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Farming practices and their effect on soil moisture and penetration resistance: Impact on maize yields in rainfed agriculture

Mordecai Mkiza^{1,2} | Monicah Mucheru-Muna¹ | Sylvia Nyawira² |
Dominic Mutambu^{2,3} | Obadiah Mwangi² | Peter Bolo² | Michael Kinyua² |
Job Kihara²

¹Department of Environmental Sciences and Education, Kenyatta University, Nairobi, Kenya

²International Center for Tropical Agriculture (CIAT) c/o International Centre of Insect Physiology and Ecology (ICIPE), Duduville Campus, Nairobi, Kenya

³Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland

Correspondence

Mordecai Mkiza, Department of Environmental Sciences and Education, Kenyatta University, Nairobi, Kenya.
Email: mordecaimkiza@gmail.com

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Abstract

In sub-Saharan Africa, there is growing interest in conservation agriculture practices, including reduced tillage (e.g., ripping), residue retention, and crop diversification, but their effects on soil moisture and penetration resistance in sub-humid regions remain unclear. This study investigated the effect of ripping, residue retention, cropping systems, and fertilizer management on soil moisture, penetration resistance, and maize (*Zea mays* L.) grain yield in a sub-humid zone of western Kenya. The study was conducted in a long-term experiment in western Kenya, using a split-split-split plot design with tillage in the main plot, while residue retention, cropping systems, and fertilizer application were the sub-plots, sub-sub-plots, and sub-sub-sub-plots, respectively. There were nine treatments and four replications. Soil moisture, penetration resistance, and maize grain yield were measured between 2023 and 2024. Residue retention resulted in significantly ($p < 0.001$) higher soil moisture (52.93–55.09 mm) in the 0- to 90-cm soil depth than residue removal (25.98–28.91 mm). Maize–soybean rotation also had significantly higher ($p < 0.001$) soil moisture in the 0- to 90-cm soil depth (41.42–45.08 mm) than the continuous maize (36.29–41.07 mm). The penetration resistance in the wet period ranged between 90 and 320 pounds per square inch (PSI), and between 200 and 492 PSI during the dry period. Ripping resulted in 12% higher maize grain yields than hand digging. Maize–soybean rotation had a higher ($p < 0.001$) maize grain yield (3.93 t/ha) than continuous maize system (1.57 t/ha). Nitrogen application at 90 kg N/ha in a continuous maize and 60 kg N/ha in maize–soybean rotation systems resulted in 118% and 85% higher maize grain yield, respectively, than when no nitrogen was applied. Similarly,

Abbreviations: CA, conservation agriculture; LR, long rain; MSI, maize–soybean intercrop; MSR, maize–soybean rotation; NPK, nitrogen, phosphorous, and potassium; PSI, pounds per square inch; PVC, polyvinyl chloride; SF, scaled frequency; SR, short rain; SSA, sub-Saharan Africa.

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applying phosphorous (60 kg P/ha) and potassium (60 kg K/ha) in maize–soybean rotation increased maize grain yield by 40% more than when potassium (60 kg K/ha) was applied as the only nutrient. Therefore, residue retention and ripping significantly improve soil health by enhancing moisture retention and reducing penetration resistance. Farmers in the sub-humid western Kenya region can increase maize yields by adopting maize–soybean rotation, applying appropriate fertilizers (nitrogen, phosphorous, and potassium, each nutrient applied at the rate of 60 kg/ha), and implementing residue retention and ripping, especially under low rainfall conditions.

Plain Language Summary

Conservation agriculture is used in sub-Saharan Africa to improve soil and crop health but has mixed results in some areas. This study looked at how reduced tillage (ripping), keeping crop residues, crop rotations, and fertilizer use affect soil moisture, compaction, and maize yields in western Kenya. The study found that keeping residues improved soil moisture, while maize–soybean rotation held more moisture and produced better yields than growing maize alone. Ripping reduced soil compaction and increased maize yields, especially during low rainfall. Fertilizer use, like applying nitrogen (up to 90 kg/ha) and balanced nutrients (nitrogen, phosphorous, and potassium at 60 kg/ha each), significantly boosted yields. This study showed that combining residue retention, ripping, crop rotation, and proper fertilizers improved soil health and maize production. Farmers in sub-humid areas can use these practices to grow more maize, especially in dry conditions.

1 | INTRODUCTION

Sustainable agricultural productivity in sub-Saharan Africa (SSA) depends heavily on the maintenance of soil health, particularly soil moisture and penetration resistance (also referred to as compaction). Soil moisture and penetration resistance are key elements of soil physical health that influence plant root growth, nutrient uptake, and agricultural productivity (Nawaz et al., 2013; Niu et al., 2022; Shah et al., 2017). Conservation agriculture (CA) practices such as reduced and no tillage, residue retention, and crop diversification are globally recognized for improving soil structure, enhancing water use efficiency, and building resilience against climate variability (Corbeels et al., 2014; Kihara et al., 2023; Sithole et al., 2016). The extent to which the CA practices improve soil moisture storage while alleviating compaction in sub-humid regions is still not well resolved.

Conservation practices are relevant in SSA, where agriculture is predominantly rainfed and farmers face recurrent challenges of soil degradation, erratic rainfall, and low productivity (Kihara et al., 2023). In this region, low soil moisture is one of the leading constraints to crop growth, causing yield losses of up to 50% (Kiboi et al., 2017; Kogo

et al., 2022; Magombeyi et al., 2018). Compounding the problem are unsustainable practices such as intensive conventional tillage, residue removal, and continuous monocropping, which exacerbate soil degradation by reducing organic matter and disrupting soil structure, causing compaction and increasing surface runoff (Dercon & Gollin, 2014; Munialo et al., 2020).

Research has demonstrated that CA practices can enhance water infiltration and retention, reduce compaction, and improve yields. However, results are mixed. For example, while no tillage conserves soil cover, it has been associated with surface crusting and higher compaction in parts of western Kenya (Kihara et al., 2008). Ripping, introduced as a form of reduced tillage to break hardpans and improve water infiltration (Mafongoya et al., 2016; Mhlanga et al., 2021), has shown some contrasting results on soil moisture content (Mbanyele et al., 2022; Miriti et al., 2012; Serme et al., 2015). Additionally, some studies report substantial maize (*Zea mays* L.) yield benefits, that is, 25%, 40%, 46%, 78%, and 110%, in Kenya, Ethiopia, Tanzania, Uganda, and Zambia, respectively (Mubiru et al., 2017; Rockström et al., 2009), while other studies report insignificant effects compared to using plows, discs, and harrows (Githongo et al., 2021; Kiboi et al., 2019; Mafongoya et al., 2016). These

inconsistencies suggest context-specific responses influenced by, probably, agroecology, management, and timescales of observation.

Beyond tillage, other CA practices also influence soil moisture and penetration resistance. Residue retention reduces soil water evaporation and reduces runoff, thereby holding rainwater on the soil surface to allow infiltration (Kiboi et al., 2017; Ngetich, Diels et al., 2014). Crop rotation enhances porosity through diverse rooting (Blanco-Canqui et al., 2010), and intercropping can improve water utilization (Capowiez et al., 2009; Tran Ba et al., 2016; Yin et al., 2020). Fertilizer application can influence root water uptake and canopy cover (Aluoch et al., 2022; Nwokoro et al., 2022), although its effects are dependent on rate and application time (Magombeyi et al., 2018; Saidia et al., 2019). Apparently, most studies on these interactions are concentrated in arid and semi-arid regions, with limited evidence from sub-humid areas (Kafesu et al., 2018; Kodzwa et al., 2020; Manyiwa & Dikinya, 2014).

Filling the knowledge gap is particularly critical in sub-humid western Kenya, where smallholder farmers face increasing rainfall variability, rising temperatures, and soil degradation. In such environments, understanding how different conservation practices affect soil moisture, compaction, and maize yields is vital for building resilient and productive systems. This work is among the first in sub-humid western Kenya to quantify how ripping influences in-season, multi-depth soil moisture dynamics and penetration resistance and to relate these changes to maize yield across residue, cropping systems, and fertilizer contrasts. Therefore, this study evaluated the effects of ripping, residue, cropping systems, and fertilizer management on soil moisture, penetration resistance, and maize yield to generate evidence that informs site-specific recommendations for conservation practices tailored to sub-humid regions.

2 | MATERIALS AND METHODS

2.1 | Study site

This study was conducted within the cropping seasons that occurred between March 2023 and August 2024, on an existing long-term trial site (CT1) in Nyabeda, Siaya County in Western Kenya. The trial was established in 2003 in one of the moisture-stressed arable areas of Kenya (Okalebo et al., 2007) at 0° 08' N and 34° 25' E and at an altitude of 1320 m above sea level (Table 1). The area receives bimodal rainfall with a mean of between 1200 and 1600 mm in two distinct seasons: long rainy season (March–July) and short rainy (September–December/January). The mean annual temperature is 22.5°C (Kihara et al., 2008). The soils are predominantly Oxidic Ferralsols with a clay texture (Sommer et al., 2018), poor to

Core Ideas

- Conservation agriculture improves soil moisture, nutrient retention, and crop yields.
- Residue retention increases soil moisture significantly compared to residue removal.
- Maize–soybean rotation performs better than continuous maize in retaining moisture and achieving higher yields.
- Ripping reduces compaction and improves maize yields, especially in low-rainfall seasons.
- Balanced nitrogen, phosphorous, and potassium application (60 kg/ha each) in maize–soybean rotations increases yields by 40%.

moderate moisture retention capacity (Bationo et al., 2012), and low fertility (Kihara & Njoroge, 2013).

The key climatic challenges affecting crop production in the area include dry spells, heat stress, and floods (Musafiri et al., 2022). Crop production is mainly subsistence and rain-fed and practiced under conventional tillage, with maize being the staple crop (Bolo et al., 2021). Maize is often cultivated as a monocrop or in association with legumes such as common beans, groundnuts, and soybeans (Ayuke et al., 2019).

2.2 | Experimental design

The trial site was laid out in a randomized complete block design, with split-split-split plots testing 48 management practices and replicated four times. The plots measured 7 × 4.5 m. The main plots consist of two tillage systems (conservation and conventional); the subplot includes crop residue management (with or without maize stovers); sub-subplots consist of three different cropping systems (continuous maize, maize–soybean rotation [MSR], and maize–soybean intercrop [MSI]); while the sub-sub-subplot consists of varying rates of nitrogen and phosphorus fertilizers (Table 2). Ripping was done in the conservation tillage plots before the long rains of the 2023 season, at a depth of 30 cm and a spacing of 75 cm using a tractor.

Nine treatments were selected (Table 2) a priori to test the study hypotheses on the effects of (i) tillage, (ii) residue retention, (iii) cropping system, and (iv) fertilizer rates on soil moisture, penetration resistance, and maize yield. The treatments were chosen to enable predefined, interpretable contrasts. The treatments used ripping (RP) with residue retained (+R) or removed (−R) under different cropping systems, and one treatment used hand digging (H) with residue retained under MSR.

TABLE 1 Climatic and soil (0–30 cm) characteristics of the CT1 trial site in Nyabeda.

Parameter	Characteristic
Climate and weather	Agro-climatic zone
	Sub-humid
	Agro-ecological zone
	Lower midland 2
	Total annual rainfall (mm)
	1200–1600
	Daily temperature (°C)
	Mean
	23.2
	Minimum
	14
	Maximum
	31
Soil characteristics	Soil type
	Oxidic Ferralsol
	Sand:silt: Clay ratio
	15:21:64
	pH (water)
	5.08
	Extractable K (me 100/g)
	0.10
	P (mg P/kg)
	2.99
	Ca (cmolc/kg)
	4.69
	Mg (cmolc/kg)
	1.68
	Total SOC (%)
	1.35
	Total nitrogen (%)
	0.15

Abbreviation: SOC, soil organic carbon.

TABLE 2 Description of treatments selected for soil moisture and compaction study in Nyabeda.

Treatments	Tillage	Residue	Cropping system	N (kg/ha)	P (kg/ha)	K (kg/ha)
RP-R+MSI+K	Ripping	–R	MSI	0	0	60
RP-R+MSR+K	Ripping	–R	MSR	0	0	60
RP+R+MSR+PK	Ripping	+R	MSR	0	60	60
RP+R+MSR+NPK	Ripping	+R	MSR	60	60	60
RP+R+M+90NPK	Ripping	+R	CM	90	60	60
RP+R+M+PK	Ripping	+R	CM	0	60	60
RP+R+MSI+K	Ripping	+R	MSI	0	0	60
RP+R+MSR+K	Ripping	+R	MSR	0	0	60
H+R+MSR+NPK	Hand digging	+R	MSR	60	60	60

Note: Maize was planted at a spacing of 75 × 25 cm, while soybean was planted at a spacing of 75 cm by 5 cm. RP = Ripping, H = Hand digging, –R = without residue, +R = with residue, MSI = maize–soybean intercrop, MSR = maize–soybean rotation, M = continuous maize.

Abbreviation: NPK, nitrogen, phosphorous, and potassium.

The selection enabled the following key contrasts: tillage (RP vs. H under +R, MSR, nitrogen, phosphorous, and potassium [NPK]), residue effects (–R vs. +R under RP for MSI and for MSR at the same fertilizer levels), cropping system effects (MSI vs. MSR under RP, +R at the same fertilizer level), and fertilizer effects within the same tillage/residue/cropping system (e.g., K vs. PK vs. NPK and N rate response in CM).

Maize and soybean variety selection (Table 3) was guided by their adaptability to the seasonal weather variations and tolerance to pest and disease attacks. Nitrogen and phosphorus application rates varied between treatments, while the potassium rate was constant. Nitrogen was applied as urea at rates

of either 90, 60, or 0 kg N/ha (one-third at planting and two-third/3 at top dressing). Phosphorus was applied at a rate of either 60 or 0 kg P/ha as triple superphosphate, and potassium as muriate of potash at a constant rate of 60 kg K/ha, both applied at planting. For residue management, maize stover from the previous season was evenly spread on the surface between the planting rows 2 weeks after sowing.

2.3 | Data collection

Seasonal weather data were recorded using an automatic weather station located 3 km from the experiment site. The

TABLE 3 Season, dates, and the variety of maize and soybean planted during the study period.

Year	Season	Crop	Variety	Planting date	Harvesting date
2023	Long rain	Maize	DK777	Mar. 28, 2023	Aug. 2, 2023
2023	Long rain	Soybean	NamSoy	Mar. 28, 2023	Aug. 2, 2023
2023	Short rain	Maize	Duma	Sept. 11, 2023	Jan. 10, 2024
2023	Short rain	Soybean	NamSoy	Sept. 11, 2023	Jan. 8, 2024
2024	Long rain	Maize	DH04	Apr. 8, 2024	Aug. 3, 2024
2024	Long rain	Soybean	NamSoy	Apr 8, 2024	Aug. 2, 2024

weather station consisted of a rain gauge, solar radiation sensor, wind vane, and anemometer. Data were collected using an automatic multi-channel ZL6 METER data logger from the METER Group (METER Group, n.d.). The rainfall data were categorized by season to examine how rainfall was distributed within each growing period and to capture seasonal variability over time. The classification of the dry spells was based on Ngetich et al. (2014), where n was the number of consecutive days without appreciable rainfall, that is, not >1 mm. The argument here is that with rainfall lower than 1 mm, soil moisture is high at the soil surface but is quickly lost through evaporation (Ceballos et al., 2004). The number of times when dry spells exceeded 5, 10, or 15 consecutive days during the study period was computed and categorized as mild, moderate, and prolonged dry spells, respectively.

Polyvinyl chloride (PVC) pipes measuring 5.08 cm in diameter and 120 cm long were cut to form moisture access tubes. The bottom end of the tubes was tightly sealed by gluing PVC end cups, but the top allowed opening and closing during soil moisture measurement. On May 2, 2023, holes measuring 100 cm deep were drilled in the middle of the plots using a soil auger. On the same day, soil moisture access tubes were installed, using soil-water slurry from the same plot. Soil moisture was monitored using the Diviner 2000 capacitance sensor probe with a portable data logger probe (Sentek Pty Ltd, 1999). This began 2 weeks after installing the moisture access tubes.

Before taking the moisture readings, the Diviner probe was normalized to convert raw counts, corresponding to the actual water content, into scaled frequency (SF) (Sentek Technologies Inc., 2011). To determine SF, the frequencies in air and water were acquired in the laboratory. The probe head was put into the Diviner 200 Normalization tube and then inserted into a 20-L bucket of about three-fourth filled of water and positioned in the middle of the bucket so that the tube was fully surrounded by water. The water count was then recorded by the Diviner 2000 data logger. The tube was dried and then suspended in the air, well away from any solids around it, and then the air count was recorded by the Diviner 2000 data logger. The Diviner probe was used with its default calibration equation (Equation 1) (preprogrammed in the Diviner based on empirical data collected from sand, sandy loam, and organic

potting soils).

$$SF = (F_A - F_S) (F_A - F_W)^{-1} \quad (1)$$

where F_A is the raw count in the access tube while suspended in air, F_S is the raw count reading in the access tube in soil, and F_W is the raw count reading in the access tube in the water.

The following assumptions were made about soil moisture data collection and interpretation of this study:

1. *Relative calibration*: The default calibration was used, which provides relative rather than absolute moisture values. This was deemed sufficient, as the primary objective was to compare moisture gain and loss trends across treatments.
2. *Uniform calibration across treatments*: The same calibration approach was applied across all treatments because of the minimal variation in soil texture and structure at the study site.
3. *Use of PVC pipes*: PVC pipes were used due to their availability. The analysis emphasized treatment contrasts.

Soil penetration resistance was measured twice during both the short rains of 2023 (SR23) and the long rains of 2024 (LR24) using a cone-index soil penetrometer (Eijkelkamp) at 5 cm intervals, up to 45-cm depth. Penetrometer readings (in pounds per square inch [PSI]) were taken at five random points in the intra-row spaces of a net plot measuring 18 m². Measurements represented a dry or wet period if cumulative rainfall in the previous 7 days was lower than 10 mm or higher than 30 mm, respectively. The effect of treatments on penetration resistance was compared against the critical value of 361 PSI, beyond which the resistance can significantly limit root elongation and access to water (Sartori et al., 2022).

Maize was harvested at physiological maturity (≈ 120 days after planting) from a net plot measuring 18 m². The total fresh weight of harvested cobs and weight of five maize cobs (one tall, three medium-sized, and one small) were recorded before grains were separated from the core. In addition, the total stover weight and that of five randomly selected plants (chopped, thoroughly mixed, and sub-sampled) for each net plot were recorded. The grain and stover samples were

TABLE 4 Rainfall characteristics during the study period, including the length of the growing period.

Season	Year	Total rainfall (mm)	Growing period (days)	Frequency of days with dry spell		
				6–10	11–15	>15
LR23	2023	947.55	125	0	1	0
SR23	2023	834.98	118	1	0	0
LR24	2024	608.60	121	5	0	0

Abbreviations: LR, long rain; SR, short rain.

oven-dried at 60°C for 24 h in the laboratory, and dry weights were recorded. Grain and stover yield, in t/ha, were calculated as described by Mupangwa et al. (2007).

2.4 | Statistical analysis

Before conducting statistical analyses, the data were subjected to a normality test using the Shapiro–Wilk test and visualized using histograms. Data were normally distributed and therefore subjected to analysis of variance to detect differences between treatments at $p \leq 0.05$ significance level. Mean differences were separated using Fisher's least significant difference test due to its power in detecting real differences between means. The relationship between soil moisture and maize grain yield was assessed using Pearson's correlation coefficient. A linear mixed-effects model was fitted with moisture as the response variable and fixed effects including tillage, residue management, cropping system, and fertilizer application. The model included random effects for variability due to depth, replicates, and seasons. Random intercepts were included for replication, depth, date, and season to account for the hierarchical structure of the data, recognizing that observations were not entirely independent due to grouping or nesting within certain variables. Effect sizes were calculated to determine whether the factors had a positive (>0) or negative (<0) influence on soil moisture. All analyses were conducted using R statistical software version 4.4.0 (R Core Team, 2024).

3 | RESULTS

3.1 | Rainfall during the study period

The highest total rainfall (947.55 mm) was recorded during the long rains of the 2023 season (LR23) (Table 4). In the short rains of 2023, the recorded rainfall was 834.98 mm (SR23) and 608.6 mm in the long rains of 2024 (LR24) (Table 3). Notably, $>55\%$ of the total rainfall was received between the vegetative and tasselling stages, which is between 30 and 60 days after sowing (DAS). Specifically, the percentages of total rainfall received during this period were 67.2% for

LR23, 59.3% for SR23, and 71% for LR24. Figure 1 shows the variation of daily rainfall in the three seasons. Periods of dry spells were observed toward the end of the seasons, but in the LR24, there were longer dry spells starting from 80 DAS.

There were one and five occurrences of mild dry spells (between 6 and 10 consecutive days with less than 1 mm rainfall) in the SR23 and LR24, respectively. There was one occurrence of a moderate dry spell (dry period lasting between 11 and 15 days) in the LR23 season. Overall, there were no prolonged dry spells (dry periods lasting >15 days) (Table 3).

3.2 | Effect of farming practices on soil moisture

Soil moisture started declining at 20–30 cm (Figure 2). Between 30 and 60 cm, soil moisture had variable trends across treatments, with some showing increases and others decreases (e.g., H-R+MSR+NPK, RP+R+MSR+PK, RP+R+MSR+K). At 70- to 90-cm depth, soil moisture content increased in certain treatments (e.g., RP+R+MSR+PK, RP+R+MSR+NPK, RP+R+MSI+K).

The relationship between rainfall and soil moisture was observed in the LR24 season, which received the least rainfall (Figure 3). The topsoil depth (10–30 cm) was more responsive to rainfall variations. Toward the end of the season, rainfall was ceasing, and there was a decline in total soil moisture between 10 and 30 cm across all treatments.

The differences between treatments were consistent during the study period. In MSR without residue (RP-R+MSR+K), the soil moisture content was consistently the highest of all treatments in LR23 (64.16 mm), SR23 (56.24 mm), and LR24 (56.20 mm) seasons (Table 5). In contrast, the lowest values were observed in the MSI (RP-R+MSI+K) (LR23: 28.91 mm, SR23: 26.68 mm, LR24: 25.98 mm).

Soil moisture in ripping (RP+R+MSR+NPK) was statistically similar to hand digging (H+R+MSR+NPK) across all seasons. Regarding the cropping systems factor, rotation retained an average of 13% higher soil moisture (RP+R+MSR+PK) than continuous maize (RP+R+M+PK). Similarly, MSR (RP-R+MSR+K) retained significantly

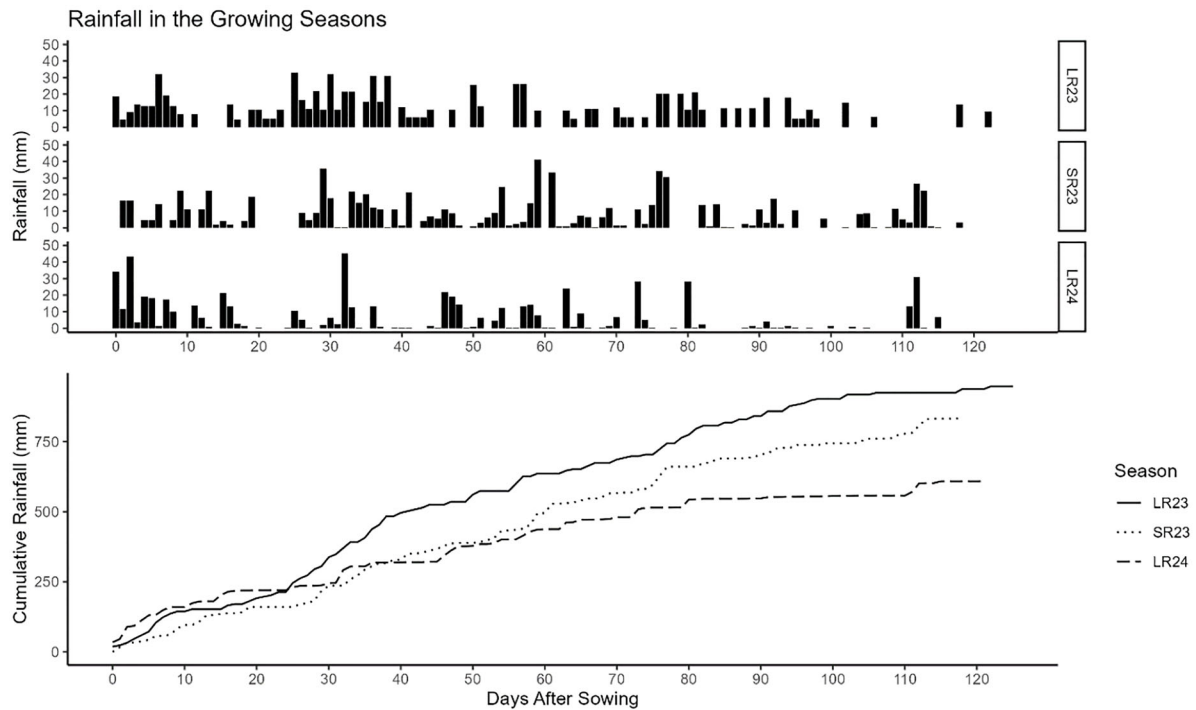


FIGURE 1 Distribution and the daily rainfall received during the study period.

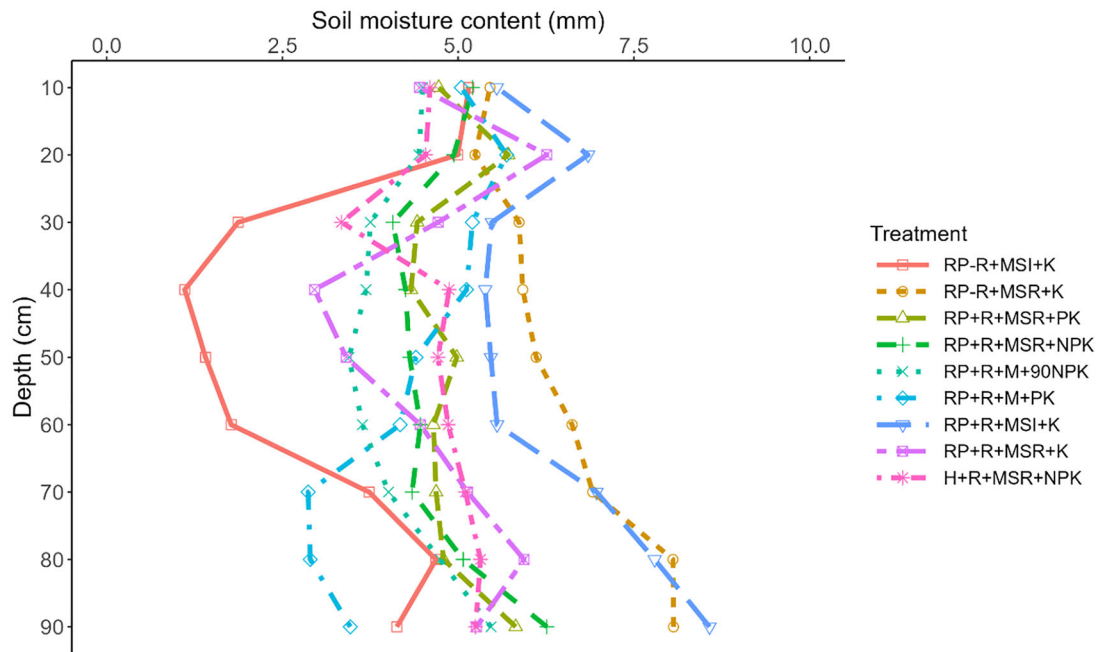


FIGURE 2 Moisture trend down the soil profile. Rp = ripping, H = hand digging, -R = without residue, +R = with residue, MSI = maize–soybean intercrop, MSR = maize soybean rotation, CM = continuous maize, 90NPK = 90 kg N/ha + 60 kg P/ha + 60 kg K/ha, NPK = 60 kg N/ha + 60 kg P/ha + 60 kg K/ha, PK = 0 kg N/ha + 60 kg P/ha + 60 kg K/ha, and K = 0 kg N/ha + 0 kg P/ha + 60 kg K/ha.

($p < 0.001$) higher moisture than MSI (RP-R+MSI+K) throughout the season. In the set of treatments where fertilizer rates were the only contrast, a significant difference was observed in the LR24, where low moisture content

(36.47 mm) was retained following the application of 90 kg N/ha (RP-R+M+90NPK) compared to when no N was applied (RP-R+M+PK). Across the seasons, total soil moisture in the MSI with residue (RP-R+MSI+K) was signifi-

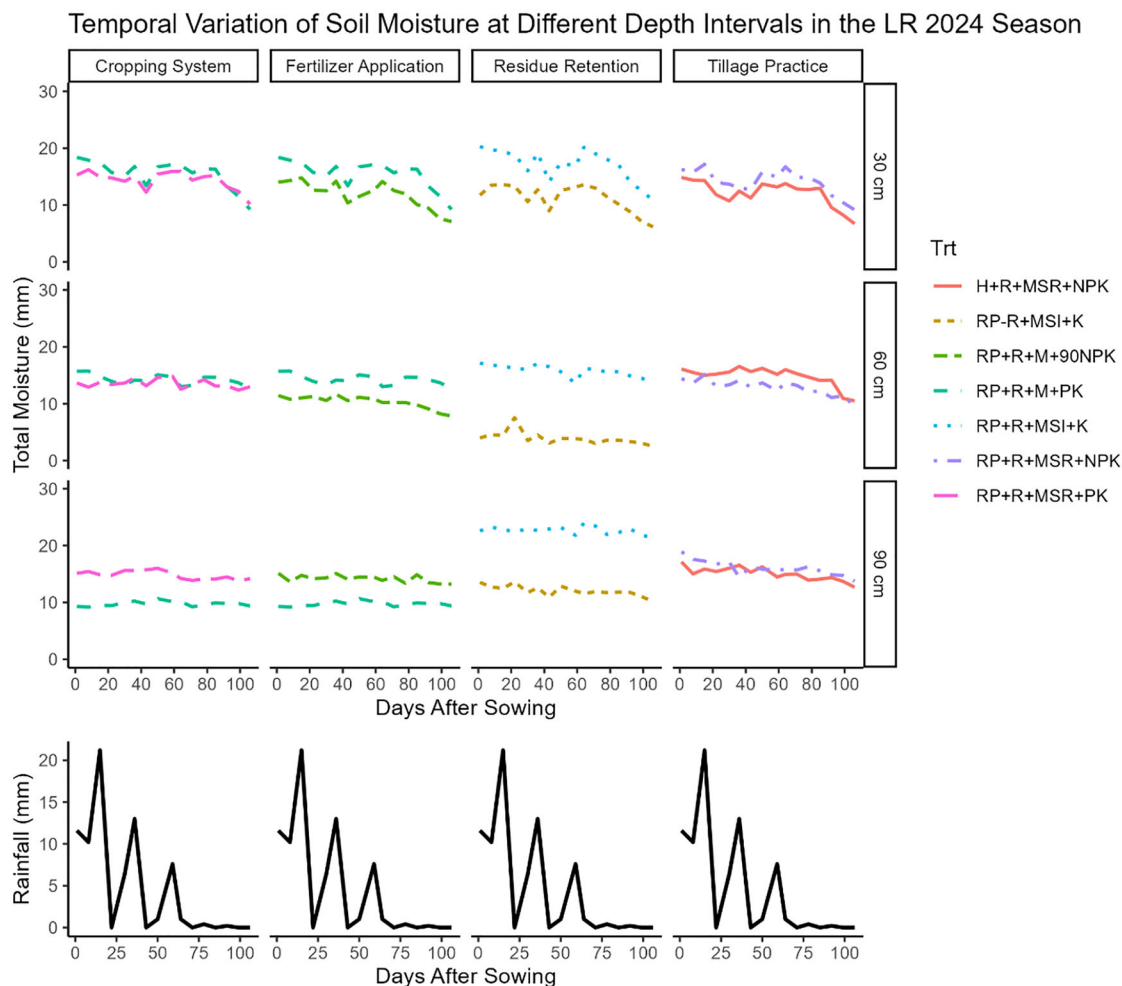


FIGURE 3 The time-series of total soil moisture at 10–30 (30 cm), 40–60 (60 cm), and 70–90 (90 cm) across various treatments during the LR24 season, plotted alongside daily rainfall. Total soil moisture trends for different treatments are depicted using colored lines. Daily rainfall trend during the season is shown using black continuous line at the bottom. RP = ripping, H = hand digging, –R = without residue, +R = with residue, MSI = maize–soybean intercrop, MSR = maize–soybean rotation, M = continuous maize, 90 nitrogen, phosphorous, and potassium (NPK) = 90 kg N/ha + 60 kg P/ha + 60 kg K/ha, NPK = 60 kg N/ha + 60 kg P/ha + 60 kg K/ha, PK = 60 kg P/ha + 60 kg K/ha, and K = 60 kg K/ha.

cantly ($p < 0.001$) higher at 20- to 90-cm depths than when crop residues were removed (RP-R+MSI+K) (Table 6).

Application of residues in the intercrop system (RP+R+MSI+K) resulted in 62.33%, 68.12%, and 68.30% higher total soil moisture in the 0- to 90-cm depth in LR23, SR23, and LR24 seasons, respectively, than residue removal (RP-R+MSI+K) (Table 5). In contrast, application of residue in the MSR system (RP+R+MSR+K) resulted in significantly ($p < 0.001$) lower soil moisture than residue removal (RP-R+MSR+K) at all the depths (Table 5). Removal of residue in the rotation (RP-R+MSR+K) resulted in 34.09%, 37.78%, and 23.66% higher soil moisture in the LR23, SR23, and LR24 seasons, respectively, than residue addition in the rotation (RP+R+MSR+K).

Throughout the study period, MSI (RP-R+MSI+K) had significantly lower soil moisture between the range of 20 and 90 cm than MSR (RP+R+MSR+K) (Table 6). The total

soil moisture content between 0- and 90-cm depth in RP-R+MSI+K was 70% lower than in RP-R+MSR+K. The total soil moisture content in MSR (RP+R+MSR+PK) was significantly higher than in continuous maize (RP+R+M+PK) by 15% in LR23 and 16% in the SR23 and LR24 seasons.

Soil moisture was significantly lower in continuous maize with 90 kg N/ha (RP+R+M+90NPK) than when no N was applied (RP+R+M+PK) at the depth ranges between 20 and 60 cm in the LR23 and SR23 seasons and between 10 and 60 cm in the LR24 (Table 6). At the depth ranges between 60 and 90 cm, soil moisture was significantly higher in RP+R+M+90NPK than in RP+R+M+PK.

The linear mixed effect model showed the summarized effects of the different factors assessed on soil moisture (Figure 4). Ripping had a positive effect on soil moisture compared to hand digging, but at insignificant margins ($p \geq 0.05$). Residue addition had a significantly ($p < 0.001$) positive effect

TABLE 5 Treatment effects on total soil moisture (0–90 cm profile) in each season.

Treatment	Season		
	LR23	SR23	LR24
Soil moisture (mm)			
RP-R+MSI+K	28.91 ^e	26.68 ^e	25.98 ^f
RP-R+MSR+K	64.16 ^a	56.24 ^a	56.20 ^a
RP+R+MSR+PK	47.88 ^c	42.57 ^b	42.73 ^c
RP+R+MSR+NPK	45.08 ^c	41.42 ^b	42.96 ^c
RP+R+M+90NPK	40.10 ^d	36.47 ^d	36.34 ^e
RP+R+M+PK	41.07 ^d	36.29 ^d	39.47 ^d
RP+R+MSI+K	55.09 ^b	54.24 ^a	52.93 ^b
RP+R+MSR+K	45.47 ^c	38.37 ^{cd}	44.31 ^c
H+R+MSR+NPK	46.00 ^c	40.70 ^{bc}	41.92 ^{cd}
<i>p</i> -value	0.001	0.001	0.001
LSD	3.146	2.795	2.756

Note: Means of total soil moisture in mm, separated by Fisher's least significant difference (LSD) at $p \leq 0.05$. Values in the same column followed by the same superscript letters are not significantly different. RP = ripping, H = hand digging, -R = without residue, +R = with residue, MSI = maize–soybean intercrop, MSR = maize–soybean rotation, M = continuous maize, 90 nitrogen, phosphorous, and potassium (NPK) = 90 kg N/ha + 60 kg P/ha + 60 kg K/ha, NPK = 60 kg N/ha + 60 kg P/ha + 60 kg K/ha, PK = 60 kg P/ha + 60 kg K/ha, and K = 60 kg K/ha.

Abbreviations: LR, long rain; SR, short rain.

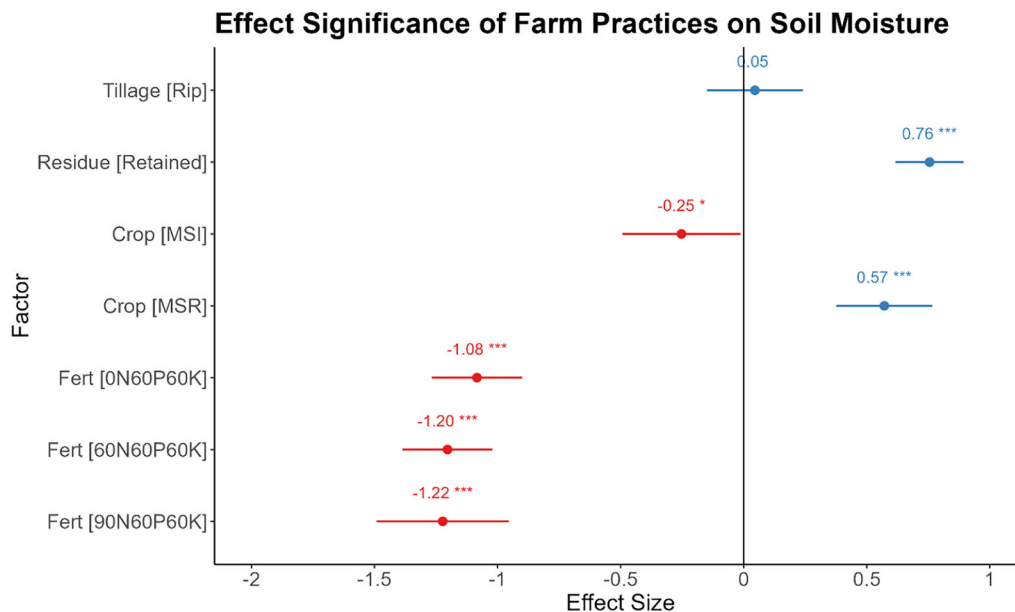


FIGURE 4 Effect of tillage, residue retention, cropping system, and fertilizer application on soil moisture. Crop, cropping system; Fert, fertilizer application; MSI, maize–soybean intercrop; MSR, maize–soybean rotation; Rip, ripping. Values before N, P, and K represent rates of nutrient application rate in kg/ha. When the horizontal line overlaps with the black vertical line at 0 effect size, the factor's effects on soil moisture are not statistically significant ($p \leq 0.05$). Significance levels are indicated with * $p \leq 0.05$ and *** $p \leq 0.001$. The red horizontal line indicates a negative effect, while the blue horizontal line indicates a positive effect.

(+0.76) on soil moisture. MSI had a negative effect (−0.25) on soil moisture content ($p > 0.05$), while the MSR had a positive effect (+0.57) on soil moisture content ($p < 0.001$),

compared to continuous maize. Fertilizer application had a negative effect (ranging between −1.08 and −1.22) on soil moisture content ($p < 0.001$).

TABLE 6 Treatment effects on soil moisture at 10- to 90-cm depths during the study period.

Soil moisture (mm) across the seasons									
LR23									
Depth (cm)									
Treatment	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90
RP+R+MSI+K	5.8 ^{ab}	5.3 ^{de}	1.9 ^e	1.2 ^g	1.6 ^f	1.8 ^g	3.9 ^f	4.9 ^c	4.3 ^f
RP+R+MSR+K	6.6 ^a	5.9 ^{cd}	6.4 ^a	6.4 ^a	6.7 ^a	7.2 ^a	7.5 ^a	8.7 ^a	8.7 ^b
RP+R+MSR+PK	5.4 ^b	6.3 ^{bc}	5.0 ^c	4.6 ^d	5.4 ^c	5.1 ^c	5.0 ^{cd}	5.0 ^c	6.2 ^{cd}
RP+R+MSR+NPK	6.0 ^{ab}	5.3 ^{de}	3.7 ^d	4.7 ^d	4.6 ^d	4.8 ^{cd}	4.6 ^{de}	5.2 ^c	6.4 ^c
RP+R+M+90NPK	5.4 ^b	4.9 ^e	3.9 ^d	4.0 ^e	3.8 ^e	3.9 ^f	4.2 ^{cd}	5.2 ^c	5.8 ^{de}
RP+R+M+PK	5.4 ^b	6.1 ^c	5.6 ^b	5.4 ^{bc}	4.5 ^d	4.4 ^e	3.0 ^g	3.1 ^d	3.6 ^g
RP+R+MSI+K	6.2 ^{ab}	7.2 ^a	5.6 ^b	5.6 ^b	5.8 ^b	5.7 ^b	7.4 ^a	8.3 ^a	9.3 ^a
RP+R+MSR+K	5.3 ^b	6.8 ^{ab}	4.6 ^c	3.3 ^f	3.7 ^e	4.6 ^{de}	5.4 ^{bc}	6.2 ^b	5.6 ^e
H+R+MSR+NPK	5.3 ^b	4.9 ^e	3.4 ^d	5.0 ^c	5.0 ^c	5.0 ^c	5.5 ^b	6.0 ^b	5.8 ^{de}
LSD	0.77	0.86	0.97	0.16	0.34	0.39	0.39	0.27	0.25
<i>p</i> -value	0.035	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
SR23									
RP+R+MSI+K	5.2 ^a	5.0 ^{cd}	1.8 ^f	1.1 ^h	1.4 ^g	1.8 ^f	3.6 ^c	4.5 ^c	3.9 ^e
RP+R+MSR+K	5.1 ^a	6.0 ^d	5.6 ^a	5.8 ^a	6.0 ^a	6.5 ^a	6.8 ^a	7.9 ^a	7.9 ^b
RP+R+MSR+PK	4.4 ^c	5.4 ^{bc}	4.2 ^c	4.1 ^{de}	4.9 ^c	4.5 ^c	4.6 ^{cd}	4.7 ^c	5.7 ^c
RP+R+MSR+NPK	5.2 ^a	4.8 ^{de}	4.0 ^{cd}	4.1 ^e	4.2 ^{de}	4.3 ^{cd}	4.2 ^d	4.7 ^c	6.0 ^c
RP+R+M+90NPK	4.5 ^{bc}	4.3 ^f	3.7 ^d	3.6 ^f	3.3 ^f	3.5 ^c	3.7 ^e	4.7 ^c	5.2 ^d
RP+R+M+PK	5.0 ^{ab}	5.6 ^b	4.9 ^b	4.8 ^c	3.9 ^e	3.9 ^{de}	2.5 ^f	2.6 ^d	3.1 ^f
RP+R+MSI+K	5.6 ^a	6.9 ^a	5.4 ^a	5.4 ^b	5.6 ^b	5.5 ^b	6.9 ^a	7.7 ^a	8.3 ^a

(Continues)

TABLE 6 (Continued)

Soil moisture (mm) across the seasons										
LR23										
Depth (cm)										
Treatment	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	
RP+R+MSR+K	4.1 ^c	5.6 ^b	3.9 ^d	2.6 ^g	3.1 ^f	4.2 ^{cd}	4.6 ^{bc}	5.3 ^b	5.0 ^d	
H+R+MSR+NPK	4.5 ^{bc}	4.4 ^{ef}	3.2 ^e	4.5 ^{cd}	4.4 ^d	4.6 ^c	4.9 ^b	5.1 ^b	5.0 ^d	
LSD	0.58	0.44	0.33	0.37	0.38	0.41	0.36	0.35	0.36	
<i>p</i> -value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
LR24										
RP+R+MSI+K	4.8	4.7 ^{cde}	1.8 ^e	1.0 ^f	1.2 ^f	1.6 ^g	3.6 ^f	4.4 ^f	4.0 ^f	
RP+R+MSR+K	5.0	5.1 ^{bc}	5.8 ^a	5.7 ^a	5.9 ^a	6.4 ^a	6.7 ^a	7.8 ^a	7.8 ^b	
RP+R+MSR+PK	5.6	5.6 ^b	4.2 ^c	4.3 ^c	4.8 ^c	4.5 ^{de}	4.6 ^d	4.6 ^f	5.6 ^d	
RP+R+MSR+NPK	4.7	4.9 ^{cd}	4.5 ^c	4.2 ^c	4.3 ^d	4.4 ^{de}	4.3 ^{de}	5.4 ^d	6.4 ^c	
RP+R+M+90NPK	3.9	4.3 ^e	3.7 ^d	3.5 ^d	3.3 ^e	3.5 ^f	4.2 ^e	4.5 ^f	5.5 ^d	
RP+R+M+PK	4.8	5.5 ^b	5.2 ^b	5.2 ^b	4.8 ^c	4.3 ^e	3.1 ^g	3.0 ^g	3.7 ^g	
RP+R+MSI+K	5.1	6.5 ^a	5.5 ^{ab}	5.2 ^b	5.1 ^b	5.4 ^b	6.8 ^a	7.5 ^b	8.4 ^a	
RP+R+MSR+K	4.2	6.5 ^a	5.5 ^{ab}	3.1 ^e	3.5 ^e	4.6 ^d	5.4 ^b	6.3 ^c	5.2 ^e	
H+R+MSR+NPK	4.2	4.4 ^{de}	3.4 ^d	5.1 ^b	4.8 ^c	5.0 ^c	5.0 ^c	5.0 ^e	5.0 ^e	
LSD	0.83	0.57	0.36	0.33	0.31	0.28	0.29	0.24	0.22	
<i>p</i> -value	0.074	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	

Note: Means of soil moisture in mm, separated by Fisher's LSD at $p \leq 0.05$. Values in the same column followed by the same superscript letters are not significantly different. RP = ripping, H = hand digging, –R = without residue, +R = with residue, MSI = maize–soybean intercrop, MSR = maize–soybean rotation, M = continuous maize, 90 nitrogen, phosphorous, and potassium (NPK) = 90 kg N/ha + 60 kg P/ha + 60 kg K/ha, NPK = 60 kg N/ha + 60 kg P/ha + 60 kg K/ha, PK = 0 kg N/ha + 60 kg P/ha + 60 kg K/ha, and K = 0 kg N/ha + 0 kg P/ha + 60 kg K/ha.

Abbreviations: LR, long rain; LSD, least significant difference; SR, short rain.

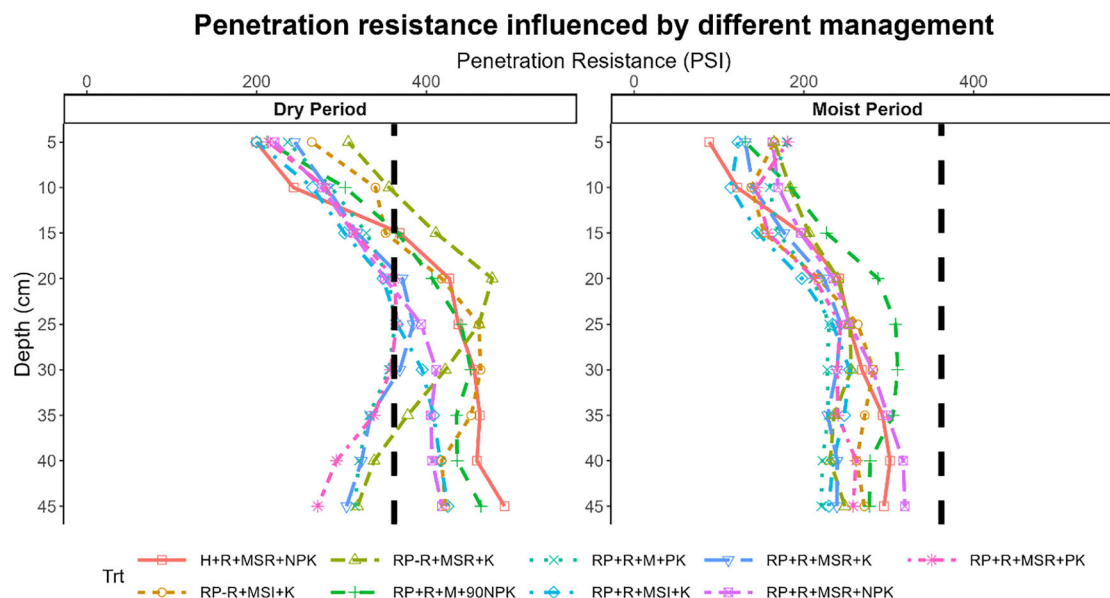


FIGURE 5 Penetration resistance down the 0–45 cm soil profile depth during the dry and moist periods. The vertical black dotted line marks the threshold of penetration resistance (362 pounds per square inch [PSI]) according to Sartori et al. (2022). RP = ripping, H = hand digging, –R = without residue, +R = with residue, MSI = maize–soybean intercrop, MSR = maize–soybean rotation, M = continuous maize, 90 nitrogen, phosphorous, and potassium (NPK) = 90 kg N/ha + 60 kg P/ha + 60 kg K/ha, NPK = 60 kg N/ha + 60 kg P/ha + 60 kg K/ha, PK = 0 kg N/ha + 60 kg P/ha + 60 kg K/ha, and K = 0 kg N/ha + 0 kg P/ha + 60 kg K/ha.

3.3 | Effect of farming practices on penetration resistance

Soil penetration resistance generally increased down the profile to between 20 and 25 cm and 25 and 30 cm in both the dry and moist periods (Figure 5). Beyond 30-cm depth, the penetration resistance plateaued in the wet period, but it did not exceed the critical level of 361 PSI. In the dry period, penetration resistance exceeded the critical value at 10–15 cm in the following treatments: RP-R+MSI+K (MSI without residue), RP-R+MSR+K (MSR without residue), H+R+MSR+NPK (hand digging), and RP+R+M+90NPK (continuous maize with 90 kg N/ha). The resistance exceeded the critical value at 20–25 cm in RP+R+MSR+NPK (ripping), RP+R+MSI+K (MSI with residue), and RP+R+MSR+K (MSR with residue) (Table 7).

During the moist period, the lowest penetration resistance was 88 PSI, observed at 0–5 cm in H+R+MSR+NPK (hand digging), while the highest was 319 PSI, observed at 45 cm in RP+R+MSR+NPK (ripping) (Table 7). In the dry period, the lowest resistance was 194 PSI at 5 cm in H+R+MSR+NPK, and the highest was 477 PSI at 20 cm in RP-R+MSR+K (MSR without residue). Penetration resistance did not differ significantly across all the treatments in the dry period. However, comparing the resistance between the tillage systems, that is, RP+R+MSR+NPK and H+R+MSR+NPK, the penetration resistance in RP+R+MSR+NPK was consis-

tently lower than in H+R+MSR+NPK (Table 6). Addition of residue (RP+R+MSI+K and RP+R+MSR+K) also resulted in consistently lower penetration resistance than residue removal (RP-R+MSI+K and RP-R+MSR+K) (Figure 5).

3.4 | Effect of farm management on maize yield

Tillage significantly influenced maize grain yield in LR24. Ripping (RP+R+MSR+NPK) resulted in a 40% higher yield (6.96 t/ha) than hand digging (H+R+MSR+NPK) (4.66 t/ha) during the LR24 season. In the LR23 and SR23, when rainfall was higher (>800 mm/season), maize yield was similar in the two tillage systems (Table 8). On average, ripping resulted in 12% higher maize grain yields compared to hand digging, but with a significantly greater (40%) difference observed during the LR24 season, which had the lowest rainfall (608 mm) out of all three seasons ($p < 0.001$).

MSR (RP+R+MSR+PK) resulted in significantly higher maize grain yield (ranging between 2.24 and 5.79 t/ha) than continuous maize (RP+R+M+PK) (ranging between 1.33 and 1.95 t/ha). Nitrogen application in continuous maize (RP+R+M+90NPK) and MSR (RP+R+MSR+NPK) resulted in 118% and 85% higher maize grain yield, respectively, than when no nitrogen was applied (RP+R+M+PK and RP+R+MSR+PK). Similarly, applying phosphorous

TABLE 7 Treatment effects on penetration resistance down the profile to the depth of 45 cm during the dry and moist periods.

Treatment	Depth (cm)															
	0–5		5–10		10–15		15–20		20–25		25–30		30–35		35–40	
	Dry	Moist	Dry	Moist	Dry	Moist	Dry	Moist	Dry	Moist	Dry	Moist	Dry	Moist	Dry	Moist
RP+R+MSI+K	265	166	340	138	352	153	418	218	462	218	464	282	453	272	418	262
RP+R+MSR+K	308	165	356	184	411	206	477	240	462	240	422	256	378	265	338	231
RP+R+MSR+PK	214	181	281	145	315	158	362	213	365	213	357	239	338	240	294	261
RP+R+MSR+NPK	221	163	276	170	314	196	351	235	440	235	411	281	405	299	406	317
RP+R+M+90NPK	212	131	304	184	366	227	406	288	362	288	452	310	435	305	436	278
RP+R+M+PK	236	179	288	159	329	170	355	211	362	211	356	227	332	299	320	222
RP+R+MSI+K	200	122	265	114	303	146	348	198	365	198	395	254	408	248	416	235
RP+R+MSR+K	244	131	282	140	318	177	371	224	384	224	368	239	334	228	323	239
H+R+MSR+NPK	199	88 ^b	243	121	368	197	427	241	437	242	456	269	463	293	459	302
<i>p</i> -value	0.73	0.304	0.925	0.611	0.948	0.521	0.768	0.547	0.772	0.724	0.798	0.692	0.57	0.468	0.369	0.408
LSD	79.33		80.86		81.05		82.16		88.86		89.91		90.78		90.78	
Mean PSI	234	147	294	151	342	181	391	230	409	254	409	262	393	261	378	260

Note: Values are means of penetration resistance in pounds per square inch (PSI) collected in the dry period (Dry) and moist period (Moist). RP = ripping, H = hand digging, +R = with residue, MSI = maize-soybean intercrop, MSR = maize-soybean rotation, CM = continuous maize, 90 nitrogen, phosphorous, and potassium (NPK) = 90 kg N/ha + 60 kg P/ha + 60 kg K/ha, NPK = 60 kg N/ha + 60 kg P/ha + 60 kg K/ha, PK = 0 kg N/ha + 60 kg K/ha, and K = 0 kg N/ha + 0 kg P/ha + 60 kg K/ha.

Abbreviation: LSD, least significant difference.

TABLE 8 Maize grain and stover yield observed between the treatments in CT1, Nyabeda.

Treatment	Maize yield (t/ha)					
	LR23		SR23		LR24	
	Grain	Stover	Grain	Stover	Grain	Stover
RP-R+MSI+K	3.50 ^c	4.07 ^{bc}	2.18 ^b	3.03 ^d	1.02 ^c	1.91 ^{ef}
RP-R+MSR+K	3.51 ^c	4.76 ^{bc}	2.53 ^b	3.20 ^{cd}	1.42 ^c	2.68 ^{def}
RP+R+MSR+PK	3.77 ^c	5.18 ^{bc}	5.79 ^a	4.85 ^{ab}	2.24 ^c	4.14 ^{bc}
RP+R+MSR+NPK	6.56 ^{ab}	8.51 ^a	5.98 ^a	5.07 ^a	6.96 ^a	5.87 ^a
RP+R+M+90NPK	6.72 ^a	6.38 ^{ab}	5.98 ^a	4.61 ^{abc}	5.63 ^{ab}	4.50 ^b
RP+R+M+PK	1.42 ^d	2.74 ^c	1.95 ^b	2.71 ^d	1.33 ^c	1.79 ^f
RP+R+MSI+K	4.23 ^c	4.88 ^{bc}	2.63 ^b	3.17 ^{cd}	1.38 ^c	3.02 ^{cde}
RP+R+MSR+K	3.56 ^c	6.26 ^{ab}	2.71 ^b	3.56 ^{bcd}	1.61 ^c	3.03 ^{cde}
H+R+MSR+NPK	5.46 ^b	6.99 ^{ab}	7.21 ^a	5.30 ^a	4.66 ^b	3.69 ^{bcd}
<i>p</i> -value	<0.001	0.05	<0.001	<0.01	<0.001	<0.001
LSD	1.049	2.979	1.770	1.448	0.779	1.090

Note: Values followed by the same superscripts in the same column indicate no significant difference between treatments at $p \leq 0.05$ using Fisher's least significant difference (LSD). RP = ripping, H = hand digging, -R = without residue, +R = with residue, MSI = maize–soybean intercrop, MSR = maize–soybean rotation, M = continuous maize, 90 nitrogen, phosphorous, and potassium (NPK) = 90 kg N/ha + 60 kg P/ha + 60 kg K/ha, NPK = 60 kg N/ha + 60 kg P/ha + 60 kg K/ha, PK = 0 kg N/ha + 60 kg P/ha + 60 kg K/ha, and K = 0 kg N/ha + 0 kg P + 60 kg K/ha.

Abbreviations: LR, long rain; SR, short rain.

and potassium each at the rate of 60 kg/ha in an MSR (RP+R+MSR+PK) increased maize grain yield by 40% more than when only potassium was applied (RP+R+MSR+K).

4 | DISCUSSION

This study examines how tillage, residue management, crop rotation, and nitrogen fertilization influenced soil moisture, penetration resistance, and maize yield across seasons in sub-humid western Kenya. Residue retention and MSR increased soil water storage, while fertilizer application reduced moisture in upper layers. Ripping lowered penetration resistance relative to hand digging, especially below 10–15 cm. Mineral N and P fertilizer and MSR contributed to higher maize yield gains. The sections that follow compare these patterns with previous work and discuss mechanisms behind them.

4.1 | Residue retention and crop rotation increased soil moisture, while fertilizer reduced soil moisture

Residue retention had higher soil moisture than residue removal, with a positive effect size of +0.76 (Figure 4). This finding corroborates with results by Mbanyele et al. (2022), who conducted a study in Zimbabwe under similar rainfall conditions (650–800 mm per season) and reported a 15%–32% increase in soil moisture content under residue retention. In a different climatic condition in lower eastern part of Kenya, Tuure et al. (2021) also reported similar findings

where residues significantly increased soil moisture compared to bare soil. The resulting effect of residue retention in improving soil moisture retention could be due to reduced soil water evaporation and enhanced water infiltration. Based on the findings in the current study, applying 2 t/ha of residue in about 2 weeks after planting can be recommended for sub-humid regions.

MSR increased soil moisture (effect size was +0.57; Figure 4), with the largest gains evident at 20- to 90-cm depth. This pattern aligns with results from central Kenya, where Waweru et al. (2024) reported greater profile water soil moisture storage in maize–beans and maize–dolichos rotations and attributed the gains to improved soil organic matter and aggregation. Higher organic matter promotes stable aggregates and porosity, which enhance infiltration and plant-available water while reducing surface sealing, processes that are consistent with the depth-wise moisture gains observed in the present study. In South Africa, a maize–fallow–soybean sequence similarly increased soil water content to 15.57% by enhancing porosity (Mtyobile et al., 2020); the authors' explanation of porosity enhancement is in line with a rotation legacy effect in which biopores and stable structure persist into the subsequent maize phase, facilitating deeper percolation (Nichols et al., 2024). The soybeans in the rotation system play a central role: legume residues typically decompose more rapidly than those of non-legumes, leaving behind root channels and promoting macro-porosity through biological activity (Nonxuba et al., 2025; Wang et al., 2024). In this study, the inclusion of soybean in MSR probably increased macropore volume and continuity, improving infiltration and storage at depth, whereas the MSI exhibited lower moisture at 20–90 cm, likely

because simultaneous and overlapping root systems intensified in-season water uptake in the profile, limiting deeper storage despite surface cover. While aggregation was not measured directly, the moisture response pattern observed could infer the improved pore connectivity under MSR and residue retention. This evidence suggests that alternating maize with soybean enhances soil structure and pore networks in ways that increase profile water storage, making MSR a practical strategy for buffering water deficits in sub-humid regions.

Mineral fertilizer application was associated with lower soil moisture (effect sizes of -1.08 to -1.22 ; Figure 4), especially in upper layers. The moisture decrease was most evident when mineral N was applied (60 and 90 kg N/ha) compared with when no nitrogen was applied, consistent with field studies showing that N fertilization often reduces topsoil water content by stimulating crop water uptake and transpiration (Bandyopadhyay et al., 2010; Corbeels et al., 1998; Zhang et al., 2021). Additionally, in the absence of organic inputs, repeated mineral nitrogen can accelerate organic matter turnover, which may weaken aggregation and reduce water-holding capacity over time (Titirmare et al., 2023; Wang et al., 2024). The current findings indicate that applying 60–90 kg N/ha improves vigor (evidenced by higher stover yield) but tends to deplete near-surface moisture. Hence, combining application of N with surface residues or other organic inputs can help reconcile crop N demand with soil water conservation in sub-humid conditions (Jiang et al., 2024).

4.2 | Ripping and residue retention reduced penetration resistance

Penetration resistance generally increased with depth and, in some cases, exceeded the commonly cited root-restrictive threshold of approximately 361 PSI (≈ 2.5 megapascal) at relatively shallow depths, especially under residue removal and hand digging during dry conditions (Figure 5; Table 7). Compared with hand digging, ripping lowered penetration resistance primarily below 10–15 cm, aligning with its mechanical objective, which is to disrupt subsurface hardpans at approximately 20–30 cm (Tiwar et al., 2022). In agreement with these results, Manyiwa and Dikinya (2014) also reported lower penetration resistance under ripping compared to conventional surface tillage in Botswana. Hand digging mainly loosens the soil only at the topsoil layer and can be associated with shallow densification just beneath the worked zone when clods reconsolidate (Diop et al., 2024; Osunbitan et al., 2005; Paul et al., 2013). These findings show that penetration resistance or compaction in clay-textured Ferralsols can be reduced by ripping to promote root elongation.

Penetration resistance was consistently lower where residue was retained than where it was removed. Consistent with this finding, studies in Ethiopia found significantly ($p < 0.1$)

lower penetration resistance with residue application due to reduced bulk density (Zeleeke et al., 2004), and work in India reported the lowest penetration resistance with residue retention versus residue removal in the no-till system, attributed to improved aggregation and pore continuity (Mondal et al., 2018). Residue application can slow drying and crusting formation, hence reducing mechanical impedance and facilitating root penetration. The management implication is that combining ripping with residue retention is more likely to keep resistance below the root-limiting threshold, whereas hand digging risks root impedance and shallower rooting even when the surface appears friable.

4.3 | When water is not limiting, soil structure and fertility control yield

The current study did not find a significant correlation between soil moisture and maize grain yield. This may be attributed to the fact that soil moisture was generally non-limiting throughout the study period since rainfall was sufficient (947.55, 834.98, and 608.60 mm in the LR23, SR23, and LR24 seasons, respectively) to meet crop water requirements, since optimal maize production requires seasonal rainfall ranging between 450 and 600 mm (Madamombe et al., 2025). In such conditions, yield variability is more likely to be driven by soil physical condition and nutrient supply than seasonal average soil moisture per se, an interpretation that is consistent with reports that management-driven changes in structure and fertility often outweigh water effects once the baseline water requirements are met (Magombeyi et al., 2018; Saidia et al., 2019). This may be particularly important in long-term experiments where system dynamics evolve with the cumulative effects of soil fertility management, cropping sequences, and tillage that can increasingly influence yield outcomes (Rao et al., 2022; Subbian et al., 2000).

The yield response to ripping in LR24, a season with the least rainfall (608 mm), highlights the contribution of improved physical conditions to water uptake and efficiency during periods of less rainfall. This is supported by the consistently lower penetration resistance observed under ripping, which indicates enhanced root growth and access to deeper soil moisture. This is consistent with findings from similar sub-humid to semi-arid agroecological zones by Rusinamhodzi et al. (2011), Mupangwa et al. (2012), and Magombeyi et al. (2018), who reported that yield increases are more likely to be observed under ripping in lower rainfall regimes (< 600 mm per season) than in wetter conditions. In the current study, LR24 was near that threshold, and the improved soil structure probably reduced water stress during the growth stages. Ripping breaks compact soil layers to enhance water infiltration and reduce penetration resis-

tance, enabling roots to grow deeper and access moisture and nutrients (Mupangwa et al., 2012).

The MSR resulted in significantly higher maize grain yield than continuous maize, which can be attributed to several agronomic benefits. Soybean, as a legume, enhances soil fertility through biological nitrogen fixation, which reduces the need for high fertilizer application in the subsequent maize crop (Mutuku et al., 2020; Thierfelder & Wall, 2012). This observation aligns with previous findings from several studies across SSA (Corbeels et al., 2020). In this study, nitrogen and phosphorus were positively correlated with maize grain yield (0.73 and 0.52, respectively), while retaining residue significantly ($p < 0.001$) increased maize grain yield (4.17 t/ha) compared to residue removal (2.36 t/ha). Application of nitrogen offsets N immobilization caused by the high C:N ratio (over 45:1) in maize stover residues (Giller et al., 1997; Wojcieszak et al., 2020), hence improving soil quality, microbial abundance, and activity (Bolo et al., 2024; Kodzwa et al., 2020). Fertilizer application improves yields because it provides essential nutrients for crop growth (Kitonyo et al., 2018; MacCarthy et al., 2023; Okebalama et al., 2016). Further, the improved microbial activity contributes to the availability of required nutrients for crop growth and development (Bolo et al., 2021).

In seasons where total rainfall is sufficient, yield is shaped less by how much water is present on average and more by crop's ability to access it and convert it into biomass, functions governed by soil structure, rotation-driven fertility, and timely nutrient application. Management that combines ripping for deep soil loosening with residue retention and legume-based rotations, supported by balanced N and P, is therefore most likely to translate to consistently higher maize yield in sub-humid regions.

5 | CONCLUSION

This study contributes to the few multi-depth time-series datasets of soil moisture from sub-humid regions. Tracking moisture through the season at different depths and under contrasting practices showed when soils store and buffer water and when those differences matter for yield. Residue retention and MSR significantly enhanced soil moisture content and made it stable, showing better water infiltration and storage. Ripping reduced subsurface penetration resistance and likely improved infiltration, but it did not translate into consistent grain yield gains. Likewise, fertilizer influenced yield but did not consistently shift in-season moisture patterns relative to residue and rotation.

In general, moisture and yield were weakly correlated, suggesting that when water is not limiting, soil structure and nutrient supply are primary determinants of crop performance. Practically, farmers should prioritize residue cover

and diversified crop rotation to stabilize the root-zone water environment and manage compaction using ripping and combining it with balanced fertility. Future work should include wetter and drier years and more sites, especially farmers' fields, to test how consistent these patterns are and when moisture becomes the main limiting factor. The dataset from this study helps address the lack of time-series soil moisture records and provides a baseline for assessing management effects in sub-humid regions.

AUTHOR CONTRIBUTIONS

Mordecai Mkiza: Conceptualization; data curation; formal analysis; writing—original draft; writing—review and editing. **Monicah Mucheru-Muna:** Supervision; writing—review and editing. **Sylvia Nyawira:** Supervision; writing—review and editing. **Dominic Mutambu:** Writing—review and editing. **Obadiah Mwangi:** Writing—review and editing. **Peter Bolo:** Writing—review and editing. **Michael Kinyua:** Writing—review and editing. **Job Kihara:** Funding acquisition; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

Mordecai Mkiza  <https://orcid.org/0009-0008-2206-8176>

Monicah Mucheru-Muna  <https://orcid.org/0000-0003-4340-7233>

Sylvia Nyawira  <https://orcid.org/0000-0003-4913-1389>

Dominic Mutambu  <https://orcid.org/0000-0002-5394-5230>

Obadiah Mwangi  <https://orcid.org/0009-0001-2231-7469>

Peter Bolo  <https://orcid.org/0000-0002-4202-7557>

Michael Kinyua  <https://orcid.org/0000-0001-6106-3599>

Job Kihara  <https://orcid.org/0000-0002-4394-9553>

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