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Response of spring wheat (*Triticum aestivum* L.) cultivars to ridge -furrow tillage systems

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Tillage system is one of the main factors influencing growth and physiology of wheat (*Triticum aestivum L.),* that eventually translates to high yield and good kernel quality. The objectives of this study were to determine the effects of the ridge (RT) and flat tillage (FT) systems on (i) growth and production of spring wheat, (ii) root growth and physiology and (iii) soil physical properties. Trials were conducted at Kenya Agricultural and Livestock Research Organization, Njoro and Egerton University. A randomized complete block design (RCBD) in a split plot arrangement with tillage system as the main plot and cultivar as sub-plot was used in the study. Data analysis was done using *PROC GLM* procedure from SAS software version 9.4. The study showed that root length, surface area and volume were 34.66, 42.17 and 47.56% higher in RT than FT, respectively. The RT had 8, 7.66, 39.19 and 20% higher NDVI, TKW, yield and HI, than FT. Soil moisture and electrical conductivity were 38.43 and 9.02% higher in the RT than FT. Soil temperature and BD were 1.05 and 38.94% higher in FT than RT. The RT provided a conducive environment for wheat growth and physiology, resulting in high yield and kernel quality.

Key words: Wheat, physiology, ridge-furrow, flat-tillage, grain yield.

INTRODUCTION

Tillage system significantly influences root penetration and absorption of nutrients, soil moisture content, availability of soil nutrients and capacity of soil to hold water which translates to yield production (Desta et al., 2021). In Kenya, annual wheat production is estimated at 300,000 tonnes as of 2020 statistics which is way below the country demand of over 1 million tonnes (Https://knoema.com/atlas/Kenya). Wheat production in Kenya has also been usually practiced on flat soils surfaces (solid stands) in rain-fed and open-field production systems which results in greater crop lodging, soil degradation, inferior water and nutrient use efficiency, limited soil volume and rhizosphere processes that ultimately result in lower yields (Tripathi et al., 2004). This, therefore, necessitates improving the physiological growth and production of wheat through increased production and management systems (Shiferaw et al., 2013). Thus, the use of tillage systems which reduced

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soil disturbance while promoting soil quality and health is key to improved yield production and food security (Kuntz et al., 2013). Ridge tillage system improves soil physical, chemical and biological characteristics which are function of crop development and production (Muñoz-Rojas, 2018). There are several tillage systems including, no-tillage, conventional tillage and reduced or minimal tillage which are widely used worldwide (Woźniak and Soroka, 2018). Soil quality properties, structure and capacity to produce high yields are related to conducive environment to express its full potential (Rühlemann and Schmidtke, 2015; Woźniak and Soroka, 2018). Root length, volume, biomass and spread which are determinants of crop growth and production are influenced by the soil properties and morphogenetic (Clark et al., 2003). The root distribution in the soil profile determines the crop's ability to extract soil nutrients and moisture. Greater root penetration resistance has been found in conventional and no-till systems due to the existence of compacted layer (Hassan et al., 2022). The increase in topsoil compaction may reduce water infiltration hence the soil may become waterlogged following heavy rainfall resulting in impaired soil aeration and restricting the growth and functions of plant roots. The ridge tillage system has been widely adopted across the globe in regions with scarce rainfall (Hassan et al., 2022).

It is estimated that ridge system yields 15% more wheat grains than flat system and conserve over 30% of soil water under irrigation management which translates to higher yields due to improved air porosity and high soil available water (Bakker et al., 2005; Zhang et al., 2021). The science behind this is that, ridge system has high soil nutrient conservation (NPK), conserves water, improves water use efficiency, facilitate easy weed control and band application of fertilizer, enhancing lodging resistance and good crop stand (Sayre and Moreno Ramos, 1997).

Ridge system is critical in flowering to late dough stage when wheat crops need high moisture content. Ridges also called raised beds promote efficient nitrogen use due to improved soil aeration and reduced nitrogen leaching and volatilization (Majeed et al., 2015). Ridge tillage system has greater soil water accumulation capacity facilitating root growth and distribution (Guan et al., 2015). The main factors influencing root growth are soil pore system, soil water content, hard pans, soil temperature, soil nutrient capacity and soil oxygen concentration (Li et al., 2002; Bengough et al., 2003). In comparison between flat and ridge tillage system, Tripathi et al. (2005) found that wheat cultivars grown on ridge systems exhibited 50% less lodging than those grown in conventional flat system. The ridge system reduces soil compaction, soil bulk density and increases macro and micronutrients availability that facilitate high yield production (Shen et al., 2016).

Majeed et al. (2015) compared ridge tillage system and flat tillage system and found that the former system improves nitrogen use efficiency and yield production than the latter system as a result of reduction in leaching. In a study by Yuan-zhi (2015) on rice (*Oryza Sativa* L.), ridge tillage system increased root number, root absorption, stomatal conductance, photosynthesis rate, and water use efficiency, gas exchange, antioxidant enzyme activity, panicle number and yield by between 22.12 and 15.18%. Therefore, the objective of this study was to determine the effect of ridge and flat tillage system on soil physical properties, root growth and production of Kingbird and *Kwale* spring wheat.

MATERIALS AND METHODS

Experimental site

This study was conducted at Kenya Agricultural and Livestock Research Organization (KALRO), Njoro (0° 20′ 47’ S, 35° 5′ 1.7’ E) and Egerton University (0° 22’ 26’’ S, 35° 56’ 1.3’’ E). KALRO is located at agro-climatic zone III at an elevation of 2141 m above sea level (m.a.s.l). The site receives an average annual rainfall of 939.3 mm and the soil type is *Mollic-Andosols*. It experiences average minimum and maximum temperatures of 9 and 24°C, respectively (Kenya meteorological station; 9031021). The site at Egerton University is situated at an altitude of 2267 m.a.s.l with an average annual rainfall of 1200 mm and minimum of 10.2°C and maximum temperatures of 22°C, respectively. The soils are *Vitric Mollic Andosols* (Kenya meteorological station; 9031021). The sites were chosen because the environmental conditions are representative of the main wheat growing areas in Kenya.

Cultivars

Two wheat cultivars Kenya-Kingbird (*TAM-200/TUI/6/PAVON-76//CAR-422/ANAHUAC-75/5/BOBWHITE/CROW//BUCKBUCK/PAVON-76/3/YECORA-70/4/TRAP-1*) and *Kwale* (*KAVKAZ/TANORI-71/3/MAYA-74 (SIB)//BLUEBIRD/INIA-66*) were used in this study. Kenya-Kingbird is an early maturing spring wheat released in 2012 to target farmers in the lowland production areas of Kenya. *Kwale* is a late maturing semi-dwarf spring wheat released in 1987. It exhibits prostrate growth, high yielding with hard, red kernel colour suitable for mid to high altitudes.

Experimental procedure

Land that was previously fallow in Egerton and KALRO sites were used for the evaluation of the 2 wheat cultivars. In both sites, land was disc ploughed and harrowed to a fine tilth suitable for wheat growth. The experiment consisted of 2 tillage systems mainly; ridge-furrow (RF) and conventional flat tillage (FT). Each ridge was raised to a height of 0.15 m, width of 0.5 m and a length of 5 m with an alleyway of 0.3 m while the conventional system was a normal flat tillage practices usually carried out by farmers. The seeds were sown on the RT and FT at a recommended depth of 5 cm at an equivalent rate of 125 kg ha^{-1} and at an inter-row spacing of 20 cm. A 1 mm gauge polyethylene film measuring 0.5 m × 0.5 m was inserted at a depth of 0.3 m in the soil for monitoring root growth and development in each treatment.

Di-ammonium phosphate fertilizer was applied at sowing time at an equivalent rate of 200 kg ha^{-1} to supply 36 kg N ha^{-1} and 92 kg P ha^{-1} as source of nitrogen and phosphorous, respectively. Calcium

Ammonium Nitrate (CAN) was applied in two splits for topdressing at an equivalent rate of 200 kg ha^{-1} to supply 52 kg N ha^{-1}. In both sites, the two wheat cultivars were sown in a randomized complete block design (RCBD) in a split plot arrangement with 4 replications. Tillage systems, RT and FT acted as the main plots whereas subplot consisted of cultivars, *Kwale* and Kingbird. The main plot measured 6.1 m × 20.9 m and sub-plot measured 5 m × 0.5 m.

Weeds were controlled using dual gold® (*S-Metolachlor*) a pre-emergence herbicide which was applied at the rate of 576 h ha^{-1} after sowing to control grasses and broadleaf weeds. Axial® which is a liquid emulsifiable concentrate (EC) containing *pinoxaden* was applied as a post-emergence herbicide at GS15 (Zadoks et al., 1974) at the rate of 30 g ha^{-1}. The wheat evaluation was carried out in the 2 main seasons of 2020 which was rainfed. Thunder (*Lambdacyhalothrin*), a systemic insecticide was applied at the rate of 25 g ha^{-1} to control chewing and other sucking insect pests such as Russian wheat aphids (*Duraphis noxia*). Rust diseases were controlled by application of Prosaro (*Prothioconazole* and *Tebuconazole*) at the rate of 32 and 32 g ha^{-1} respectively to control rust diseases.

Data collection

Weather data

The meteorological data were acquired from the KALRO and Egerton meteorological department, respectively for each site. The accumulated degree days for both environments were calculated as the sum of the degrees' day from sowing to harvesting time considering the base temperature for wheat as 4°C following equation described by Wang and Engel (1988).

$$GDD = \sum \left[\frac{T_{max}+T_{min}}{2} - T_{base}\right] \quad (1)$$

where T_{max}= the maximum temperature accumulated in a day, T_{min}= the minimum temperature accumulated in a day and T_{base}= the base temperature (4°C).

Soil water content and temperatures

Data on soil moisture, temperature and electrical conductivity were taken using Time Domain Reflectometry (TDR) equipment (Model No. 36143) when wheat attained growth stage GS61–69 and GS71-87 (Zadoks et al., 1974). The TDR technique is based on the measurement of the velocity (*v*) of an electromagnetic wave in the soil. This will depend on the dielectric constant of the soil which depends on the water content as described by Topp (1970) expressed as:

$$v = \frac{C_o}{\sqrt{\sum r.\mu r}} \quad (2)$$

where; $\boldsymbol{v}$ is the velocity in soil, Co is the velocity in vacuum, $\sum r$ is the dielectric constant of soil and $\mu \boldsymbol{r}$ is the magnetic permeability.

Soil bulk density

Soil bulk density was measured when wheat was at growth stage GS30 (stem elongation) using direct method as described by Ali (2010). The soil cores were taken at the depth of 15 cm $plot^{-1}$ in the 2 environments. From the main plot, 8 samples of soil were collected and measurements on the mass and volume of the soil were taken using the coring method as described by Walter et al. (2016). The wet soil samples were weighed (g) to estimate the moisture conditions in the field at the time of sampling. Thereafter, the total volume (v) of the soil was estimated as the internal volume of the cylinder. Samples were oven dried at 105°C for 3 days and the mass of the dry soil sample measured. The dry and wet soil bulk density was estimated using a formula proposed by Han et al. (2016):

$$pb = \frac{Ms}{Vs} \quad (3)$$

Where; pb is the bulk density in gcm^{-3}, Ms is the mass of the soil in grams (g) and Vs is the volume of the soil in cm^3.

Root scanning

Root sampling was conducted using soil-core method (Böhm, 1979; Mackie-Dawson and Atkinson., 1991) at maturity (GS92) to provide a range of different diameter, branching and shapes of roots. The removal of roots from 30 cm soil depth was conducted cautiously to prevent root damage and losses. An array of 0.5- and 0.2 mm mesh-size sieve was used to collect washed roots. The roots were then collected and placed in a petri plate with a small amount of water and stored below 10°C. The image of root depth, rooting density and distribution was determined from five selected plants in each plot using a scanner and the images analysed using *WinRHIZO*, software version 2003b (Regent Instrument).

Total length and surface area of roots from each plot was measured using the above-mentioned equipment. The roots were arranged in the scanner and the resolution set at 400 dpi. Root length analyses were carried out with grayscale images. After scanning, the roots were filtered through the 0.5 mm mesh and put in a labelled paper bag. They were oven dried at 70°C for 72 h to obtain the root dry weight. The program detected overlapping parts and took them into account when calculating root parameters. Roots from the RT and FT planting were analysed in order to test their effects on the root length and diameter. In this study, only results related to total root length and root surface area was used for comparison

Agronomic traits

Days to ear emergence was taken at GS59 and flowering at GS65 in all plots when 50% of the plants had produced heads and flowers, respectively. Flag-leaf senescence was measured from GS65 to full senescence at an interval of 4 days using a 0 to 10 scale where 0 is fully green and 10 fully senescenced (Gaju et al., 2011). Plant height was determined from a sample of 5 plants per plot and measured commencing on the ground base to the tip of the spikes excluding awns. Physiological maturity was determined when the peduncle was golden in colour. The Normalized Difference Vegetative Index (NDVI) spectral reflectance index was measured using a hand held Spectroradiometer (Trimble Navigation Ltd, USA). All plots were measured on the same dates, approximately 15 days post-anthesis in each season. The spectro-radiometer was held 50 cm above the crop canopy. A reading was taken per plot when the sky was clear and when there was sufficient radiation. The NDVI was estimated using an equation described by Ozyavuz et al. (2015);

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (4)$$

Where NIR is near infra-red and red is red light

Yield and yield components

Each plot was harvested for the purpose of measuring kernel yield and yield components including, spikelet spike^{-1}, seeds spike^{-1}, 1000 kernel weight and harvest index. 1000- kernel weight (TKW) was determined by counting 1000 kernels from threshed clean seed lot from each plot and weighed using an electronic balance. A sample of 5 spikes was obtained from each plot, threshed and mean number of kernels per spike was estimated. Kernel yield, biological yield and harvest index (HI) in each subplot were determined and then converted into kg ha^{-1} (Passioura, 1977).

$$\text{Kernel Yield (kg/ha)} = \frac{\text{Kernel yield subplot}^{-1}}{\textit{Area subplot}^{-1}} \quad (5)$$

$$\text{Biological yield (kg/ha)} = \frac{\textit{Biological yield (kg)}\ \text{subplot}^{-1}}{\text{Area subplot}-1} \quad (6)$$

$$\text{Harvest index} = \frac{\textit{Kernel yield}}{\textit{Biological yield}^{-1}} \quad (7)$$

Data analyses

The effects of the two tillage systems were determined by analysis of variance (ANOVA) using *PROC GLM* procedure from the SAS software version 9.4 (SAS Institute, Cary, NC, 2013) using the following statistical model:

$$Y_{ijklm} = \mu + L_i + R_{j(i)} + T_k + C_l + (LT)_{ik} + (LC)_{il} + (RT)_{jk} + (TC)_{kl} + (LRT)_{ijk}\ (LTC)_{ikl} + \varepsilon_{ijklm} \quad (8)$$

where; Y_{ijklmn} = Observation of the experimental units; μ=is the Overall mean; L_i = Effect due to ith location; $R_{j(i)}$ = is the Effect of the j^{th} replicate nested in the i^{th} location; T_k = Effect due to kth tillage, C_l = is the effect due to l^{th} cultivar in the i^{th} location; LT_{ik} = Effect of interaction due to k^{th} tillage in the i^{th} location; LC_{il} = interaction effect due to l^{th} cultivar in the i^{th} location; RT_{jk} = Effect of k^{th} tillage in the j^{th} replicate; TC_{kl} = Effect of l^{th} cultivar in the k^{th} tillage system; LTC_{ikl} = Effect of interaction due to k^{th} tillage and l^{th} cultivar in the i^{th} location and ε_{ijklm} = Random error component.

Means were compared by use of Fischer's protected least significance difference (LSD) test at P≤0.05 probability level whenever the main effects are significant using the following formulae described by Fisher and Ronald (1935).

$$LSD = t_{\frac{\alpha}{2}} \times \sqrt{\frac{2MSE}{r}} \quad (9)$$

Pearson's correlation coefficient was employed to determine the relationship between the agronomic traits using the following described by Cohen et al. Cohen (2002).

$$r = \frac{n(\sum x_i y_i) - (\sum x_i)(\sum y_i)}{\sqrt{[n\sum x^2 - (\sum x_i)^2]\ [n\sum y_i - (\sum y_i)^2]}} \quad (10)$$

where; r is the Pearson's correlation coefficient, n is the number of samples, x is the dependable variable and y is the independent variable. The following SAS procedure was used to correlate agronomic parameters evaluated in this study.

RESULTS

Weather conditions

In both locations, rainfall amount was in a progressive increase in the first 4 months, however, it was in a decreasing trend from the fifth month in Njoro while an increasing trend in Egerton (Figure 1). This might have resulted to 223 mm higher rainfall in Egerton than Njoro. Despite receiving higher rainfall, Egerton was 1.1°C (maximum), 2.0°C (minimum) and 1.5°C (mean) warmer than KALRO, Njoro (Figure 1). Temperature changes significantly influences crop growth that is simulated by growth degree days. In this study the wheat crops in Njoro had high growth rate than those in Egerton.

Analysis of variance for agronomic traits, root and soil physical properties

Statistical analyses revealed the major sources of variations to be locations and tillage systems. Location had significant effects on days to heading, days to flowering, days to maturity, flag leaf senescence, plant height, grain yield, TKW, spike length, number of seeds spikelets^{-1}, NDVI, soil temperature, electrical conductivity, root length, root diameter, root surface area and root volume. On the other hand, tillage systems had significant (*P*≤0.001) effects on all the traits except germination percentage (Table 1).

Location × tillage interaction significantly (*p*≤0.001) affected days to heading, days to flowering, days to maturity, plant height, spike length, No. of seeds spike^{-1}, No. of seeds spikelets^{-1}, NDVI, soil temperature, root length, root surface area and root volume. The Location × Cultivar interaction had significant effect on days to flowering, flag leaf senescence, plant height, yield, TKW, spike length, No. of seeds spike^{-1}, No. of seeds spikelets^{-1}, root surface area and root volume. The Tillage × Cultivar interactions were only significant for TKW, root surface area and root volume. Location × Tillage × Cultivar interactions had significant (*p*≤0.001) effects on yield, TKW, spike length, root length and root surface area (Table 1).

Effects of location and tillage system on soil and root physical properties, growth and physiology of cultivar Kwale and Kingbird

Soil and root physical properties

Soil moisture (9.81%) and soil electrical conductivity (1.33 dsm^{-1}) were 38.43 and 9.02% higher in the RT than FT. On the other hand, soil temperature (20.92°C) and bulk density (1.57gcm^{-3}) were 1.05 and 38.94% higher in FT than RT. Root growth was also influenced by both location and tillage systems (Table 2). The mean root length (219.02 cm), root surface area (146.97 cm^2), root diameter (2.24 mm) and root volume (8.45 cm^3) were 13.81, 24, 12.95 and 33.49% higher in Njoro than Egerton. Similarly, the mean root length (246.63 cm), root surface area (163.89 cm^2), root diameter (2.19 mm) and root volume (9.23 cm^3), were 34.66, 42.17, 8.68 and 47.56% higher in RT than FT (Table 2). In cultivar comparison, root length, root surface area and root

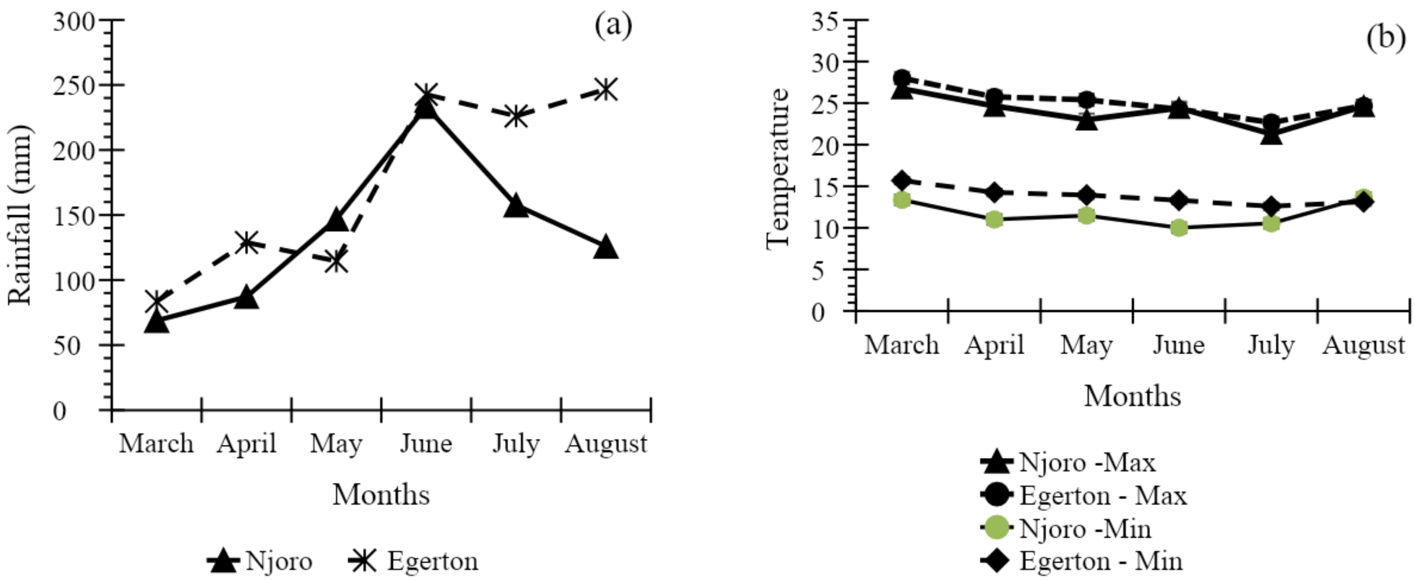

Figure 1. Mean monthly (a) rainfall and (b) maximum and minimum temperature at KALRO, Njoro and Egerton University.
Source: Egerton University Weather Station, 2020 and KALRO, Njoro Weather Station, 2020.

diameter were significantly (p≤0.05) different however, no difference was found in root surface area. Kingbird (220.64 cm) had 15.18% longer root length than *Kwale* (187.15 cm) whereas *Kwale* had root diameter of 2.28 mm and root volume of 8.18 cm^3 which were 16.67 and 28% respectively higher than Kingbird (Table 2).

Agronomic traits

The mean comparison between Egerton and Njoro showed that ear emergence, flag leaf senescence, flowering, maturity, height, yield, TKW, spike length, number of seeds spikelets^{-1} and NDVI were significantly (p≤0.05) different between the 2 sites (Table 3). The RT and FT significantly (p≤0.05) influenced all the variables except for percent germination. The RT had significantly higher mean for all the test variables than FT (Table 4). The cultivars mean for ear emergence, flag leaf senescence, days to flowering, days to maturity, plant height, TKW, spike length, seed spike^{-1}, seed spikelets^{-1} and HI were significantly (p≤0.05) different (Table 4). Interestingly, the two cultivars had no significant difference in yield and NDVI across locations hence attributed to the performance of the tillage systems. Despite that, the TKW of Kingbird was 30.88 grams with 31 seeds per spike. These resulted in 5.45 and 18.15% higher TKW and number of seeds per spike, than *Kwale*. It is important to note that, flag leaf in cultivar *Kwale* took 7 more days to senescence compared to that of Kingbird. Days to flowering (91 days), days to maturity (131 days), plant height (92.91cm) and number of seeds per spikelets (18 seeds), were 31.59, 15.10, 19.10 and 18.65% higher in cultivar *Kwale* than Kingbird. This study further revealed that the RT had higher NDVI (0.50) TKW (33.03g), yield (2.22 tonnesha^{-1}) and HI (0.65) which were 8, 7.66 and 39.19% higher than FT respectively. (Table 4).

Effects of tillage system on growth and physiology of wheat across locations

Results of days to heading, flag leaf senescence, days to flowering and maturity averaged across the environments and tillage systems (Table 5) showed that flowering and heading was delayed for 3 and 4 days respectively in the RF tillage system while flag leaf senescence and maturity took 7 days more than the conventional flat tillage practices. Averaged across the environments, cultivars and tillage systems, the results further showed that ridge tillage promoted the development of the yield components. For example, the wheat yield in the ridge tillage system (2.22 tonnes ha^{-1}) was 24.37% higher than the conventional flat tillage system. The ridge tillage practice also had higher number of seeds spike^{-1} (41 seeds spike^{-1}) that was 18.07% higher than the conventional tillage (28 seeds spike^{-1}). Results of NDVI showed that the RT system (0.50) was higher than the conventional tillage system (0.47).

Across the 2 locations and tillage systems, cultivar Kingbird took less time (55 and 111 days) to attain heading and maturity compared to *Kwale* which took 77 and 131 days, respectively. In both tillage systems and locations, cultivar Kingbird, had short spike length (6.69 cm) 16.74 lower than *Kwale* (9.38 cm), and high harvest index (0.65) that was 10.17% higher than *Kwale* (0.53). However in Njoro cultivar, Kingbird (0.56) had higher

Table 1. Effect of location, tillage and cultivar on yield, yield components and soil properties on physiology and growth of spring wheat.

Source of variation	df	Days to heading	Days to flowering	Days to maturity	Flag leaf senescence (days)	Plant Height (cm)	Yield (Tonnes ha^{-1})	TKW (g)	Spike length (cm)	Harvest index	No. of seeds $spike^{-1}$
Location (L)	1	1501.56***	529.00***	576.00***	529.00***	364.81***	8.39***	1859.77***	21.62***	0.02	108.16
Replicate (R)	3	3.500	56.10	54.63	56.10	68.79	0.48	4.56	4.02	0.16	22.35
L× R	3	2.73	26.54	43.88	26.54	67.29	0.94	0.72	1.81	0.02	43.85
Tillage (T)	1	225.00***	756.25***	812.25***	756.25***	359.10***	12.00***	102.52**	48.30***	0.30*	2485.02***
R × T	3	0.92	31.79	18.63	31.79	6.62	0.13	2.72	0.25	0.05	23.89
L× T	1	10.5.063***	52.56	441.00***	52.56	153.76**	1.53	3.52	5.52***	0.02	256.00*
L×R×T (Error a)	3	1.396	14.432*	87.542*	46.271	15.950	0.013	1.141	0.018	0.002*	9.295
CV_a (%)		1.792	4.951	7.713	17.262	4.753	5.985	3.363	1.671	2.710	8.845
Cultivar (C)	1	7965.56***	552.25***	6280.56***	552.25***	5041.00***	0.82	50.77*	115.56***	0.23*	759.00***
L × C	1	4.00	370.56**	14.06	370.56**	122.10*	8.07***	301.89***	1.56*	0.03	1568.16***
T × C	1	0.56	18.06	3.06	18.06	28.09	0.01	37.52*	0.30	0.02	66.42
L × T × C	1	1.00	9.00	45.56	9.00	0.06	2.80*	112.89***	4.20***	0.003	7.29
CV (%)		1.85	2.83	4.62	16.43	6.32	36.41	9.35	6.19	37.14	17.91
R^2		0.99	0.99	0.85	0.57	0.83	0.66	0.86	0.95	0.38	0.75
Mean		65.94	76.73	121.31	39.41	84.03	1.78	31.77	8.03	0.58	34.47

Source of variation	df	No. of seeds $spikelets^{-1}$	NDVI	Soil moisture (%)	Soil temperature (°C)	Electrical conductivity (dsm^{-1})	Soil bulk density (gcm^{-3})	Root Length (cm)	Root surface Area (cm^2)	Root diameter (mm)	Root Volume (cm^3)
Location (L)	1	100.50***	0.35***	6.55	734.75***	0.93***	0.03	14646.75*	19913.80***	1.32*	128.06***
Replicate (R)	3	0.15	0.003	12.84	3.72	0.078	0.01	3879.30	3771.76	0.74	21.56
L× R	3	5.94	0.02	0.61	3.61	0.10	0.05	4547.19	1797.02	0.05	5.68
Tillage (T)	1	122.66***	0.02*	227.29***	0.75***	0.21*	3.12***	116915.27***	76428.06***	0.56	308.13***
L× T	1	7.98*	0.01*	0.23	1.47***	0.02	0.01	62889.98***	18985.74***	0.39	49.19**
R × T	3	1.02	0.0006	2.42	0.13*	0.07	0.01	6111.62	1299.76	0.81*	5.18
L×R×T (Error a)	3	3.397	0.002	0.114*	0.114*	0.087	0.019	5531.833	1297.737	0.038	0.023
CV_a (%)		15.19	26.27	1.622	1.622	23.262	10.241	36.478	27.854	9.314	6.231
Cultivar (C)	1	174.90***	0.006	4.87	0.01	0.04	0.001	17939.59*	2038.18	2.32**	83.38***
L × C	1	19.58**	0.002	0.05	0.04	0.03	0.003	2182.88	8557.87	0.21	61.41**
T × C	1	3.15	0.003	4.50	0.02	0.12	0.01	1390.45	6992.93*	2.27**	108.45***
L × T × C	1	5.64	0.01	0.12	0.11	0.05	0.02	17861.99*	3247.15	0.03	0.06
CV (%)		8.30	11.77	18.17	0.97	17.28	0.82	28.63	24.48	25.10	34.09
R^2		0.85	0.75	0.75	0.99	0.49	1.35	0.63	0.77	0.479	0.76
Mean		16.04	0.48	7.93	20.81	1.27	9.50	203.89	129.33	2.09	7.04

CV=Coefficient of Variation; R^2 =coefficient of determination, df=degree of freedom, *, **, ***, significant at $p\leq0.05$ and $p\leq0.01$, $p\leq0.001$, NDVI=normalised difference vegetative index, TKW-thousand kernel weight.
Source: Authors

Table 2. Effect of environment and tillage system on root length, surface area, diameter, and volume of *Kwale* and Kingbird spring wheat.

Location	Root length (cm)	Root surface area (cm^2)	Root diameter (mm)	Root volume (cm^3)	Electrical conductivity (dsm^{-1})	Soil moisture (%)	Soil temperature (°C)	Bulk density (gcm^{-3})
Njoro	219.02[a]	146.97[a]	2.24[a]	8.45[a]	1.15[b]	8.25[a]	24.20[a]	1.33[a]
Egerton	188.77[b]	111.69[b]	1.95[b]	5.62[b]	1.39[a]	7.61[a]	17.42[b]	1.37[a]
LSD 0.05	29.36	15.92	0.26	1.21	0.11	0.72	0.10	0.06
Tillage								
Ridge	246.63[a]	163.89[a]	2.19[a]	9.23[a]	1.33[a]	9.81[a]	20.70[b]	1.13[b]
Flat	161.15[b]	94.77[b]	2.00[b]	4.84[b]	1.21[b]	6.04[b]	20.92[a]	1.57[a]
LSD 0.05	29.36	15.92	0.26	1.21	0.11	0.72	0.10	0.06
Cultivar								
Kingbird	220.64[a]	123.69[a]	1.90[b]	5.89[b]	1.24[a]	7.65[a]	20.80[a]	1.34[a]
Kwale	187.15[b]	134.97[a]	2.28[a]	8.18[a]	1.29[a]	8.20[a]	20.82[a]	1.35[a]
LSD 0.05	29.36	15.92	0.26	1.21	0.11	0.72	0.10	0.06

Means followed by the same letters are in a column are not significantly different based on Fischer's least significant different.
Source: Authors

Table 3. Means of environments for agronomic and yield components evaluated across environments.

Location	Ear emergence (Days)	Flag leaf senescence (Days)	Days to flowering	Days to maturity	Plant height (cm)	Yield (Tonnesha^{-1})
Njoro	61.09[b]	42.28a	71.97[b]	124.31a	86.42a	1.42[b]
Egerton	70.78a	36.53[b]	81.50a	118.31[b]	81.64[b]	2.15a
LSD 0.05	0.61	3.26	1.09	2.82	2.67	0.33
Location	**TKW (g)**	**Harvest index**	**No. of seeds spike^{-1}**	**No. of seeds spikelets^{-1}**	**NDVI**	**Spike length (^{c}m)**
Njoro	26.38[b]	0.57[a]	33.17[a]	17.29[a]	0.56[a]	8.61[a]
Egerton	37.16[a]	0.60[a]	35.77[a]	14.79[b]	0.41[b]	7.45[b]
LSD 0.05	1.49	0.11	3.11	0.67	0.03	0.25

Means followed by the same letters in the column are not significantly different at $p \leq 0.05$.
Source: Authors

NDVI than *Kwale* (0.55) under flat system whereas *Kwale* (0.57) had higher NDVI than Kingbird (0.55) under RT (Table 5).

The interaction of location, tillage and cultivar also showed that the 2 wheat cultivars had contrasting yield performance. In Njoro, under RT, Kingbird (1.75 tonnes ha^{-1}) had higher yield than *Kwale* (1.66 tonnes ha^{-1}) while in Egerton, *Kwale* had higher grain yield (2.98 tonnes ha^{-1}) than Kingbird (2.49 tonnes ha^{-1}) (Table 5). Differences in yield performance due to tillage system showed that, in Njoro under both tillage systems, Kingbird performed better than *Kwale* for grain yield. Under FT, Kingbird had a mean grain yield of 1.58 tonnes ha^{-1} whereas *Kwale* had 0.70 tonnes ha^{-1}. In the RT, the mean grain yield was 1.75 for Kingbird and 1.66 tonnes ha^{-1} for *Kwale*. In contrast, the mean grain yield in FT for Kingbird (0.87 tonnes ha^{-1}) was lower than *Kwale* (2.25 tonnes ha^{-1}) in Egerton. Similarly, Kingbird had higher TKW than *Kwale* under FT and RT in Njoro. However, in Egerton, *Kwale* had higher TKW than Kingbird in both FT and RT systems. The difference was also seen in the TKW between the 2 locations on FT (Table 5).

Effects of tillage system on soil and root physical properties

In both RT and FT, Njoro had higher soil moisture content (8.25%) and soil temperature 24.2°C compared with 7.61% and 17.42°C recorded at Egerton, respectively. On the other hand, soils in Egerton had higher electrical conductivity 1.39 dsm^{-1} and bulk density 1.37gcm^{-3} than

Table 4. Effect of cultivar and tillage systems on yield and agronomic components across two environments.

Cultivar	Ear emergence (Days)	Flag leaf senescence (Days)	Days to flowering	Days to maturity	Plant height cm)	Yield (tonnes ha^{-1})	TKW (g)	Spike length (cm)	NSS	NSPK	NDVI	HI
Kwale	77.09^a	36.47^b	91.13^a	131.22^a	92.91^a	1.90^a	30.88^b	9.38^a	31.03^b	17.69^a	0.49^a	0.52^b
King bird	54.78^b	42.34^a	62.34^b	111.41^b	75.16^b	1.67^a	32.66^a	6.69^b	37.91^a	14.39^b	0.47^a	0.64^a
LSD $_{0.05}$	0.61	3.26	1.09	2.82	2.67	0.33	1.49	0.25	3.11	0.67	0.03	0.11
Tillage												
Ridge	67.81^a	42.84^a	78.81^a	124.88^a	86.40^a	2.22^a	33.03^a	8.90^a	40.70^a	17.43^a	0.50^a	0.65^a
Flat	64.06^b	35.97^b	74.66^b	117.75^b	81.66^b	1.35^b	30.50^b	7.16^b	28.24^b	14.66^b	0.46^b	0.52^b
LSD $_{0.05}$	0.61	3.26	1.09	2.82	2.67	0.33	1.49	0.25	3.11	0.67	0.03	0.11

Means followed by the same letters down the column are not significantly different $P \leq 0.05$.
Source: Authors

soils in Njoro (Table 5). In both locations, soils in the RT had high soil moisture content (9.81%), 23.79% higher and electrical conductivity (1.33 dsm^{-1}), 4.72% higher than the conventional FT system. Results across the 2 environments further indicated that soils in the FT had high soil temperature (20.92°C) and soil bulk density (1.57 gcm^{-3}), 16.3% higher than RT. In Njoro under FT, soils under growth of cultivar *Kwale* had higher soil moisture content (6.36%) and electrical conductivity (1.12 dsm^{-1}) whereas soils under growth of cultivar Kingbird higher soil temperature (24.47°C) and soil bulk density (1.60 gcm^{-3}). In the RT, soils under growth of Kingbird had high; soil moisture content (10.75%), soil temperature (24°C), and electrical conductivity (1.21 dsm^{-1}) while soils under growth of *Kwale* had high bulk density (1.11 gcm^{-3}) (Table 5).

In Egerton, under FT, soils under growth of cultivar Kingbird had high soil moisture content (5.87%) and soil temperature (17.42°C) whereas soils under growth of *Kwale* had high electrical conductivity (1.34 dsm^{-1}) and soil bulk density (1.58 gcm^{-3}). However, under RT soils under growth of Kingbird had high soil moisture (9.96%), electrical conductivity (1.58 gcm^{-3}) whereas soils under growth of *Kwale* had high soil temperature (17.54°C). Further, soil under both cultivars had same mean soil bulk density of 1.16 gcm^{-3} (Table 5).

In both environments, RT had high means for root length (246.63 cm) which was 20.96% longer, root surface area (163.89 cm^2) was 26.72% larger, root diameter (2.19 mm) and root volume (9.23 cm^3) 31.20% higher than those in FT system. However, Njoro had higher means for root surface area (95.19 cm^2), root diameter (2.22 mm) 11% higher, and root volume (5.38 cm^3), 11.16% larger in flat tillage system compared to Egerton. The RT in the 2 locations showed that all the root traits had higher growth rate in Njoro than Egerton (Table 6). Cultivar Kingbird and *Kwale* had higher mean for all the tested root traits in Njoro than Egerton. *Kwale* had higher root surface area (164.18 cm^2) 11.71% larger, root diameter (2.49 mm) 11.16% larger and root volume (10.57 cm^3) was 25.09% larger than Kingbird in Njoro. However in Egerton, Kingbird had higher root length (211.35 cm), 11.96% longer and root surface area (117.61cm^2) was 5.3% larger than *Kwale*. Further, *Kwale* had a root diameter of 2.09 mm which was 6.91% larger than Kingbird and root volume was 5.78 cm^3. In the FT, Kingbird had higher mean for root length (212 cm) 19.52% longer, root surface area (117.85 cm^2) 24.9% larger and root volumes (5.47cm^3) 27.21% larger than *Kwale*. However, the 2 cultivars did not differ in root diameter. In the RT, *Kwale* had higher mean for all the root traits than Kingbird except for the root length (Table 6).

Correlation between yield and yield components with tillage systems, soil properties and root morphology and architecture of the roots

Flag leaf senescence significantly correlated (r=0.76*) with number of seeds spike^{-1}. Days to flowering influenced duration of plant maturity (r=0.79*) and plant height (r=0.83*). Days to maturity was highly correlated with plant height

Table 5. Means of environments, tillage system and cultivar for yield, yield components and soil properties.

Location	Tillage system	Cultivar	Days to heading	Flag leaf senescence	Days to flowering	Days to maturity
Njoro	Flat	Kingbird	49.63±0.18	45.25±1.56	54.00±0.19	112.38±2.49
	Flat	*Kwale*	71.38±0.46	34.25±3.06	87.00±0.53	134.38±2.07
	Ridge	Kingbird	50.75±0.31	50.00±2.73	56.50±0.19	115.50±1.05
	Ridge	*Kwale*	72.63±0.32	39.63±2.65	90.38±0.62	135.00±2.10
Egerton	Flat	Kingbird	56.00±0.46	33.63±1.39	66.00±1.27	103.75±2.81
	Flat	*Kwale*	79.25±0.49	30.75±1.80	91.63±1.05	120.50±2.20
	Ridge	Kingbird	62.75±0.45	40.50±2.44	72.88±1.30	114.00±1.69
	Ridge	*Kwale*	85.13±0.72	41.25±1.99	95.50±1.24	135.00±1.00

Location	Tillage system	Cultivar	Plant height (cm)	Spike length (cm)	Yield (tonnes ha^{-1})	TKW (g)	Harvest index	No. of seeds $spike^{-1}$
Njoro	Flat	Kingbird	74.65±2.45	6.35±0.14	1.58±0.11	28.50±0.65	0.51±0.07	35.98±0.99
	Flat	*Kwale*	96.55±0.93	9.73±0.19	0.70±0.04	21.25±0.41	0.46±0.05	21.90±2.30
	Ridge	Kingbird	77.68±2.11	7.88±0.24	1.75±0.13	30.38±0.42	0.70±0.09	47.15±2.36
	Ridge	*Kwale*	96.80±2.97	10.50±0.18	1.66±0.35	25.38±0.75	0.60±0.08	27.65±1.19
Egerton	Flat	Kingbird	69.60±2.16	5.43±0.29	0.87±0.18	32.75±1.75	0.61±0.09	25.35±2.49
	Flat	*Kwale*	85.85±1.52	7.15±0.26	2.25±0.37	39.50±0.76	0.49±0.06	29.73±2.08
	Ridge	Kingbird	78.70±0.97	7.10±0.26	2.49±0.25	39.00±0.89	0.76±0.12	43.18±3.06
	Ridge	*Kwale*	92.43±1.79	10.13±0.41	2.98±0.24	37.38±1.44	0.55±0.08	44.83±1.92

Location	Tillage system	Cultivar	Spikelets	NDVI	Soil moisture (%)	Soil temperature (°C)	Electrical conductivity (dsm^{-1})	Bulk density (gcm^{-3})
Njoro	Flat	Kingbird	14.58±0.34	0.56±0.02	6.24±0.44	24.47±0.28	1.10±0.05	1.60±0.06
	Flat	*Kwale*	17.95±0.77	0.55±0.03	6.36±0.45	24.45±0.32	1.12±0.04	1.52±0.05
	Ridge	Kingbird	15.60±0.25	0.55±0.02	10.75±0.58	24.00±0.30	1.21±0.04	1.07±0.02
	Ridge	*Kwale*	21.05±0.56	0.57±0.02	9.64±0.74	23.88±0.34	1.17±0.02	1.11±0.02
Egerton	Flat	Kingbird	11.88±0.36	0.34±0.02	5.87±0.60	17.42±0.09	1.29±0.04	1.57±0.07
	Flat	*Kwale*	14.23±0.58	0.41±0.03	5.70±0.65	17.34±0.06	1.34±0.03	1.58±0.06
	Ridge	Kingbird	15.50±0.45	0.45±0.02	9.96±0.51	17.39±0.13	1.58±0.20	1.16±0.04
	Ridge	*Kwale*	17.55±0.34	0.44±0.02	8.91±0.50	17.54±0.14	1.35±0.05	1.16±0.03

Means; *n*=8, TKW=thousand kernel weight, NDVI=normalised difference vegetative index.
Source: Authors

Table 6. Means of environment, tillage system and cultivar for root length, surface area, diameter and volume of spring wheat.

Location	Root traits					
	Tillage system	Cultivar	Length (cm)	Surface area (cm^2)	Diameter (mm)	Volume (cm^3)
Njoro	Flat	Kingbird	134.47±13.68	81.31±3.02	2.19±0.38	4.53±0.86
Njoro	Flat	*Kwale*	155.40±23.70	109.07±15.15	2.26±0.12	6.23±0.95
Njoro	Ridge	Kingbird	325.38±30.36	178.21±18.97	1.79±0.16	8.13±1.18
Njoro	Ridge	*Kwale*	260.84±18.66	219.29±14.36	2.71±0.13	14.91±1.31
Egerton	Flat	Kingbird	212.00±22.20	117.85±12.61	1.81±0.18	5.47±0.81
Egerton	Flat	*Kwale*	142.74±19.98	70.86±7.44	1.75±0.23	3.13±0.57
Egerton	Ridge	Kingbird	210.70±18.36	117.37±9.45	1.82±0.14	5.44±0.74
Egerton	Ridge	*Kwale*	189.62±19.76	140.68±10.03	2.42±0.11	8.43±0.53

Means; *n*=8.
Source: Authors

Table 7. Correlation coefficients of yield and yield components for Kingbird and *Kwale* wheat cultivars.

Trait	Days to flowering	Days to maturity	Plant height	Yield	Thousand kernel weight	Spike length	Harvest index	Number of seeds spikes^{-1}	Number of seed spikelts^{-1}
Flag leaf senescence	-0.58	-0.10	-0.23	0.24	-0.12	0.07	0.48	0.76*	0.16
Days to flowering		0.79*	0.83*	0.32	0.12	0.69	-0.39	-0.29	0.55
Days to maturity			0.98***	0.20	-0.33	0.97***	-0.40	-0.13	0.88**
Plant height				0.13	-0.34	0.94***	-0.42	-0.25	0.87**
Yield					0.76*	0.20	0.28	0.73*	0.13
Thousand kernel weight						-0.37	0.34	0.51	-0.47
Spike length							-0.21	-0.01	0.94***
Harvest index								0.59	-0.09
Number of seeds spikes^{-1}									-0.05

*, **, ***, indicate significance at P≤0.05, P≤0.01 and P≤0.001, respectively.
Source: Authors

(*r*=0.98***), spike length (*r*=0.97***) and number of seeds spikelets^{-1}. Plant height affected spike length (*r*=0.94***) and number of seeds spikelets^{-1} (*r*=0.88**). The TKW (*r*=0.76*) and number of seeds spikes^{-1} (*r*=0.73*) significantly influenced grain yield. Long spike length highly correlated with number of seed spikelets^{-1} (*r*=0.94***) (Table 7).

Root surface area correlated with root length (*r*=0.83**) and root volume (*r*=0.94**). Soil moisture, increased with increase in root length (*r*=0.80*) whereas soil bulk density increased with a decrease in root length (*r*=-0.78*) and root surface area (*r*=-0.81*) (Figure 3). Root surface area increased with increase in root volume (*r*=0.94***) and soil moisture (*r*=0.76*). Root diameter correlated with root volume (*r*=0.75*) (Figure 3).

DISCUSSION

Growth of crops is confounded by management and environmental factors such as rainfall and temperature. These factors are keys in growth and physiology of wheat due to their influence on heat units (Aslam et al., 2017). Zhang et al. (2015) suggested wheat cultivars are sensitive to photoperiod while Wang and Engel (1998) suggested both photoperiod and temperature are critical in wheat phenology especially in days to anthesis and days to maturity.

Location has significant influence on wheat genotypes especially on those that do not have dynamic stability. However, agronomic practices can influence performance of such genotypes. The RT had lower soil bulk density than the FT; this might be due to hardpans and settling of soil particles after tillage in FT and the gentle soil compaction in RT. There was rather no effect between the two cultivars due to soil bulk density. This indicates, soil compaction and penetration resistance uniformly influence wheat growth irrespective of their genetic make-up.

The root system is one of the key components

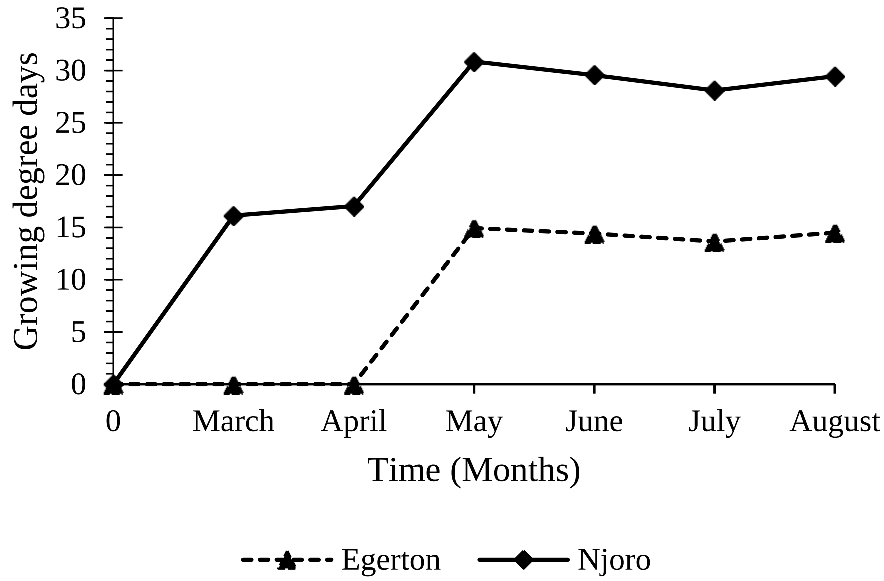

Figure 2. Effects of the environments on the growing degree days at different times during the growing period.
Source: Authors

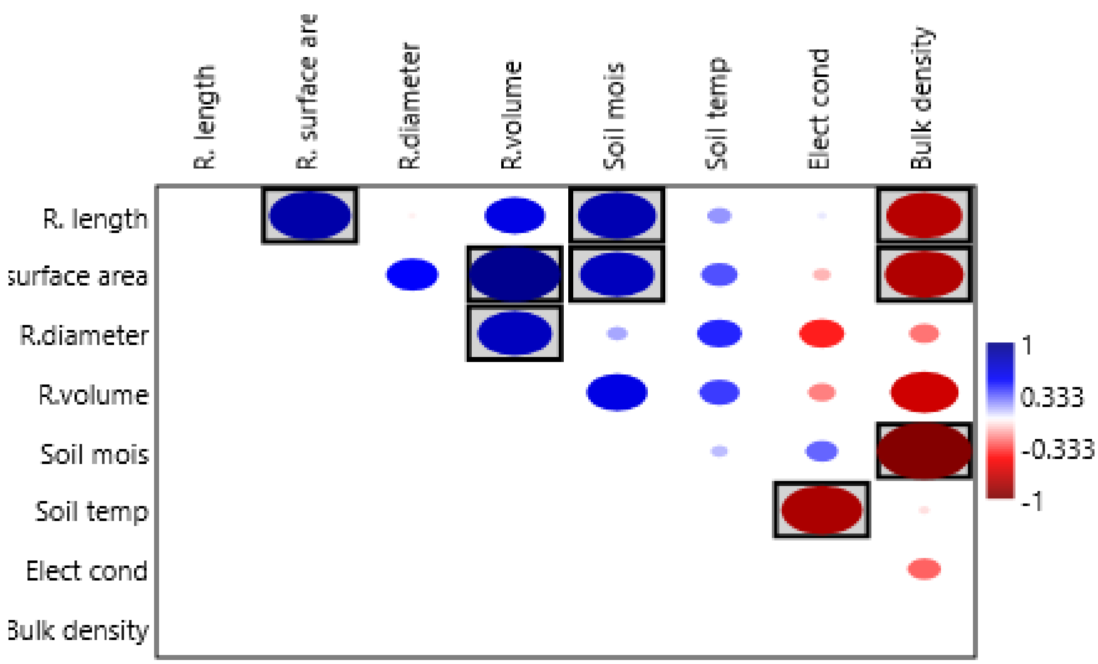

Figure 3. Correlation coefficients among root traits and soil physical properties. Bold squares indicate significant difference at p≤0.05.
Source: Authors

soil-plant linkage during crop life (Manschadi et al., 2008; Paez-Garcia et al., 2015). Soil penetration resistance is one of the important soil properties that limits root growth and absorption of water and nutrients. Njoro and Egerton locations were significantly different for root length, root surface area, root diameter and root volume which is in agreement with Moraes et al. (2014).

The FT had lower soil moisture content than RT. This indicates the effect of ridge system in soil moisture conservation irrespective of location difference. The differences in moisture content might be related to soil aeration, ease of water infiltration and control of water runoff during precipitation. The RT has been reported to control soil erosion and conserve water post precipitation which indicates that cultivars on the RT had more duration of exposure to water during growing stages than those in the FT (Lal, 1990; Ren et al., 2010). On the other hand, the FT seems to accumulate more heat than the RT. The results showed that increase in soil temperature simultaneously led to increase in soil moisture content and rooting activity (Xie et al., 2005). However, starch synthase enzyme which is responsible for synthesis and deposition of starch in wheat kernel is sensitive to temperature over which at high temperatures its activity declines leading to shrivelled kernel with low weight and quality (Zi et al., 2018; Lu et al., 2019). Soil temperature directly influences soil electrical conductivity which directly affects soil nutrient concentration, soil salinity and yield production (Ma et al., 2011; Othaman et al., 2020). The FT had high bulk density which increased with decrease in soil moisture, soil temperature and electrical conductivity. This might be the reason why RT had high grain yield and TKW across locations (Ma et al., 2011).

Growth and production of wheat crops highly depends on the root architecture, ease of growth and absorption of nutrients which is influenced by soil properties. Tillage systems have a significant influence both on soil properties and root growth. The RT had higher mean for root length, root surface area, root diameter and root volume due to reduced bulk density (Lynch, 1995). Under RT there is high competition for nutrients compared to FT. As a result, there is high root extension and growth. Further, RT has a well aerated soil with reduced bulk density which increases soil permeability facilitating better root growth and penetration. This may also result to low crown-root ratio. Better root growth reflects the suitability of the RT in growth of wheat cultivars due to readily available soil water content and efficient nutrient supplementation (Chen et al., 2020). However, the utilization of the absorbed water and nutrient might also be a function of ability of the crop to take up the limited water and nutrients at a reduced metabolic rate. Shift in water availability at the pre and post anthesis stage in wheat, might have great impact on grain yield, thousand kernel weight and test weight. Therefore, adoption of cropping system which cautions wheat crop from water stress in vital (Kirkegaard et al., 2007; Elazab et al., 2016).

Yield is a trait that is influenced by the environment. In this study, high yield, TKW and HI were observed in Egerton than Njoro. As much as environment influence cultivar performance, the genetic yield potential of wheat cultivars greatly determines the production ability of the cultivars. Previous studies have shown that RT can improve wheat yield by 12% more than FT (Hussain et al., 2018). In this study, RT had 39.19, 7.66, 20 and 8% higher yield, TKW, HI and NDVI, respectively than FT.

Wheat cultivar *Kwale* had the highest yield while Kingbird had the highest TKW. The differences in yield and yield related traits between the RT and FT might be prompted by soil physical properties. The RT is effective in promoting soil water conservation, soil aeration, optimum soil temperature, increase soil electrical conductivity, reduced soil bulk density, increased root growth and penetration to deeper soils which ultimately improve yields (Ren et al., 2010).

The RT had high normalised difference vegetative index which is highly correlated with leaf area index, biomass, fractional of absorbed photosynthetic active radiation and grain yield suggesting that plants had higher vegetation and high red light compared to infrared reflected absorbed (Tucker, 1979; Teal et al., 2006). This enhances photosynthesis which translates to high kernel yield and quality. According to Sultana et al. (2014), NDVI is highly correlated with grain filling days, days to maturity and grain yield of wheat.

Cultivars planted on RT took long to flower, head, had longer spike length, high number of seeds per spike and spikelets, and took long time to mature. This is presumed to high moisture content and low temperatures in RT than FT implying cultivars in RT had longer exposure to moisture increasing their growth period. Adequate soil moisture increases grain filling period by delaying maturity and leaf senescence (Motzo et al., 2010). Therefore, there is extended photosynthesis period increasing duration of assimilate partition to the grain resulting to high yield and kernel quality. Wu et al. (2019) found that variation in yield is positively associated with grain filling period which was also related to grain number per unit area.

Conclusion

The ridge tillage system facilitates improved soil aeration, conserves soil moisture, optimum soil temperature and ease of root penetration. Good tillage practice, root system and soil physical characteristic generally influence the final root structure of wheat crop which translates to improved yield. This study revealed that ridge tillage system provided essential elements of water and nutrient in the growth and development of wheat. Furthermore, high electrical conductivity made sure essential soil nutrients and salts were available for plant uptake. High yield, TKW and harvest index in the ridge system is an important affirmation of effectiveness of ridge tillage system to wheat growth. The results suggest that ridge tillage is an efficient tillage practice for improving wheat production due to long grain filling period, high NDVI, and maturity period facilitating photosynthesis, chlorophyll and dry matter accumulation. Therefore, the ridge tillage was an effective conservatory soil management practice for maintaining suitable hydrothermal conditions for the growth and performance of spring wheat cultivars under high crop water consumption conditions.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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