properties and maize growth.

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Compliance with ethical standards. This research did not require any ethical clearance.

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Author contribution statement (CRediT). T. Nekesa - Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft, Writing - review and editing. **A.N. Karuma** - Methodology, Supervision, Writing - review and editing. **S. Kamau** – Methodology, Writing - review and editing. **C.N. Akello** – Conceptualization, Methodology. **C.K.K. Gachene** - Conceptualization, Methodology, Supervision, Writing - review and editing.

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