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VARIATIONS IN PLANT NUTRIENT ALLOCATION, PHYSIOLOGICAL DEVELOPMENT PATTERNS AND SOIL STRUCTURAL CHARACTERISTICS AS INFLUENCED BY ZERO TILLAGE SYSTEMS IN THE CENTRAL HIGHLANDS OF KENYA

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ABSTRACT

The global food requirements are projected to rise above the current demand. Surface application of residues in zero tillage results to nitrogen immobilization, posing nutrient use efficiency challenges, while tillage and crop residue removal destroys soil structure. Little is documented on how integrated use of crop residues and inorganic nitrogen under zero tillage could affect plant nutrient allocation, physiological development, and soil structural improvement relative to conventional tillage systems. A study was conducted to: (i) assess how nitrogen and phosphorus accumulation in maize grain and stover are affected by application of different rates of residue and inorganic nitrogen in conventional relative to zero tillage systems, (ii) examine how maize development is influenced by application of different levels of residue, inorganic nitrogen and tillage and (iii) assess how application of residues, inorganic nitrogen and tillage influence soil aggregate stability. An on-station trial was set in a randomized complete block design replicated three times during the 2015 short rain season. Six treatments were laid, comprising a combination of different rates of maize stover residues (0, 3 and 5 tons/ha) and nitrogen as urea (0, 80, 120 kg/ha), in conventional relative to zero tillage systems. Soil was sampled to assess nitrate- nitrogen concentration at four depths, namely, at sowing, 8th leaf, 10th leaf and dent stage, soil carbon and aggregates at the four depths at the end of the season. Minidisc infiltrometer of 0.25 radius was used monthly to assess treatment effects on soil hydraulic conductivity and leaf chlorophyll recorded every fortnight from maize topdressing to tasselling using SPAD-502 meter. Analysis of variance was done using GenStat analysis software 14th edition, means separated using least significant difference ($P \leq 0.05$). Residue application in conventional tillage increased nitrogen (56%) and phosphorus (29%) allocation in maize grain compared to when equivalent rates of inputs were applied in zero tillage while increasing residue quantity from 3 to 5 t/ha increased grain phosphorus allocation by 24% ($P \leq 0.05$). When equal rates of inputs were applied in zero and conventional tillage, the latter had taller (12.3%) plants ($P \leq 0.05$) but with similar leaf area index and chlorophyll content as those of zero tillage. At 0-5 cm, the large macro aggregates were affected by depth and treatment × depth interaction ($P \leq 0.01$) with zero tillage+5R+80N having 41% higher large macro aggregates than zero tillage+3R+80N. The ability of zero tillage+5R+80N treatment to increase grain phosphorous allocation, moderate leaf nitrogen levels through maize vegetative stages and produce higher macro aggregate proportions prompts its consideration as a best nutrient management zero tillage strategy for central highlands of Kenya. Its feasibility under mixed farming system characterized by stiff competition for stover with the livestock component requires a further study.

Key words: Soil structure, residue management, nutrient management, zero tillage

INTRODUCTION

The declining stock of soil available nitrogen (N) and phosphorus (P) in humic nitisols of the Central Highlands of Kenya is compromising attempts to improve agricultural productivity (Boomsma *et al.,* 2009). Zero tillage (ZT)

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with application of crop residues has been promoted as a promising technology for addressing this type of decline. Positive effects of zero tillage with crop residue mulch on micro and macro fauna richness and abundance has been documented (Micheni *et al.,* 2016a; Ayuke *et al.,* 2019). However, studies on crop performance (Munyao et al., 2019) and establishment of site-specific rates of nutrient input suitable for zero tillage in this region are ongoing (Kitonyo *et al.,* 2018; Kinyua *et al.,* 2021) but more studies around this scope are recommended (Otieno *et al.*, 2020). This is as result of different studies indicating both positive (Micheni *et al*., 2016b; Otieno *et al*., 2019) and negative (Otieno *et al*., 2020) yield responses to zero tillage system. The reduced N mineralization during a period of high N demand (Vanlauwe *et al*., 2005) and inherently high P fixation (Kanyanjua *et al.,* 2002) and targeting zero tillage systems to high rainfall environments (Rusinamhodzi *et al.,* 2011) could result in associated reduction in grain yields.

Conventional tillage (CT) is associated with soil disturbance which enhances aeration resulting in disintegration of soil aggregates (Zotarelli *et al*., 2007). This exposes organic matter to microbial attack which increase N and P mineralization and chances of nutrient losses in the environment (Kinyua *et al.,* 2021). The result could include plant nutrient deficiency contributing to delays in structural and morphological development hence significant yield reduction (Fageria and Baligar, 2005). Crop residue application can improve N and P uptake by plants (Verhulst *et al*., 2010) and enhance P desorption (Murphy *et al*., 2016; Martínez-Lladó *et al.,* 2011) through the release of organic acids. However, residue application in conventional tillage is uncommon practice in many smallholder farmer fields with more efforts required to promote its adoption for increased nutrient utilization efficiency.

Zero tillage systems, actively promoted in smallholder fields, offer an alternative nutrient management strategy that can be used to synchronize N and P mineralization to crop demand; thereby, increasing productivity while minimizing losses in areas where fertilizer application is requisite (Chivenge *et al*., 2009). Nitrogen management in ZT is achieved through controlled microbial mediated immobilization, leading to a longer nutrient retention period (Wright *et al.,* 2007). However, uncontrolled mineralization-immobilization processes are associated with nutrient deficiency in early crop growth stages (Vanlauwe *et al*., 2005; Alijani *et al*., 2021) and low grain yields (Mupangwa *et al*., 2020). Simić *et al.* (2020) indicated significant reduction on produce nutritional quality under zero tillage systems relative to conventional tillage. Assessment of plant physiological traits such as chlorophyll content can be used to predict and determine the timing, and amount of N inputs to apply (Edalat *et al.*, 2019) and the effectiveness of the applied field management practices on quality of produce (Subedi and Ma, 2009) under zero tillage systems.

An efficient nutrient management system will not only minimize nutrient losses, but also match their supply to meet crop requirements (Kramer *et al*., 2002). It is necessary to increase understanding on the effects of applied residues and their quality on crop physiological development and the soil fertility (Chivenge *et al*., 2009). Balancing the applied organic and inorganic resources under ZT is also indispensable if appropriate crop nutrient supply, growth and soil structural development for increased food production is to be achieved. Currently, little is documented on how integrated use of crop residues and inorganic N under ZT could affect plant nutrient allocation, physiological development, and soil structural improvement relative to conventional tillage systems

This study used different combinations of crop residues and inorganic N under variable tillage systems to explore options for maintaining the correct nutrient supply during crop growth, at the same time increasing soil aggregation for soil structural development. The objectives of the study were to: (i) assess how N and P allocation in maize grain and stover are affected by application of different rates of residue and inorganic N in conventional relative to zero tillage systems, (ii) examine how maize plant physiological traits are influenced by application of different levels of residue, inorganic N and tillage and (iii) assess how application of residues, inorganic N and tillage influence soil aggregate stability.

MATERIALS AND METHODS

Study area

An on-station trial was conducted in the short rains (SR) 2015 and the long rains (LR) 2016 seasons in Embu County, Kenya (Figure I). The site is located between latitudes 0° 33’ 18” S and longitudes 37° 53’ 27”

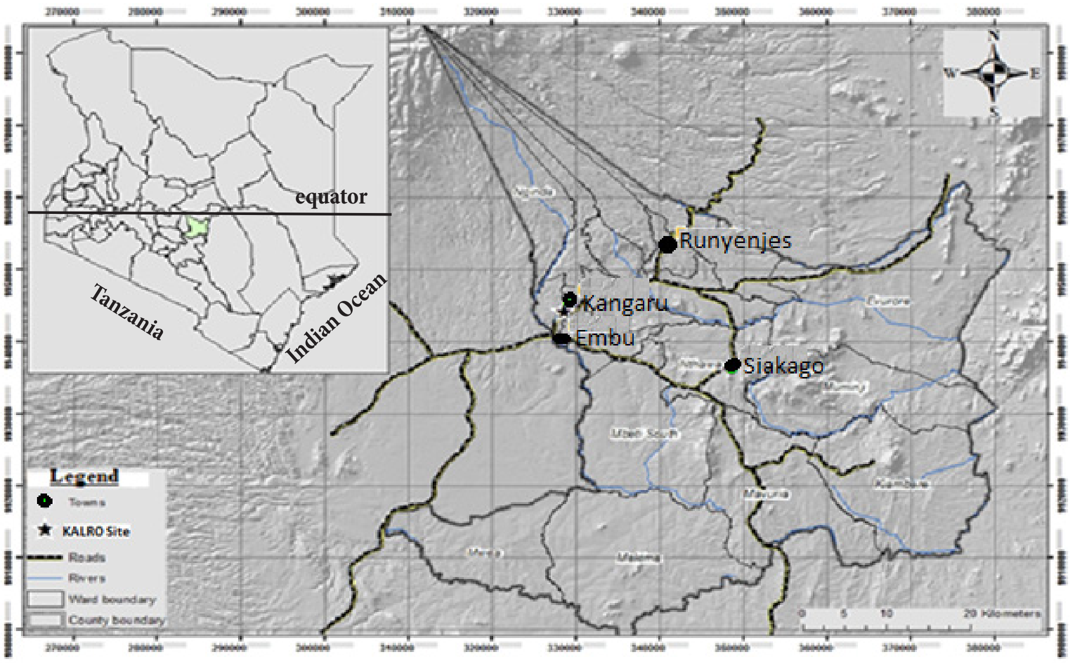

Figure I. Map of the study area showing the site in Embu County where experimental trials were established

E and lies at altitude 1,420 m above sea level. The area lies in the Upper Midland semi-humid zone (Jaetzold *et al.*, 2006) along the eastern slopes of Mount Kenya.

The mean annual temperature ranges between a minimum of 14 °C and a maximum of 21 °C with a bi-modal rainfall pattern of 1250 mm per annum. Long rains are received from March through May and short rains from October through December. The soils of the area are humic nitisols with basic volcanic loam and moderate to high fertility (Jaetzold et al., 2006). The soils of the study area contain < 2.0 % organic carbon, < 0.2 % total nitrogen, < 10 ppm phosphorus and pH ranges between 4.8 and 5.4 which has tremendously affected crop production (Kitonyo *et al.*, 2018).

Experimental treatments and layout

A randomized complete block design was used in 6 × 4.5 m plots with six treatments, comprising a combination of maize stover residues (R) and inorganic fertilizer (N kg/ha) set in CT and ZT systems replicated three times. Treatments included: (i) conventional tillage+0R+0N (control), (ii) conventional tillage+0R+80N, (iii) conventional tillage+3R+80N, (iv) zero tillage+3R+80N, (v) zero tillage+3R+120N, and (vi) zero tillage+5R+80N. Sole maize crop was grown in a rain-fed system where two seeds (later thinned to one) per hill were planted at a spacing of 25 × 75 cm. Crop residues were applied two weeks before planting, while N in form of Urea was split applied. All fertilizer applied treatments received ⅓ of basal Urea application when maize had developed six fully expanded leaves (V6) and ⅔ at twelve expanded leaves (V12). Phosphorus in form of triple supper phosphate was applied to all plots at a uniform rate of 60 kg P/ha during sowing (V0).

Data collection

In the second season of crop growth cycle, leaf chlorophyll was recorded every fortnight from V6 to tasselling stage using SPAD-502 meter. This was done in the mid leaf of ten randomly sampled and tagged plants. Maize was also harvested from the net plots and sub-sample cobs and stover collected. After the cobs were shelled, they were oven-dried together with the stover sub-samples at 60 °C for 24 hours for N and P analysis. Leaf area index (LAI) was determined by measuring the length of the fifth (at V6), seventh (at V8), and eighth leaf (at V10, V12 and V13) of five randomly selected plants from the junction of leaf sheath and the leaf blade (of fully expanded leaves). Width measurements were taken from the widest part of a fully developed leaf using measuring tape (Rop *et al.*, 2019). The LAI was determined using equation 1 by Mokhtarpour *et al.* (2010).

$$LAI = (0.75LW \times i)/ G \qquad \text{Equation 1}$$

Where LAI = leaf area index, LW = product of green leaf length and width, i = i^{th} leaf sampled and G = plant spacing.

A 4-parameter log logistic non-linear model was fit to LAI using package drc in R statistical environment.

In each plot, a small pit, about 15 cm wide and 30 cm deep, was dug and a slice of soil cut, well labelled, and transported to the laboratory with minimal disturbances for aggregate fractionation. Two minidisc infiltrometers (0.25 radius) were used each month to assess soil water infiltration in all plots at two suction levels i.e., -2 cm sec^{-2} and -6 cm sec^{-2} suctions. Readings were taken every 30 seconds of infiltration for 15 minutes. Hand-pushing electronic cone penetrometer was used, every month, to test for soil penetration resistance. Base area of cone was 2 cm^2 and the index was the peak value of resistance recorded after driving a 50 cm shaft at 5 cm intervals.

Laboratory analysis

Grain and stover subsamples were ground using Cyclotec mill and passed through a 0.5 mm sieve. A sample of 0.1 g was digested at 330 °C for three hours. For total N and P analysis, the procedure by McKenzie and Wallace (1954) was used.

Data analysis

Data on pooled means calculated through repeated measures of analysis of variance (ANOVA) using GenStat 14th edition. The variables examined were leaf chlorophyll content, plant height, LAI, soil penetration resistance and infiltration. A two-way ANOVA was used in aggregate analysis. Orthogonal contrasts between treatments were run using R environment. Means were separated using least significant difference at $P \leq 0.05$.

RESULTS

Treatments affected N ($P \leq 0.05$) and P ($P \leq 0.01$) allocation in maize grain, but not the stover (Table I). Nitrogen uptake in the grain ranged from 13.8 to 21.6 kg N/ha in the control and CT with residues, respectively, while P uptake in the grain ranged from 7.7 to 14.4 kg P/ha in the control and ZT with 5 tons/ha of residues, respectively. Phosphorus content in the grain was 40 % higher ($P \leq 0.01$) after application of 80 kg N in CT than the control. Incorporation of residues in CT increased ($P \leq 0.01$) N and P allocation in maize grain by 21% and 23%, respectively, compared to application of equivalent rates of inputs in ZT. Increasing residue rates from three to five tons/ha in ZT with equal inorganic N rates enhanced ($P \leq 0.01$) grain P by 24%, which was not the case with N content.

TABLE I - TREATMENTS EFFECT ON NITROGEN AND PHOSPHORUS UPTAKE BY MAIZE GRAIN AND STOVERS DURING THE LR 2016 SEASON IN EMBU COUNTY

Treatment	Uptake by grain (kg/ha)		Uptake by stover (kg/ha)	
	Nitrogen	Phosphorus	Nitrogen	Phosphorus
Conventional tillage + 0R + 0N	13.8^{a}	7.7^{a}	31.4	2.4
Conventional tillage + 0R + 80N	20.3^{bc}	12.8^{bc}	44.1	3.3
Conventional tillage + 3R + 80N	21.6^{c}	14.2^{c}	48.4	3.6
Zero tillage + 3R + 80N	17.0^{ab}	11.0^{b}	45.3	3.2
Zero tillage + 3R + 120N	18.9^{bc}	12.2^{bc}	33.2	3.0
Zero tillage + 5R + 80N	19.0^{bc}	14.4^{c}	39.3	2.8
Mean	18.4	12.1	40.3	3.1
$LSD_{(0.05)}$	4.39	2.62	18.01	1.30
p-value	0.03	0.01	0.29	0.46

Note: Means with the same letter in a column do not differ (P=0.05)

Leaf Chlorophyll

Leaf chlorophyll was affected by treatments ($P\leq0.01$) and sampling time ($P\leq0.05$). Chlorophyll content on maize leaves ranged between 49.4 and 56.6 SPAD units in the control and zero tillage +3R+120N treatments, respectively. Except for the period preceding 33 DAS and after 71 DAS, fertilizer application in conventional tillage +0R+80N had higher ($P\leq0.05$) leaf chlorophyll content than the control (Table II). Averaged over the sampling periods, an increment in N from 80 to 120 kg in zero tillage + 3R resulted in a 3.3% increase ($P\leq0.05$) in leaf chlorophyll content. Similarly, chlorophyll content was 8.2% higher ($P\leq0.05$) after application of 80 kg N/ha than in the control.

TABLE II - CLASS ORTHOGONAL CONTRASTS OF TREATMENTS ON LEAF CHLOROPHYLL AT DIFFERENT STAGES OF PLANT GROWTH DURING LR 2016 SEASON IN EMBU

	Estimated leaf chlorophyll values (SPAD Units)						
Contrasts	33 DAS	46 DAS	52 DAS	58 DAS	65 DAS	71 DAS	Average SPAD
Conventional tillage+0R+80N vs. conventional tillage+0R+0N	0.26	9.00	4.07	6.03	4.57	2.63	26.56
P-value	<.91	<.00	<.08	<.01	<.05	<.26	<.03
Conventional tillage+3R+80N vs. conventional tillage+0R+80N	1.87	0.93	0.14	0.5	3.17	0.43	7.04
P-value	<.42	<.69	<.95	<.83	<.17	<.85	<.78
Conventional tillage+3R+80N vs. zero tillage+3R+80N	-1.63	-2.30	0.16	-0.80	-3.47	-0.93	-8.97
P-value	<.48	<.32	<.94	<.73	<.14	<.69	<.45
Zero tillage+3R+80N vs. zero tillage+5R+80N	0.26	-2.96	-1.56	-3.3	-1.33	-2.14	-11.03
P-value	<.06	<.04	<.45	<.72	<.51	<.17	<.55
Zero tillage+3R+80N vs. zero tillage+3R+120N	4.33	4.94	1.77	0.83	-1.53	-3.24	13.58
P-value	<.91	<.20	<.50	<.16	<.57	<.36	<.35

DAS =t Days after Sowing; R is crop residue in t/ha while N is amount of nitrogen applied in kg/ha

Plant physiological traits

Plant height and LAI were significantly affected by treatments, growth stage ($P\leq0.01$) and interaction of both factors ($P\leq0.05$). The plant height increased in the order of control < zero tillage+5R+80N ≤ conventional tillage+0R+80N ≤ zero tillage+3R+80N < conventional tillage+3R+80N < zero tillage+3R+120N. In conventional systems, residue retention resulted to taller plants (43.3 and 24.2%) than removal at 27th and 40th DAS, respectively. Residue incorporation in conventional tillage increased maize height by 12.3% compared to surface application of residue under zero tillage ($P\leq0.05$). Zero tillage+3R+120N resulted in taller plants during 40, 47 and 61 DAS. LAI increased ($P\leq0.01$) in the order of control ≤ zero tillage+5R+80N ≤ conventional tillage+0R+80N ≤ zero tillage+3R+80N ≤ conventional tillage+3R+80N ≤ zero tillage+3R+120N with a mean index of 1.7, 1.9, 2.0, 2.0, 2.2 and 2.2, respectively (Figure 2). The effect of fertilizer application on LAI in conventional tillage against the control was visible from 54 to 61 DAS. There was no significant difference in LAI amongst the zero tillage treatments, however, increasing fertilizer rate to 120 kg/ha resulted in a significant LAI increase relative to increasing residue rates to 5 t/ha.

Soil aggregate fractions distribution

Soil aggregates were ($P\leq0.05$) affected by depth, treatment and treatment × depth interaction ($P\leq0.05$). Across the treatments, large macro-aggregate distribution was in the order of 15-20 cm < 5-10 cm ≤ 0-5 cm ≤ 10-15 cm with aggregate proportions of 9.4, 15.1, 16.3 and 16.6%, respectively ($P\leq0.01$). Small macro-aggregate distribution was in the order of 0-5 cm ≤5-10 cm ≤ 10-15 cm < 15-20 cm with aggregate proportions of 53.1, 54.5, 54.6 and 61.9%, respectively ($P\leq0.01$), and 15-20 cm ≤ 10-15cm ≤ 5-10cm < 0-5 cm with proportions of 1.9, 2.1, 2.4 and 2.5% of silt + clay, respectively ($P\leq0.01$).

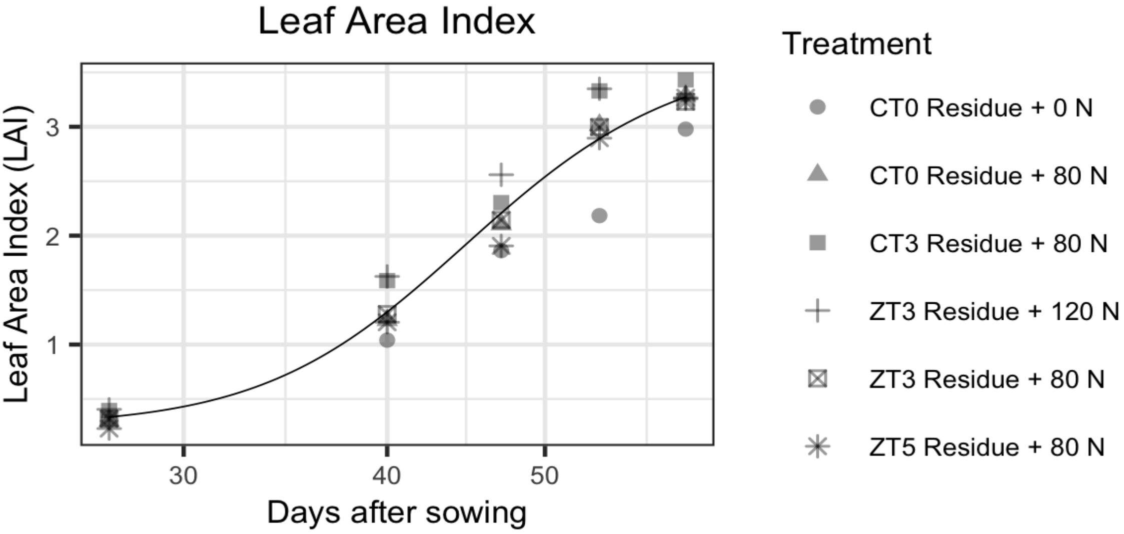

Figure 2. Effect of treatments and time on leaf area index during LR 2016 in Embu.
CT = Conventional tillage, ZT= Zero or no tillage

Micro-aggregates were not significantly affected by changes in soil depth. When averaged across soil depth, the proportion of large macro-aggregate ranged from 12.2% in conventional tillage + 3R+ 80N to 19.2% in zero tillage + 5R+80N ($P \leq 0.05$). For the micro-aggregates and silt + clay, proportions ranged from 23.9% and 1.9% in zero tillage + 5R+80N to 29.7% and 2.5% in conventional tillage + 0R+ 80N, respectively ($P \leq 0.05$). Generally, application of 5 t/ha of residues in zero tillage resulted in higher ($P \leq 0.05$) proportion of large macro-aggregate fraction at 0 - 5 cm depth than other treatments under zero tillage systems (Table III). However, a consistent trend on distribution of the different aggregate fractions was lack across the soil depth.

Soil penetration resistance

Soil penetration resistance was affected ($P \leq 0.05$) by treatment × depth interaction. Across treatments, the highest (368-392 N cm^2) soil penetration resistance ($P \leq 0.05$) was recorded at 15-20 cm and 20-25 cm depths followed by a consecutive reduction with increased depths. At 15-20 cm and 20-25 cm, application of crop residues, both on the surface and incorporations, in conventional and zero tillage systems reduced soil penetration resistance compared to conventional tillage treatments without residues (Figure 3).

Soil water infiltration

Generally, the rate of soil water infiltration was affected ($P \leq 0.01$) by the different treatments, and its interaction with the time of sampling ($P \leq 0.05$). Water infiltration in the control treatment was significantly lower at reduced (-6 cm sec^2) suction rate than conventional tillage + 80 N. Conventional tillage resulted to a higher soil water infiltration rate at -6 cm sec-2 suction when residues are retained than when removed. When sampling test was conducted after weeding (at V6), zero tillage system had higher infiltration rate than conventional tillage with residue application under greater (-2 cm sec^2) suction than lower (-6 cm sec^2) suction (Table IV). Infiltration rates were often higher in zero tillage + 5R + 80N than the zero tillage + 3R + 80N when exposed to higher (-2 cm sec^2) suction rate, however, the trend under low suction (-6 cm sec^2) was inconsistent.

TABLE III - DISTRIBUTION OF SOIL AGGREGATE FRACTIONS AT DIFFERENT DEPTH INTERVALS DURING LR 2016 SEASON IN EMBU COUNTY

Treatment	Large macro aggregates (%)				Small macro aggregates (%)				Micro aggregates (%)				Silt + Clay (%)			
	(≥ 2 mm)				(≥250 μm ≤2 mm)				(≥ 53 μm ≤ 250 μm)				(≥ 53 μm)			
	Depths (cm)															
	0-5	5-10	10-15	15-20	0-5	5-10	10-15	15-20	0-5	5-10	10-15	15-20	0-5	5-10	10-15	15-20
CT + 0R + 0N	15.0^{abc}	22.6^{a}	15.1^{ab}	5.5^{b}	54.4^{a}	50.5^{a}	49.7^{a}	66.7^{a}	27.3^{ab}	23.7^{a}	25.9^{ab}	25.9^{a}	2.7^{ab}	2.5^{ab}	1.7^{a}	1.7^{a}
CT + 0R + 80N	9.1^{c}	13.6^{a}	16.7^{ab}	12.0^{a}	52.2^{a}	52.8^{a}	51.9^{a}	60.4^{ab}	34.8^{a}	30.7^{a}	27.3^{a}	24.4^{a}	3.1^{a}	2.8^{a}	2.3^{a}	1.8^{a}
CT + 3R + 80N	10.7^{bc}	11.4^{a}	15.5^{ab}	11.1^{ab}	55.9^{a}	55.6^{a}	57.5^{a}	60.6^{ab}	30.4^{ab}	30.5^{a}	24.2^{ab}	26.1^{a}	2.7^{ab}	2.4^{ab}	2.2^{a}	2.2^{a}
ZT + 3R + 80N	14.9^{abc}	9.0^{a}	25.7^{a}	8.8^{ab}	53.3^{a}	58.8^{a}	62.6^{a}	61.1^{ab}	28.2^{ab}	28.9^{a}	19.3^{b}	26.8^{a}	2.4^{ab}	2.4^{ab}	2.1^{a}	2.0^{a}
ZT + 3R + 120N	23.1^{ab}	15.9^{a}	16.4^{b}	5.0^{b}	51.3^{a}	54.9^{a}	51.9^{a}	64.1^{ab}	22.5^{b}	26.7^{a}	27.4^{ab}	27.9^{a}	2.2^{b}	2.0^{b}	2.3^{a}	2.2^{a}
ZT + 5R + 80N	25.2^{a}	17.9^{a}	20.9^{a}	13.1^{a}	51.5^{a}	54.2^{a}	54.0^{a}	58.1^{b}	21.0^{b}	24.9^{a}	22.8^{ab}	26.7^{a}	1.9^{b}	2.4^{ab}	1.6^{a}	1.6^{a}
Mean	16.3	15.1	18.4	9.3	53.1	54.5	54.6	61.8	27.4	27.6	24.5	26.3	2.5	2.4	2.0	1.9
LSD$_{(0.05)}$	13.62	13.61	11.82	6.74	8.94	9.10	13.50	8.60	10.11	9.51	8.19	7.89	1.14	0.76	0.86	1.92
P-value	0.02	0.36	0.05	0.05	0.83	0.50	0.37	0.33	0.01	0.50	0.04	0.95	0.03	0.5	0.38	0.96

Means in a column with same letter do not differ (P=0.05). ; CT = conventional tillage; R = crop residues in t/ha and N = nitrogen applied in kg/ha.

TABLE IV - EFFECT OF TREATMENTS ON SOIL WATER INFILTRATION RATES DURING THE LR 2016 SEASON IN EMBU

Treatment	Infiltration (-2 cm sec^{2})				Infiltration (-6 cm sec^{2})			
	V6	V11	R1	R6	V6	V11	R1	R6
Conventional Tillage + 0R+0N	5.5^{a}	5.5	5.2^{a}	5.7^{a}	4.0^{a}	4.6^{a}	4.5^{ab}	4.0^{a}
Conventional Tillage + 0R+80N	5.2^{a}	5.4	5.2^{a}	5.7^{a}	3.3^{b}	4.1^{b}	4.9^{a}	3.0^{b}
Conventional Tillage + 3R+80N	5.4^{a}	5.4	4.8^{ab}	5.7^{a}	2.4^{cd}	1.7^{d}	4.2^{b}	1.5^{d}
Zero Tillage + 3R+80N	4.3^{b}	5.5	4.8^{ab}	5.1^{b}	3.0^{bc}	1.0^{e}	2.5^{c}	2.5^{bc}
Zero Tillage + 3R+120N	4.4^{b}	5.4	4.4^{b}	5.7^{a}	2.1^{d}	2.5^{c}	2.5^{c}	1.6^{d}
Zero Tillage + 5R+80N	5.1^{a}	5.2	4.9^{ab}	5.6^{a}	2.4^{cd}	2.0^{d}	2.2^{c}	2.3^{c}
Mean	5.0	5.4	4.9	5.6	2.9	2.7	3.5	2.5
LSD$_{(0.05)}$	0.46	0.777	0.51	0.36	0.58	0.43	0.52	0.45
P-Value	0.001	0.410	0.015	0.01	0.001	0.001	0.001	0.001

Means within a column with the same letter are not different (P=0.05);

V6, and V11 represent vegetative stages with six and eleven fully expanded leaves, respectively; R1 and R6 represent reproductive stages at silking and physiological maturity, respectively.

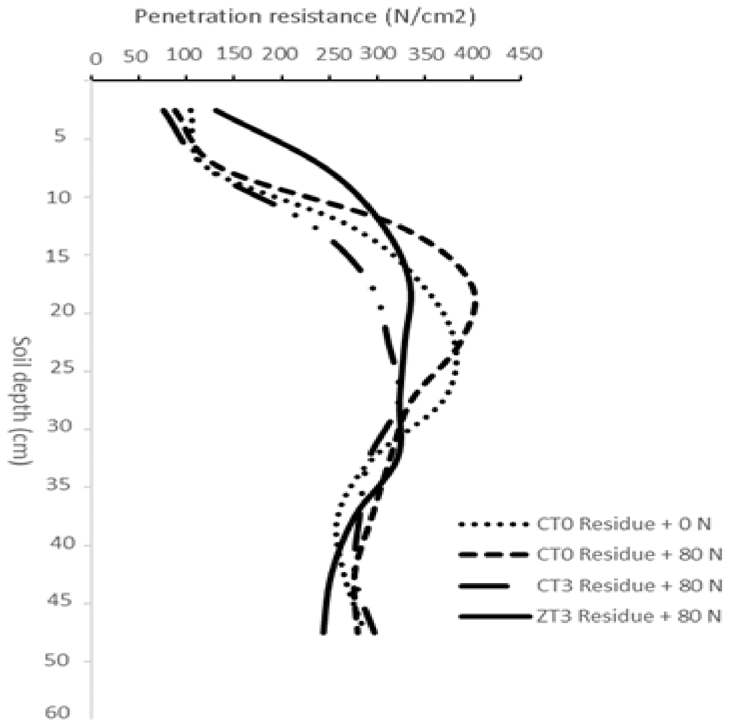

Figure 3: Effect of treatment and depth on soil resistance at the end of LR 2016 in Embu

DISCUSSION

Grain and biomass N and P accumulation

Application of inorganic fertilizers and the quantities supplied to crops defines the nutrient concentration in the plant biomass. This is because they influence both nutrient availability and supply to the growing plants as observed in this study. The lesser the quantities of available nutrients, the lower the amounts supplied and allocated to the grains. Besides, N fertilization influenced P accumulation in the plant biomass; that is, crop response to P was dependent on whether N was applied (Kihara and Njoroge, 2013). This is attributed to the synergistic nature between the two nutrients; whereby, the application of one lead to a corresponding increase in the uptake of the other (Fosu-Mensah and Mensah, 2016). Besides, P plays an active role of promoting effective root development, which could result in increased N uptake and its accumulation in the grain (Vandamme *et al.*, 2014). Phosphorus accumulation in the grain might have also been influenced by tillage-associated disturbances, which induced its availability and access by plants. Increasing the quantity of applied residues in zero tillage system, might have also improved P concentration in the maize grain. Such increments of grain P after residue application have also been reported by Zafar *et al.* (2011). Residues might have also enhanced the synchrony between N supply and crop demand, as well as helped in P desorption from iron and aluminium oxides (Martínez-Lladó *et al.*, 2011).

Maize leaf chlorophyll density

Failure to apply N in the control could have led to crop N deficiency, hence lagging the structural development of maize. This is evident by the low chlorophyll levels recorded in the control. On the contrary, despite the highest leaf chlorophyll being recorded after application of 120 kg N/ha, the rates applied were beyond the optimal plant nutrient requirements resulting in luxurious N consumption with reduced nitrogen allocation due to dilution effect (Stevens *et al.*, 2005). Application of 120 kg N/ha could be unsuitable fertilizer recommendation for soils with similar characteristics like those of the study area.

Maize height and leaf area index

The field management practices applied during crop development affects the various plant growth parameters.

For example, increased height and LAI following N fertilization could be attributed to the availability of growth metabolites (Kacar and Katkat, 2007), enhanced chlorophyll (Le Maire *et al.*, 2004) and augmented photosynthates level. Improved LAI is an indicator of enhanced photosynthesis process with high energy production and increased mass exchange in plants (Fan, 2011). Reducing the amount of soil available N could result in negative impacts on plant growth parameters (Memon *et al.*, 2013), as was observed in the control. This may be attributed to reduced ability to assimilate other growth substrates like P from the soil (Sun *et al.*, 2008), resulting in shorter roots, low light interception and photosynthetic potential hence poor structural development (Ahmad *et al.*, 2016). Besides, application of organic residues improves soil moisture conservation, which might have enhanced assimilation of growth substrates by the crop roots compared to systems without residues. Organic residues also enhance soil structural development, leading to well-aerated soils that enable plant roots to access moisture and nutrients from lower depths (Peng *et al.*, 2011). The high amount of residue applied in zero tillage +5R +80N treatment might have immobilized N hence reduced nutrient supply at early growth stages. This might have reduced the allocation of photo-assimilates with implication for plant height and LAI throughout the season.

Tillage and crop residue effects on soil aggregate distribution

Application of organic resources not only enhance macro-aggregation, but also helps in cushioning soil aggregates from disintegration through exposure to the direct impacts of raindrops, slaking and erosion. High residue volume (5 t/ha) on the surface of undisturbed soils during the study might have also reduced organic matter oxidation rate (Choudhury *et al*., 2014). Organic residue oxidation enhances its decomposition; hence, slowing the rate of macro-aggregate build-up. This concurs with results from other studies (Lichter *et al.*, 2008; Paul *et al.*, 2013), which associated surface residue cover with reduced microbial contact to the applied organic matter compared to systems with complete residue removal. Conversely, conventional tillage enhances the production of micro-aggregates through tillage associated disturbances. During the tillage process, macro-aggregates are disintegrated into smaller micro-aggregate particles with reduced organic matter content (Udom *et al.*, 2022). Elaborate trends of aggregate fractions distribution across the soil depth and among the treatments were not clearly visible which can be attributed to the short-term nature of this study. However, the benefits of zero tillage system against conventional tillage were noticed following greater proportions of large macro-aggregate distribution in the 0-5 cm depth, signifying a potential for build-up of organic C stock within this system.

Tillage and crop residue effects on soil compaction

Tillage is a major factor influencing soil compaction. Continuous tillage loosens the soil at the upper soil depth, increasing water infiltration a period after the disturbance, as was observed under control treatment. Tillage associated disturbances lead to downward mobility of loose soil particles, resulting in hardpan formation, as was recorded between 15 and 25 cm depth. Under moist soil conditions, electrostatic forces might have increased soil compaction, leading to cementation of the loose particles deposited below the plough layer.

Tillage and crop residue effect on soil water infiltration

Conventional tillage systems are characterized by high soil water infiltration rate at the upper soil layers, however, tillage associated disturbances distort the soil pore system, hindering longitudinal infiltration beyond the plough layer. This may encourage lateral water flow which heightens the chances of waterlogging and sub-surface runoff. Conventional systems lacking nutrient input had lower infiltration than that with fertilizer application, an effect associated with more degraded soil structure in the former than the latter. Fertilizer application enhances plant biomass (hence below ground biomass) and indirectly (or by its residual effect) improves weed biomass (Little *et al.*, 2021) whose organic matter might have improved soil structure and infiltration in the N applied conventional tillage upon decomposition. The significance of residue application in improving soil water infiltration was also evident and attributed to improved organic matter content that might have improved soil structure enhancing water passage (Franco *et al.*, 2020). However, the efficiency of conventional tillage in promoting soil water infiltration was affected by soil disturbance after weeding, attributed to disruption of soil pore systems. In residue applied zero tillage systems, reduced soil crusting and increased macro-faunal activities improve soil biophysical conditions that lessen soil compaction and encourage postulate soil pores, enhancing infiltration (Subbulakshmi *et al.,* 2009). In the events of heavy rainfall, the improved pore system under zero tillage increases water passage than residue-incorporated conventional tillage whose efficiency is only observed under moderate rains.

During this study, zero tillage systems with retention of crop residues were observed to improve crop physiological growth and soil structural development, however, the benefits were less pronounced for some parameters because of the short-term nature of the study. Application of maize stover residue at a rate of 5 tons/ha more often provided a better environment for crop development and can be considered as a best recommendation for similar environments. However, application of such residue quantities might result in competition from the livestock component, limiting its adoption by smallholder farmers.

CONCLUSION

Zero tillage+5R+80N has great potential for improved N and P supply in the maize grain component, as well as immobilizing N at the early growth stages, reducing its losses. Besides, zero tillage+5R+80N results in increased aggregate stability compared to conventional systems: hence, an increased potential of improving soil structural development, the carbon stock and, ultimately, long-term nutrient management. Zero tillage can be promoted as the best recommendation for tillage systems that enhance maize physiological and soil structural development in the study area. This may result in competition on residues for use as soil amendment and livestock feed in an intensive crop-livestock mixed farming system.

RECOMMENDATION

Feasibility studies to assess the uptake of zero tillage + 5R+80N in smallholder farming systems need to be conducted. In addition, there is need to examine the alternative organic resources that can be used to complement maize stover to reduce competition on stover residues. Further assessments of the right residue recommendations and long-term effects of the different levels of residues on soil nutrient and structure and crop physiological development under zero tillage systems characterized by reduced decomposition and comminution by macro-fauna, as those of the study area, are necessary.

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