RESPONSE OF SPRING WHEAT (*Triticum aestivum* L.) CULTIVARS TO RIDGE-FURROW TILLAGE SYSTEMS

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DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been presented in this university or any other for the award of a degree.

Signature: Date: 11th July, 2023

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KM121/13706/19

Recommendation

This thesis has been submitted with our approval as university supervisors.

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DEDICATION

This thesis is dedicated to my family for their prayers, unwavering moral support, and understanding they accorded during the course of my studies.

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ABSTRACT

Soil tillage has influence on soil conditions and rhizosphere, ultimately influencing growth and productivity of plants. The objectives of this study were to (*i*) determine the effects of ridge-furrow on the physiology and growth of spring wheat, (*ii*) determine the effect of ridge-furrow planting on kernel yield and yield components and (*iii*) to determine the effect of ridge-furrow on root growth and soil physical characteristics. This experiment was conducted at Egerton University (0º 22' 26'' S, 35º 56' 1.3'' E) and Kenya agricultural and livestock research organization, Njoro (0° 22′ 47'' S, 35° 56′ 1.7'' E) in a randomized complete block design (RCBD) as a split-plot arrangement. Tillage systems served as the main plot and cultivars (*Kwale* and *Kingbird*) as the sub-plot. Location had a significant ($p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$) effect on (ear emergence, flowering, maturity, flag leaf senescence, plant height. Yield, 1000 kernel weight, spike length, number of spikelets, chlorophyll, NDVI and soil traits (temperature, electrical conductivity, and bulk density). Tillage system was significant ($p \leq 0.001$) for ear emergence, flowering, maturity, flag leaf senescence, plant height, yield, 1000 kernel weight, spike length, harvest index, kernels per spike, number of spikelets and chlorophyll content. Cultivar *Kwale* and *Kingbird* were significantly ($p \leq 0.05$) different for all the traits. The ridge system had higher means for yield (2.22 tonnes ha^{-1}) than the flat system (1.35 tonnes ha^{-1}). Cultivars in the ridge system took 4 days longer to flowering and heading and 7 days longer to maturity and flag leaf senescence than the cultivars in the flat tillage system. Yield significantly correlated (r=0.76*) with thousand kernel weight and the number of seeds $spike^{-1}$ (r=0.73*). Soil bulk density negatively correlated to root length (r=-0.78*), root surface area (r=81*), root diameter (r=-0.27) and root volume (r=-0.68). Soil moisture positively associated with root length (r=0.80*) and root surface area (r=0.76*). This study has shown that ridge tillage system improved wheat roots and plant growth, kernel yield and yield components. Therefore, the approach could be implemented for wheat cultivation in Kenya.

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LIST OF ABBREVIATIONS AND ACRONYMS

CT	Canopy Temperature
DF	Days to Flowering
DH	Days to Heading
DTM	Days to Maturity
FAO	Food and Agriculture Organization
FLS	Flag Leaf Senescence
NUE	Nitrogen Use Efficiency
PAR	Photosynthetic Active Radiation
PHS	Post-Harvest Sprouting
RF	Ridge – Furrow
RUE	Radiation Use Efficiency
SAS	Spike component
SC	Spike Length
WUE	Water Use Efficiency

CHAPTER ONE

INTRODUCTION

1.1 Background information

Agricultural management practices such as soil tillage affects soil physical, chemical, and biological properties in both short and long term. These therefore have direct impacts on crops development and productivity as well as agricultural sustainability. 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). Soil tillage have a great impact on the spring wheat rooting pattern, water holding capacity, aeration, penetration, soil temperature, soil compaction and microbial activities (Hosl & Strauss, 2016; Kisic *et al.,* 2017; Troldborg *et al.,* 2013). The ridge system is suitable to varying areas where the rains are scarce, abundant or even in areas prone to flash-floods since the plants are protected from run-off and hence maintaining the plant populations in the field (Liu *et al.,* 2020; Wang *et al.,* 2016).

Ridge and furrow planting systems improves water distribution. The technique improves irrigation, nutrient management, saving in water, better crop stand, lower seed rate, permits mechanical weed control, band application of fertilizers and reduction in lodging (Govaerts *et al.,* 2006). It has also been demonstrated that ridge tillage affects soil properties such as soil temperature and mineralization of organic matter which will further affect crop traits such as leaf area index, photosynthesis and kernel yields (Liu & Wiatrak, 2012; Qu *et al.,* 2014; Shi *et al*., 2012).

Conventional soil tillage practices may affect soil physical properties both positively and negatively resulting in variable crop yields (Alvarez & Steinbach, 2009). Conventional primary tillage also results in high rates of soil erosion (Kisic *et al*., 2017) thus there is need for more sustainable management practices (Mwango *et al.,* 2016). Selection of the variety is also important in ridge planting. Wheat varieties with the broad leaf area and ground cover have higher kernel yield in comparison with upright and compact structure varieties lower in ridge planting. have indicated that Plants grown in ridges are less exposed to salt than flat land planting in areas where salt rises by capillary action during wet seasons (Rawson *et al.,* 2007). Boulal and Gomez-Macpherson (2010) asserted that, the ridge system ensures minimal soil compaction and improved soil aeration as machines move along the furrows ensuring minimal disturbance of the soil flora and fauna during the growing seasons. Land with a slope exceeding 2 % will usually require some conservative measures to control soil erosion in order to create long-term agricultural sustainability (Partey *et al.,* 2018).

In Pakistan, wheat sown on ridge and furrow system in the rice (*Oryza sativa*) - wheat area of Punjab produced good yields due to better spike length, number of kernels per spike (Mollah *et al., 2015*). The RF system enables the use of inter-row cultivators to break and stir the soil between the ridges therefore enabling mechanical control of the weeds as well as hand weeding which is an economical option because of the orientation of the rows (Mollah *et al.,* 2015).

further studied the raised bed planting method of wheat in Bangladesh and found higher wheat productivity in the ridge than flat tillage system by planting wheat on a 70 cm bed in the rice-wheat cropping system. Iqbal *et al.* (2022) illustrated that ridge and bed planting techniques resulted in higher yield, water use efficiency and less consumption of water than the conventional tillage and planting systems. Fertilizers can also be applied at the sides of the ridges giving the highest nutrient use efficiency (NUE) and in semi-arid areas, ridges can be modified to form tied ridges which can be used to collect rainwater for irrigation during dry periods (Kumar *et al.,* 2007).

Wheat production in Kenya has been usually practiced on flat soil tillage system (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 to lower yields (Sayre *et al.,* 2004).

1.2 Statement of the Problem

Conventional soil tillage practices have had significant effects on soil degradation through decline of soil structure, low organic matter content, rhizosphere processes and a fragile soil-physical structure, which in turn leads to low crop yields and low water and fertilizer use efficiency. These has resulted to soil compaction, limited root growth (root length, surface area, length and volume) limiting the absorption of moisture and nutrients. This is coupled with the adverse effects of climate change and high temperatures during reproductive stages of the wheat that have caused significant yield losses and kernel quality reduction mainly because of reductions in the duration of developmental stages through early leaf senescence, decreased biomass, and adverse physiological and biochemical changes. Wheat production systems in Kenya also normally involves production in flat land surfaces which are prone to flooding in flat areas, runoffs in uneven topographies, poorly aerated soils and canopy conditions which, moreover, affects crop yields due to lodging, leaching of nutrients and causes changes in pathogen spectra. This is further worsened by the limited volume of the soil within the root zone limiting the rhizosphere processes limiting root growth, penetration resistance, microbial activities, mineralization and nutrient cycling. Furthermore, the population of Sub-Saharan Africa is projected to hit 1.2 billion by the year 2050 and the changes in precipitation in the future due to climate change are likely to decrease rainfall causing a decrease in wheat production and increase vulnerability to food shortages. The proximal technological solutions to address these challenges is proper agronomy. Ridge tillage improves soil aggregate stability that enhances nutrient retention and reduces soil erosion thereby contributing to soil fertility and mediates air permeability, water infiltration, and nutrient cycling. These therefore calls for changes in agricultural systems and adoption of more sustainable agricultural production technologies to improve the wheat crop physiological functions and productivity to meet the current global demands for nutritious food. In this study, the challenges were addressed by examining the effect of ridge-furrow (RF) planting systems on wheat morphology, root growth, leaf senescence, and production of two spring wheat cultivars. This rationale is intended to provide the appropriate agronomic and soil management solutions to improve the wheat development processes and increase its yield per unit area.

1.3 Objectives

1.3.1 General objective

To contribute to increased food security and wheat productivity through ridge-furrow (RF) tillage system.

1.3.2 Specific objectives

The objectives of this study were to determine the effect of ridge-furrow tillage on the;

i. Physiology and growth of spring wheat.
ii. Kernel yield and yield components
iii. Root growth and soil physical characteristics.

1.4 Hypotheses

i. Ridge-furrow technology has no significant effect on spring wheat growth and physiology.
ii. Ridge-furrow planting has no significant effect on the kernel yield and yield components of spring wheat.

iii. Ridge-furrow planting technology has no significant effect on the root growth and soil physical characteristics.

1.5 Justification

Kenya produces an estimated 350,000 tonnes of wheat annually against an annual consumption of 1,000,000 tonnes thus relying largely on wheat importations from other countries (Gitau *et al.,* 2010). In Kenya, wheat yield is as low as 2 tonnes per hectare on smallholder farmers against a potential yield of 8 tonnes per hectare resulting in yield gaps of at least 6 tonnes per hectare (more than 70 %) (Fischer *et al.,* 2015). Moreover, soil factors affect rooting depth which then have a greater effect on yield. Low soil moisture, poor soil nutrient content and limited rhizosphere processes and activities in the conventional flat planting systems affects wheat productivity as it influences leaf senescence, tillering, flowering, thousand kernel weight (TKW), harvest index (HI) and yield potential (Gan *et al.,* 2013). Currently the recovery of applied fertilizer efficiency is less than 50 % for N, 10 % for P and less than 40% for K which is attributed to leaching, run-off, gaseous losses, fixation as well as potential soil and environmental degradation-(Singh *et al.,* 2018). Wheat is sensitive to water limitation especially during ear emergence to flowering stages. Ridge-furrow technology will ensure maintenance of optimum soil moisture at this critical period to ensure higher wheat yield and yield stability. The crop is the only crop for which area under cultivation has been reducing in the recent decades and yield has become more variable (Tadele, 2017). There is need in developing efficient, intensive and profitable management practices and technologies in order to improve the livelihoods of the smallholder farmers and build their interest to venture into wheat production while at the same time enhancing environmental resilience. In the past decades, ridge-furrow technology was used mainly in crops with small row distances such as potato (Gan *et al.,* 2013). Therefore, can yield increase be achieved by improving soil conditions to offset the losses caused by climate change and reduced cultivation area? The answer to this question will be essential for adoption of RF planting systems in different areas. The row spacing in conventional flat land cultivation systems limits radiation use efficiency leading to decrease in growth and photosynthetic characteristics of the wheat. However, little is known on the effects of ridge-furrow technology on soil conditions, root morphology, spring wheat growth and productivity in Kenya as well as Sub-Saharan Africa.

CHAPTER TWO

LITERATURE REVIEW

2.1 Wheat origin, production, and yield

Wheat (*Triticum aestivum* L.*)* is a grass widely cultivated for its seed, a cereal kernel which is a worldwide staple food. It is one of the most widely cultivated crops in the world (Fischer *et al.,* 2014). The many species of wheat make up the genes *Triticum,* and the most widely grown is common wheat. The global wheat production increased linearly at a rate of 8.7 tonnes year^{-1} during the past 60 years (Fischer *et al*., 2014). It is one of the 'top three' staple cereal crops cultivated and consumed by 33% of the world's population and livestock, with an annual harvest of over 600 million tonnes (Abbas *et al.,* 2009; Hussain *et al*., 2002). World trade in wheat is greater than for all other crops combined (Curtis *et al.,* 2002). In 2017, world production of wheat was 772 million tonnes, with a forecast of 2020 production at 768 million tonnes (USDA, 2020) making it the second most-produced cereal after maize (FAOSTAT, 2014). About 734 million tonnes of wheat was produced from 214 million hectares of land cultivated in the world in 2018 with the leading producers being China, India, Russia and the US (FAOSTAT, 2018). Approximately one-third of wheat grown in the world is irrigated and is the most irrigated crop after rice with Asia making up 37% of the irrigated wheat area (Toureiro *et al.,* 2017).

Wheat originated in Levant in the Middle East (Abbo & Gopher, 2020). This area features a large diversity of *Triticum* L. species; for example, *T. aethiopicum, T. araraticum, T. boeoticum, T. dicoccoides, T. dicoccum, T. carthlicum, T. ispahanicum, T. karamyschevii, T. macha, T. monococcum, T. sinskajae, T. spelta, T. timopheevii, T. turanicum, T. urartu, T. vavilovii, and T. zhukovskyi and related species such as Aegilops spp.* The evolution of domesticated wheat was characterized by interspecific hybridization events, showing positive correlation between increased ploidy and productivity (Dubcovsky & Dvorak, 2007).

The most important wheat producing countries in Sub-Saharan Africa (SSA) are Ethiopia, South Africa, Sudan, Kenya, Tanzania, Nigeria, Zimbabwe and Zambia (FAOSTAT, 2018). The crop takes up about 30 % of the land area under cereal cultivation constituting 15.4 % of the world's arable land (Curtis, 2002) and account for about 27% of the world cereal production (Singh & Trethowan, 2007). Spring wheat cultivars are the most dominantly cultivated in the SSA region except in South Africa where the spring wheat is grown during the winter season under irrigation, while the winter/facultative wheat types are dominantly grown during the summer rainfall season accounting for about 20 % of production (Negassa *et al.,* 2013). In Kenya, wheat production systems are majorly done by the smallholder farmers with less than 8 hectares while the rest of production is medium (8 to 20 hectares) with the large-scale farmers cultivating more than 20 hectares (Justina & Jonas, 2008). Africa produces more than 25 million tonnes of wheat on 10 million hectares. SSA produced a total of 7.5 tonnes on a total area of 2.9 million ha accounting for 40 and 1.4 per cent of the wheat production in Africa and at global levels, respectively.

Grain yield has been the major driver of wheat production increase driven by improved cultivars and agronomic practices. Arata *et al.* (2020) conducted a detailed study on yield trends and concluded that differences in climate variability and agronomic management are the major causes of differential yield variability. In the most productive areas, climate variability is associated with year-to-year yield variation (Ray *et al*., 2015) e.g., in China and India, who are the top wheat producers, 32 % of their yield variation is associated to rainfall temperature. The present average global yield now stands at 3400 kg ha^{-1} (FAOSTAT, 2020) and the leading countries are Ireland, Netherlands, Belgium, New Zealand and the United Kingdom averaging (7900 – 9200 kg ha^{-1}).

2.2 Economic importance of wheat

Wheat is an important source of carbohydrates (Shewry *et al.,* 2015). Globally, it is the leading source of plant protein in human food, having a protein content of about 13 %, which is relatively high compared to other major cereals. However, it is relatively low in protein quality for supplying essential amino acids. When eaten as the whole kernel, wheat is a source of multiple nutrients and dietary fibre (Shewry *et al.,* 2015). In Kenya wheat products are mainly consumed by middle- and high-income earners in the rural and urban areas and its demand exceeds domestic production by more than 50 %. Wheat is a major staple food crop which provides approximately 20 % of the calories and proteins consumed in the global diets. Wheat kernels contain 13 % protein and 78 % carbohydrate hence an important source of carbohydrate compared to other cereals (Shewry *et al*., 2015).

The wheat demand is expected to spiral up as a result of the changing dietary needs and preferences of the growing population and with wheat being a preferred food, continuing to account for a substantial share of human energy needs in 2050 (Giovannucci *et al.,* 2012). Wheat is the world's third important staple food crop after maize (*Zea mays*) and rice (FAOSTAT, 2018).

Wheat is used for food, industrial raw material to prepare alcoholic beverages, starch and straws, and animal feed (Kirsten & Nhemachena, 2017). Wheat productivity increases favourably affecting human well-being primarily through the income effect for producers and lower food prices for consumers. For low-income countries, this leads to higher wheat consumption (Reynolds *et al*., 2010).

2.3 Botany and physiology of wheat

Morphologically, the wheat plant is rhizomatous (showing relationship with the grass family) with the shoot bearing several leafy culms/tillers (Wheat growth guide). Wheat roots can extend as far as 2 metres and the plant accumulates energy store in the stem in form of fructans as a result of root growth helping the plant to yield under drought and stressful conditions (Zhang *et al*., 2015). The flag leaf (last leaf) along with the second and third highest leaf supply the majority of carbohydrate in the kernel and thus very vital to yield formation (Pajevic *et al.,* 1999). Wheat usually has more stomata on the upper (adaxial) side of the leaf than the under (abaxial) side. The culms are cylindrical, generally hollow with solid nodes; the diameter reduces gradually towards the top internode (peduncle) which bears the spike (Kirby, 1987). The plant height is attributed to variation in length of the internodes, and it is mostly genetically determined. The leaf sheath encases the culm and extends from the node to which it is attached to the next higher node. The leaf-blade is long, narrow and flat with parallel veins (Kirby & Perry, 1987).

The inflorescence, commonly called 'ear' or 'head', is a spike having florets (spikelets) arranged on opposite sides of the flat rachis. Each spikelet in turn is a condensed reproductive shoot consisting of two sterile bracts (glumes) that enclose 3-5 florets (Kirby ***et** al.,* 1989). The florets consist of two bract-like structures, the lemma and the palea, which encase the reproductive organs. The lemma extends to form the awns that may be short, long, or absent (awnless). The spikes in durum wheat are dense having long awns. There are three stamens and the pistil bears two styles with a feathery stigma. Pollination is predominantly by self-pollination (Kirby ***et** al.,* 1989).

The kernels on maturity are variously classified on the basis of colour into white, amber and red, the texture being hard or soft (Noda *et al*., 2003). Wheat varieties are soft if the gluten content is low and are hard if they have high gluten content. White flour is made from endosperm, brown flour from the kernel's germ and bran, whole grain from the entire kernel, while the germ flour is made from the endosperm and germ. Changes in phenology is critical for domestication of crops (Gao *et al.,* 2017; Lu *et al*., 2019) and is equally important in matching crop and environment for two seasons (Dreccer & Sadras, 2015).

Wheat undergoes a series of developmental phases from sowing to harvest. There are at least five scales used worldwide to describe stages of wheat growth. Wheat growth phases include tillering, jointing, booting, heading, anthesis, and grain filling (Hossain *et al.,* 2013). Crop phenology controls the life cycle, partitioning of assimilates between crop organs and determines the timing of various agronomic management practices. Phenology has been shown to change worldwide as temperature has risen in recent decades affecting most crops (Zhang *et al.,* 2013). The existing genetic variability for the different photoperiod sensitivity, vernalization requirement and earliness allowed developing adapted cultivars for almost all regions of the world (Chen *et al.,* 2015). Wheat growth stages have been identified at the physiological and the agronomical levels (Haun, 1973; Zadoks *et al*., 1974). Wheat is categorized into spring, winter and facultative types. Zadoks *et al.* (1974) developed a scale used for agronomic research and farming decisions such us application of agrochemicals and fertilisation. This puts in consideration two digits in a decimal code whereby the first digit from 0 to 9 refers to the main stage or organ and the second digit simplifies the advancement of the stage or organ. The *Feeks* scale (1941) championed by Large (1954) has 1 for each of the stages and thus less detailed. The *Haun* scale (1973) focused on appearance of leaves and it describes the number of leaves in the main shoot. The growth habit reflects the need to survive in different climates and affects productivity by timing crop stages to more favourable conditions. The physiological stage of ear emergence is delayed until the plant experiences vernalization which is a period of cold winter temperatures 0 to 5 ºC (Curtis *et al.,* 2002). Facultative wheat varieties require shorter periods of vernalization and temperatures of 3 to 15 ºC than winter wheat varieties thus they can be grown as either winter or spring wheat depending on the sowing time (Brooking & Jamieson., 2002).

Extreme climatic events result into, manipulating planting dates and cultivar phenological phase to match critical stages with favourable environmental conditions is pivotal in reducing yield loss (Dreccer *et al.,* 2018; Flohr *et al.,* 2018). The time from anthesis is divided into 2 phases i.e., the vegetative (from sowing to floral initiation) and reproductive phase (from floral initiation to anthesis) with the latter being divided into early and late reproductive phases (Ochagavia *et al.,* 2017). Phenology, vernalization and earliness also alter different phases of development (Ejaz & von Korff, 2016; Ochagavia *et al*., 2017; Perez-Gianmarco *et al*., 2018).

2.4 Agronomy of wheat

2.4.1 Global wheat production and yield gains

The global production has shown a linear increase with the rate of 8.7 tonnes per year (tonnesy^{-1}) in the past 60 years. The production has however averaged at 750 tonnes over the last 5 years with China (124.9 tonnes year^{-1}), India (91 tonnes year^{-1}), Russia (60.2 tonnes year^{-1}), US (56.7 tonnes year^{-1}) and France (56.7 tonnes year^{-1}) producing 52 % of the global wheat (FAOSTAT, 2020). China and India account for one-third of the global production (FAOSTAT, 2020). Other countries such as Canada, Argentina, Ukraine, and Turkey produce a significantly large amount of wheat (FAOSTAT, 2018). Among African countries, Ethiopia, Algeria, Egypt, Kenya, Morocco, and South Africa have the largest area devoted to wheat production with total production above 1 million tonnes per year. Variable wheat kernel yield response unit area^{-1} is reported from New Zealand (9 tonnes ha^{-1}), Saudi Arabia (6 tonnes ha^{-1}), Zambia (6.6 tonnes ha^{-1}), Egypt (6.5 tonnes ha^{-1}), and China (5.4 tonnes ha^{-1}) in 2016 (FAOSTAT, 2018). The world average wheat yield is 2.9 tonnes ha^{-1} (FAOSTAT, 2018). Worldwide, about 33% countries achieved yield levels less than 2 tonnes ha^{-1}, while 21% countries recorded more than 3 tonnes ha^{-1} and 22% more than 5 tonnes ha^{-1} (FAOSTAT, 2018).

2.4.2 Agronomic traits of wheat

Agronomic traits such as plant height, harvest index (HI), biomass, number of productive tillers, kernel number spike^{-1}, spike length (SL), number of kernels spike^{-1}, thousand kernel weight, kernel weight spike^{-1} and physiological traits such as canopy temperature (CT), chlorophyll content, photosynthetic rate, water-soluble carbohydrates (WSC) have contributed to kernel yield improvement in wheat (Beche *et al*., 2014; Chen *et al*., 2016; Foulkes *et al*., 2007; Gao *et al*., 2017; Lopes *et al.,* 2012; Zhang *et al*., 2016). Important agronomic traits have been exploited in wheat improvement programmes to aid cultivar development and increase kernel yield potential and genetic gains. Root traits influence the amount of water and nutrient absorption and are important for maintaining crop yield under drought conditions (Gupta *et al.,* 2012). Root-related traits such as root**:** shoot ratio have negative relationship with agronomic traits such as plant height, number of tillers, shoot biomass, thousand kernel weight, and kernel yield. The growth and yield of wheat are affected by the absorption of water and nutrients in the root system (Gaire *et al.,* 2016).

Deep root system helps the plant to avoid drought stress by extracting water stored in deep soil layers (Curtis *et al.,* 2002). Increased root diameter is associated with drought tolerance because thicker roots have large xylem vessels with increased axial conductance and are more efficient in penetrating deep soil layers to extract water (Godfray *et al.,* 2010). Root length density increases the prolificacy of the root system and is the most important trait for increased phosphorus uptake in wheat (Shewry *et al.,* 2015). Fine roots increase increase root surface area per unit mass water and nutrient absorption (Dunn *et al*., 2019). Fine roots constitute the major component of the root systems and are the most active part of the root system in extracting water and nutrients (Tanno *et al.,* 2006). Number of active tillers is defined as the number of tillers that produce spikes and seeds. It is a key agronomic trait that affect biomass production and kernel yield potential in wheat (Tausz-Posch *et al.,* 2015). Wheat cultivars with reduced tillering capacity are more productive than free-tillering cultivars under drought stressed conditions (Houshmandfar *et al.,* 2019; Naruoka *et al.,* 2011; Wang *et al*., 2016) due to reduced sterile spikelets (Gaju *et al.,* 2014).

Optimal flag leaf morphology can improve light absorption, which improves photosynthesis and grain yield potential (Liu *et al.,* 2018). Flag leaf length, width and area are correlated with some important agronomic traits (Liu *et al*., 2015). Leaf traits influence yield-related traits (Liu *et al.,* 2018). Wheat cultivars with relatively larger flag leaf size produces more kernel number per spike (Zhao *et al.*, 2018), suggesting appropriate flag leaf size promotes development of high kernel yield potential. Flag leaf area is the most yield contributing trait, followed by its width and length (Fan *et al*., 2015).

Increased biomass has resulted in kernel yield improvement in wheat. The increase in biomass has been largely attributed to higher photosynthetic rate, stomatal conductance, leaf chlorophyll content and improved radiation-use efficiency (Bustos *et al.*, 2013). Improvements in kernel yield can be achieved by increasing photosynthetic capacity by optimizing biomass production while maintaining lodging resistance (Beche *et al*., 2014). Several studies showed that biomass contributed significantly to increased kernel yield (Aisawi *et al.,* 2015; Bustos *et al*., 2013; Gao *et al.*, 2017; Shearman *et al*., 2005; Xiao *et al.,* 2012), whereas other studies indicated very little contribution of this trait (Royo *et al.*, 2007; Sun *et al*., 2014; Tian *et al*., 2011; Zhang *et al.,* 2016; Zheng *et al.,* 2011). Zheng *et al*. (2011) reported that further increase in above-ground biomass and HI may continue to contribute to kernel yield improvement in cultivars within optimum plant height. In some instances, positive association has been reported by Aisawi *et al.* (2015) that manipulation of this trait can improve genetic gains in kernel yield even further.

Early maturing wheat cultivars are an adaptive mechanism for environments experiencing terminal heat and drought stress (Giunta & Motzo, 2007; Mondal *et al*., 2016). Yield increase is not usually associated with early flowering in wheat (Chairi *et al.*, 2018; Flohr *et al.*, 2018). The limited genetic gains incorporating early maturity may be due to reduced time available for assimilate partitioning required for high kernel yield development (Royo *et al.*, 2007) partly explained by the negative association between kernel weight per spike and heading date (Zhou *et al.*, 2007).

Wheat has a high source to sink ratio a strategy that ensures grain filling and viable seed size (Sadras, 2007). Number of kernels and yield are sensitive to stress especially towards anthesis (Prasad & Djanaguiraman, 2014). Zhang *et al.* (2010) indicated that a longer phase in florets development influences kernels setting. Therefore, optimizing the developmental pattern by changing the partitioning of developmental phases of anthesis into different durations occurring earlier or later than the initiation of the terminal spikelet may contribute to increasing spike fertility (Reynolds *et al.,* 2012). Gonzalez *et al.* (2014) has shown that the duration of the various pre-anthesis phases vary in sensitivity to vernalisation, photoperiod and temperature. According to Sadras and Slafer (2014), grain number has high plasticity and further improvements in yield must be focused on grain number. This is backed up by Foulkes *et al.* (2011) and Slafer *et al.* (2014). An increased period of stem elongation provides further allocation of biomass to the spike and thus providing greater spike weight at anthesis (Gonzalez *et al.,* 2011). Survival of floret primordia can be improved by providing more photo-assimilates to the spike by extension of stem elongation period (Ferrante *et al.,* 2013).

Many wheat improvement programmes have developed wheat cultivars incorporating the height reducing genes resulting in increased kernel yield according to Grover *et al.* (2018) thus increasing assimilate partitioning to the ear. This has resulted to higher harvest index (HI) and lodging resistance (Divashuk *et al.,* 2012). Spike fertility (SF) is a kernel yield component that influences the increase in the number of kernels per spike (Reynolds *et al*., 2017; Wurschum *et al*., 2018). Increase in the number of kernels spike^{-1} are attributed to increased SF (Wurschum *et* *al.,* 2018). Other useful spike characteristics include spike length (SL) and spike component (SC) (Chairi *et al*., 2019; Wurschum *et al*., 2018). Harvest index is calculated as the ratio of harvested product to total above-ground biological yield, which is the total dry matter accumulation of a plant system. HI is usually calculated from unit area yield and dry matter data (Gao *et al*., 2017; Zhang *et al.*, 2016).

2.4.3 Photosynthetic capacity

Understanding changes in photosynthetic capacity among wheat cultivars is important for improving yield gains (Parry *et al.,* 2010; Reynolds *et al*., 2012; Zheng *et al.,* 2011). Fischer *et al.* (1998) reported that wheat yield gains are associated with increased stomatal conductance and photosynthetic rate. High yield can be achieved by integrating photosynthesis related traits (e.g stomatal conductance and transpiration rate) with yield-related agronomic traits as evinced by Zhang *et al*. (2016) to develop cultivars with high yield potential (Rebetzke *et al.*, 2013).

Increasing photosynthesis by enhancing the substrate CO_2 has been clearly demonstrated to increase yields (Ainsworth & Long, 2005). There are opportunities to increase photosynthesis by improving early vigour and by manipulating senescence to delay its onset. Despite the fact that there is considerable variation in the structure of modern wheat canopies (e.g. flag leaf size and leaf angle) light interception is very important for further improvements in photosynthesis (Murchie *et al.* 2009, Reynolds *et al.,* 2012). The biggest potential gains in cumulated photosynthesis would be achieved by increasing the photosynthetic rate. In wheat, only 4.6% of the intercepted radiation is converted to photosynthate, therefore, there is a good scope for improvement (Zhu *et al.,* 2010). Numerous potential ways to increase photosynthetic rate have been identified (Parry *et al.,* 2011). Many of these focus on increasing the concentration of CO_2 within the leaf. Simply increasing stomatal and mesophyll conductance will increase photosynthetic rate and yield (Fischer *et al.,* 1998) but may decrease water use efficiency. Photosynthetic capacity and efficiency can be increased by improving performance and regulation of Rubisco, improving light interception, optimizing spike and canopy photosynthesis. Amount of intercepted radiation during the critical period is key determinant of yield (Sandana *et al.,* 2009). The potential yield of spring and winter wheat is similar in high yielding environments (Bustos *et al.,* 2013).

The effect of nutrient availability on radiation interception in wheat is largely dependent on leaf area index [LAI] (Sandana *et al*., 2012). LAI and radiation interception accounts for nitrogen and sulphur supply on growth rate and shoot biomass of wheat. Consequently, phosphorus deficiency reduces LAI (Sandana *et al*., 2012). Radiation use efficiency (RUE) varies with developmental processes (ontogeny) and usually decreases from anthesis to maturity. Leaf senescence processes, ageing of photosynthetic tissues and higher respiration is attributed to the fall in post-anthesis radiation use efficiency (RUE). This is since N is remobilized to the grains at the expense of the leaf N concentration (Moreau *et al.,* 2012). Sink limitation commonly downregulates photosynthesis during grain filling. Therefore, increasing post-anthesis sink is related to improvement in post-anthesis RUE at similar levels of pre-antheis (Bustos *et al.,* 2013). Richards *et al*. (2019) evinced that the relationship of RUE with leaf inclination in that electrophile lines yielded 13 % more than planophile lines and this was associated with high shoot biomass. Consequently, lines with higher RUE before and after anthesis produced 20 % more biomass (Bustos *et al.,* 2013; Garcia *et al.,* 2013). High vapour pressure deficit (VPD) limits radiation use efficiency in wheat (Dreccer *et al.,* 2013). This is since high proportion of diffuse radiation increases RUE and crop simulation models have confirmed this (Asseng *et al.,* 2015).

2.4.4 Capture and efficiency in the use of resources

There is variation of evapotranspiration and rainfall amongst different environments and water deficit is the main abiotic stress affecting wheat production worldwide (De Oliveira Silva *et al.,* 2020; Ding *et al.,* 2018). Simple techniques conserve soil moisture and improve productivity of most crops (Amede *et al.,* 2011*;* Zougmore *et al;* 2004). Soils with high water-holding capacity (WHC) buffer the plants against occasional dry spells between rainfall events. Therefore, management of water has high impact on wheat yield (Dreccer *et al.,* 2018).

Kernel yield is associated with shoot biomass when environment and management are the key factors driving yield variation across genotypes (Cossani *et al.,* 2009; Garcia *et al.,* 2013). Leaf area index (LAI) and radiation interception accounts for the combined impact of Nitrogen and sulphur supply on growth rate and shoot biomass. The decline in post-anthesis RUE is ascribed to increased respiration, leaf senescence processes and ageing of photosynthetic tissues (Moreau *et al.,* 2012). A weak sink may down-regulate photosynthesis during grain filling since grain growth is sink-limited (Serrago *et al*., 2013).

Crop water uptake depends on the depth and distribution of the root system (Kirkegaard & Thorup-Kristensen, 2016). Rate of leaf appearance, pattern of tillering contributes to early vigour (Zhao *et al.,* 2019). Nutrient deficiencies may also restrict water availability to crops according to De Oleveira Silva *et al.* (2020) and early fertilization improves vigour, increases root density and volume as well as water uptake in deeper layers (Wang *et al.,* 2018). Root traits such as architecture, lateral branching and thinner roots, length and density of root hairs also contributes to increased water uptake (Lynch, 2019). Allocation of resources to roots largely depends on management rather than breeding (Allard *et al.,* 2014).

Water use efficiency (WUE) of wheat is defined as gas exchange (mol of CO_2 mol of H_2O) to biomass or yield per unit seasonal ET and it ranges from 29 to 105 kg ha^{-1} mm^{-1} for biomass and 5.4 to 24 kg ha^{-1} mm^{-1} for yield (Fan *et al.,*2018; Lawson & Sadras, 2013). WUE is usually estimated from successive shoot biomass samples at different phenological stages and evapotranspiration estimates using soil water balance or lysimeter. WUE declines with increasing vapour pressure density (Angus & Sadras, 2006) and CO_2 concentration impacts positively on WUE of C_3 plants such as wheat (Asseng *et al.,* 2015). Management practices reduces soil evaporation and increases transpiration as well as WUE (Hatfield & Dold, 2019). Fererr *et al.* (2013) proposed that maximum yield and maximum WUE are not always compatible goals thus compromising on crop and water production further emphasizing on the importance of environmental conditions.

2.5 Constraints of wheat production

Losses in wheat production are mainly due to abiotic factors such as soil acidity, poor soil fertility, flooding, waterlogging, erosion and pre-harvest losses (sprouting) are the main abiotic stresses in rain-fed environments (Abhinandan *et al.,* 2018). These stresses have tremendous effects on plant growth and development resulting to lower absorption and utilization of absorbed nutrients thus leading to reduced NUE (Fageria *et al.,* 2008*).* Rainfall, temperature and solar radiation have major influence on nutrient transformation and availability in soil and plant's ability to take up and utilize these nutrients (Baligar *et al.,* 2001).

2.5.1 Environmental factors affecting development in wheat.

Environmental effect can be highlighted by comparing the phenological responses across the different planting dates and locations (Slafer, 1995). The research conducted by Lobell *et al*. (2011) indicated that high temperatures during crops' reproductive phase lowers kernel quality and causes significant yield loss as a result of reduction in development stage, early leaf senescence coupled with adverse biochemical and physiological changes. Further, Asseng *et al.* (2015) illustrated that wheat production reduces by 6 % for every 1 ºC rise in temperature.

Spring wheat genotypes are less sensitivity to vernalisation as compared to winter wheat (Valle *et al.,* 2009). Plants have evolved the capacity to use photoperiod as a strategy to speed up or slow down development towards flowering. The leaves can detect photoperiod by changes in isomer form of phytochrome (Slafer *et al.,* 2021). Wheat is a long day plant thus the development slows down when photoperiod is shorter than critical. This will generally increase the number of primordia initiated (Zhang *et al.,* 2010).

2.6 Tillage systems

Tillage systems influences chemical, physical and biological characteristics (e.g. soil bulk density, temperature, moisture, and the vertical distribution of crop residue) thus having a major effect on soil productivity and sustainability (Al-Kaisi & Yin, 2005). Traditional soil tillage plays a great role in influencing the balance between GHG emissions and soil health via decreasing SOM and altering soil structure (Baker *et al.,* 2006; Cole *et al*., 1997; Victoria *et al*., 2012). Primarily, tillage operations are aimed at loosening the soil (i.e., increasing porosity and reducing soil bulk density). The consequences of the soil interacting with equipment used for tillage and the timing of operations may result in localized compaction of a particular soil zone and smearing (Batey, 2009; Reicosky, 2003). Soil smearing is defined as the outcome of a sliding process creating a thin but intense compaction layer, in which the soil structure has collapsed under a high compressive stress occurring at the soil–tool interface (Ashworth *et al*., 2010). Particle -to- particle or aggregate-to-aggregate contact affects the physical status of the soil matrix and its associated water, air, and temperature properties (Six *et al.,* 2002). If the soil hardens upon drying, smearing may quickly develop as a physical barrier to root development (Iqbal *et al*., 1998). Any change in soil porosity can affect the hydraulic conductivity and heat transmission characteristics of soil (Putkonen, 1998). Thus, physical parameters (such as soil moisture content, aeration, temperature, and penetration resistance) are affected by tillage and can have a direct effect on the process of seedling emergence and root growth.

Tillage has been used to optimize edaphological conditions, such as soil–water and soil–temperature regimes, soil aeration, seed–soil contact, nutrient availability, porosity, pore size distribution, and pest activity. Tillage aims to support seed germination, seedling establishment, and plant growth (Lal, 2004). All forms of soil disturbance (even in discrete rows), however, allow the soil pore–space water vapour to escape, even though most seeds germinate in an atmosphere of 90% to 100% relative humidity (Baker *et al.,* 2006). In agricultural systems, soil structure and soil organic matter are two dynamic properties which are sensitive to both crop and soil management and are found to impact soil-related properties such as fertility (Bauer & Black, 1994), erosion (Basher & Ross, 2002), tilth (Koehn *et al*., 2014) and water retention (Głab & Kulig, 2008; Salem *et al.,* 2015). The current agricultural developments, innovations and availability of tractor implements which can form ridges and are multipurpose can be used in conventional tillage as well as planting on the ridges while the seeds at the desired depths with just a single pass. Furthermore, ridge tillage can also be done with the use of ox drawn plough, disc plough or mouldboards by ploughing in alternate directions.

2.6.1 Reduced tillage

Reduced tillage leaves between 15 and 30% crop residue cover on the soil per acre (560 to 1100 kg ha^{-1}) of small kernel residue during the critical erosion period (Li *et al.,* 2005). This may involve the use of a chisel plough, field cultivators, or other implements. Reduced (RT) is widely recommended in production to improve soil structure, reduce soil erosion, and enhance soil organic matter as compared with conventional tillage (Zhang *et al.,* 2007). However, the effect of RT on climate change mitigation has been intensively debated because of the substantial inconsistency in individual field experiments (Abdalla *et al.,* 2016). Previous studies have demonstrated that RT significantly reduced (Harada *et al.,* 2007), increased (Zhang *et al.,* 2015) or did not affect (Bayer *et al.,* 2015) CH_4 emission from the soil, compared with conventional tillage (CT). RT management can improve soil quality by conserving soil organic carbon (Halvorson *et al.,* 2002), increasing crop residue inputs (Qin *et al.,* 2004), augmenting microbial biomass, activity and increasing root biomass production (Ghimire *et al.,* 2014). RT also increases crop production and profitability by minimizing soil disturbance, improving soil quality and creating more consistent soil environments for microbial growth and activity (Pengthamkeerati *et al.,* 2011)

2.6.2 Intensive tillage

Suppressing weeds helps crops to use the available soil nutrients without competition (Guan *et al.*, 2015). As plant debris is mixed with the soil through tillage, the incidence of foliar diseases that may survive from previous infections could decline (Bockus & Shroyer, 1998; Krupinsky *et al*., 2007). It also increases soil moisture by increasing water infiltration rate (Guan *et al*., 2015; Temesgen *et al*., 2008) and by softening the soil and allowing the preparation of fine seedbed, intensive tillage facilitates uniform seed germination. Uniform seed germination in turn increases the density of the plant and suppresses weeds (Hobbs *et al.*, 2008; Mouazen *et al.*, 2007; Weiner *et al.*, 2001).

2.6.3 Conservation tillage

Conservation tillage leaves at least 30 % of crop residue on the soil surface (Soil Science Society of America, 2008) or at least (1,100 kg ha^{-1}) of small kernel residue on the surface during the critical soil erosion period (Tamburini *et al.,* 2016). This slows water movement, which reduces the amount of soil erosion and improves soil structure (Erhart & Hartl, 2009) but might as well increase soil compaction in organic farming (Piegne *et al.,* 2018). Additionally, conservation tillage has been found to benefit predatory arthropods that can enhance pest control. It can also benefit farmers by reducing fuel consumption and soil compaction (Tamburini *et al.,* 2016).

2.7 Effects of tillage on soil

Tillage loosens and aerates the top layer of soil or horizon A, which facilitates planting the crop. It helps in mixing harvest residues, organic matter (humus), and nutrients evenly into the soil as well as mechanically destroying weeds. It is also fundamental in drying the soil before seeding and in wetter climates tillage aids in keeping the soil drier (Garbout *et al.,* 2013)

There are also some negative effects of tillage. Soil loses nutrients e.g. Nitrogen and fertilizer, and its ability to store water (Garbout *et al*., 2013). It decreases the water infiltration rate of soil resulting in more runoff and erosion since the soil absorbs water more slowly than before (Gebhardt *et al*., 1985). Tilling the soil results in dislodging the cohesiveness of the soil particles thereby inducing erosion thus causing chemical runoff and reducing the organic matter in the soil (Garbout *et al.,* 2013). Tillage reduces soil microbes and destroys soil aggregates causing soil compaction. It can also attract slugs (*Arion hortensis*), cut worms (*Agrotis ipsilon*), army worms (*Spodoptera frugiperda* and others to the leftover residues harbouring crop diseases (Wilkes *et al.,* 2021). Research by Purdue University has also indicated that ridges are usually 4 to 5 ºC warmer than the conventional and no-till systems. The use of RF system maintains apical dominance with efficient conversion of intercepted solar radiation, as well as increased leaf area index (LAI), photosynthetic active radiation (PAR) and radiation use efficiency (Echarte *et al.,* 2008; Tan *et al.,*2018).

CHAPTER THREE

EFFECT OF RIDGE-FURROW ON GROWTH AND PHYSIOLOGY OF SPRING WHEAT (*Triticum aestivum* L.)

Abstract

Ridge and furrow (RF) tillage system has demonstrated great potential to improve spring wheat (*Triticum aestivum* L.) productivity, however little is known whether this practice can yield desired results in Kenya. This study was conducted to determine the effects of ridge-furrow planting on physiology and growth of wheat. The study was conducted at Egerton University (0º 22’ 26’’ S, 35º 56’ 1.3’’ E) and Kenya Agricultural and Livestock Research Organization, Njoro (0° 22′ 47’’ S, 35° 56′ 1.7’’ E) . In both locations, wheat cultivars, *Kingbird* and *Kwale* were evaluated in a randomized complete block design (RCBD) in a split-plot arrangement with tillage system as the main-plot and the cultivars as the sub-plot. The ridge system had higher mean yield than the conventional system. . The mean grain yield across locations were 2.22 tonnes ha^{-1} for ridge and 1.35 tonnes ha^{-1} for the flat system. Yield had a significant(r=0.76*) correlation with thousand kernel weight and number of kernels $spike^{-1}$ (r=0.73*). The RF and conventional system were significantly ($p \leq 0.001$) different for all the agronomic variables. The results indicated that planting of wheat on RF system over the conventional system of flat-surface planting resulted into improved wheat production in a unit area. The RF system not only improved the physiology and growth of wheat but also delayed flag leaf senescence and promoted development of wheat root systems. Thus, it could be concluded that RF cultivation system would provide an opportunity for sustainable intensification of wheat production.

3.1 Introduction

Tillage system is one of the main factors that determine soil moisture content, availability of soil nutrients and capacity of soil to hold water which translates to yield production (Desta *et al*., 2021; Hobbs, 2007). In Kenya annual wheat production is estimated at 300,000 tonnes as of 2020 statistics which is way below the country demand (Https://knoema.com/atlas/Kenya). Wheat a major cereal crop in Kenya is mainly cultivated in Eastern and Rift valley region of Kenya generally in flat tillage system. Climate change has led to increased temperature regimes which directly affect agricultural production (Govaerts & Sayre, 2009). For instance, 1ºC increase in mean global temperature results to 6% reduction in mean global wheat production (Zhao *et al*., 2017). In the recent years, the cost of production has been escalating constantly due to increased cost of inputs such as fertilizer, stringent government policies, unfavourable weather conditions, and land subdivision which necessitates adoption of improved agricultural techniques which favour growth and production of wheat (Hassan *et al*., 2018). Approximately 80% of farmers in Kenya practice small scale farming. Therefore, improving production system would provide food security and increase food availability (Stilwell & Munyua, 2009).

The ridge tillage system has been widely adopted across the globe in regions with scarce rainfall (Hassan *et al*., 2018). 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 (Ahmed *et al*., 2011; Bakker *et al*., 2005). Tillage systems determines soil physical, chemical and biological characteristics which are function of crop development and production (Muñoz-Rojas, 2018). Ridge system has high soil nutrient conservation, conserve water, improves water use efficiency, facilitates easy weed control and band application of fertilizer, and enhances lodging resistance and good crop stand (Sayre *et al*., 1997). Although many studies have not been done on comparison of flat and ridge tillage system, Zhang *et al*. (2017) found that ridge system has greater yield potential and water use efficiency in wheat.

Ridge system is critical in flowering to late dough stage when wheat crops need high moisture content. Compared to the conventional tillage system, ridges also called raised beds promote efficient nitrogen use due to improved soil aeration and reduced nitrogen leaching and volatilization (Majeed *et al*., 2015). Root growth which is a function of tillage system is the most important component of growth and yield production in wheat. Ridge tillage system has greater soil water accumulation capacity facilitating root growth and distribution (Guan *et al*., 2015). 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 which facilitate high yield production (Shen *et al*., 2016).

Selection of tillage system which favours soil physico-chemical and biological characteristics may therefore enhance production especially in developing world where wheat production is reportedly low and is under irrigation. Majeed *et al.* (2015) compared bed tillage system and flat tillage system andfound that the former system improves nitrogen use efficiency and yield production than the latter system. Yao (2015) found that ridge system improves stomatal conductance, photosynthesis rate, and water use efficiency in rice. Therefore, the objective of this study was to determine the effect of ridge and flat tillage system on growth and production of *Kingbird* and *Kwale* spring wheat cultivars.

3.2 Materials and methods

3.2.1 Environment

This study was conducted at Egerton University (0º 22' 26'' S, 35º 56' 1.3'' E) and Kenya Agricultural and Livestock Research Organization (KALRO), Njoro (0° 22′ 47'' S, 35° 56′ 1.7'' E) during the main wheat growing season and off-season respectively. KALRO is located at agro-climatic zone III at an elevation of 2141 meters 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*. The site experiences an 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 and maximum temperatures of 10.2 and 22 ºC, respectively. The soils in this site are *Vitric Mollic Andosols.* The sites were chosen because the environmental conditions are representative of main wheat growing areas in Kenya.

3.2.2 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 that was 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. It also has good tolerance to stem, ear and yellow rust.

3.2.3 Experimental procedure

Land that was previously fallow in Egerton and KALRO sites respectively, were used for the evaluation of the two 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 and conventional flat system. 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. A 1 mm gauge polyethylene film measuring 0.5m × 0.5m was inserted at a depth of 0.3m in the soil for monitoring root growth and development in each treatment. The seeds were sown on the ridge and flat tillage system at a depth of 5 cm at an equivalent rate of 125 kg ha^{-1} and at an inter-row spacing of 20 cm.

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 40 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. Main plots were the tillage system; ridge and flat whereas subplot consisted of cultivars; *Kwale* and *Kingbird*. The main plot measured 6.1 m × 20.9 m and sub-plot measured 5m × 0.5m.

Weed growth was restricted by application of herbicide dual gold® (*S-Metolachlor* 576 g ha^{-1}) a pre-emergence herbicide which was applied after sowing to control grasses and broadleaf weeds. Axial® which is a liquid emulsifiable concentrate (EC) containing *pinoxaden* 30 g ha^{-1} was applied as a post-emergent herbicide at *GS15* (Zadoks *et al.,* 1974). The wheat evaluation was carried out in two main seasons of 2020 which was rain-fed. Chewing and other sucking insect pests like Russian wheat aphids (*Duraphis noxia*) were controlled by application of Thunder (*Lambdacyhalothrin* 25 g ha^{-1}) insecticide. Rust diseases were controlled by application of Prosaro (*Prothioconazole* 32 g ha^{-1}*, Tebuconazole* 32 g ha^{-1}) fungicide.

3.3 Data collection

3.3.1 Weather data

The meteorological data were acquired from the KALRO and Egerton meteorological department, respectively for each site. The maximum and minimum daily temperature and rainfall were determined. The average daily temperature was calculated as mean of the maximum and minimum daily temperature. The growth duration of the wheat growth in both locations was measured in accumulated days and the temperatures recorded. The growing degree days was calculated considering the base temperature for wheat as 4°C following equation described by Wand and Engel (1988).

$$GDD = \sum[\frac{T_{max}+T_{min}}{2} - T_{base}] \quad \text{......Equation 1}$$

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 ºC). The accumulated degree days for both environments were calculated as the sum of the degree day from sowing to harvesting time.

3.3.2 Soil water content and temperatures

Data on soil moisture, temperature and electrical conductivity were taken using Time Domain Reflectometry (TDR) equipment (Model No. 36143.) at GS61–69 and GS71-87 of the wheat (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 of the soil as described by Topp *et al*. (1970) and expressed as;

$$v = \frac{C_o}{\sqrt{\sum r.\mu r}} \quad \text{......Equation 2}$$

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

3.3.3 Soil bulk density

Soil bulk density was measured at *GS30* using direct method as described by Ali, (2010). The soil cores were taken at the depth of 15 cm plot^{-1} in the two environments. Eight samples were collected from the main plot and measurements on the mass and volume of the soil were taken using the coring method as described by Walter (2016). The core ring as pressed to a depth of 15 cm following the procedure by Walter *et al.* (2016) to take the eight core samples. The wet soil samples were weighed to estimate the moisture conditions in the field at the time of sampling. Thereafter, the total volume of the soil was estimated as the internal volume of the cylinder. Samples were oven dried at 105ºC for 3 days and the mass of the dry soil sample measured. The dry and wet soil bulk density were estimated using a formula proposed by Han *et al*. (2016);

$$pb = \frac{Ms}{Vs} \quad \text{......Equation 3}$$

where pb is the bulk density in g/cm^3, Ms is the mass of the soil and Vs is the volume of the soil.

3.3.4 Agronomic traits

Data on days to ear emergence was taken at *GS59* and flowering at *GS65* in all plots when 50% of the plants have produced heads and flowers, respectively. Flag-leaf senescence was measured from *GS65* to full senescence at an interval of 4 days using a visual senescence score chart ranging from 0 to 10 where 0 is fully green and 10 fully senescenced (Gaju *et al*,. 2011). Plant height was determined by selecting five plants and measured from the ground base to the tip of the spikes. Physiological maturity was determined when the peduncle was golden in colour. The Normalized Difference Vegetative Index (NDVI) spectral reflectance index was measured using a handheld Spectroradiometer (Trimble Navigation Ltd, USA). All plots were measured on the same dates, at approximately 15 days post-anthesis in each season. The Spectroradiometer was held 50 cm above the crop canopy. A reading was taken plot^{-1} when the sky was clear and when there was sufficient radiation. The NDVI was estimated using an equation described by Pask *et al.* (2012).

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad \text{.. Equation 4}$$

where NIR is Near Infra-red and RED is red light

3.3.5 Yield and yield components

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

$$K = \frac{K}{A^{-1}} \text{..Equation 5}$$

where K is Kernel yield and A^{-1} is area subplot^{-1}

$B = \frac{B}{A^{-}}$ ……………………………………………………………………………Equation 6

where B is biological yield and A^{-1} is area subplot^{-1}

$HI = \frac{K}{B^{-1}}$…………………………………………………………………………Equation 7

where HI is harvest index, k is kernel yield and B is biological yield subplot^{-1}

3.4 Data analyses

All the data collected was subjected to *Shapiro -Wilk* test of normality to assess the normality of the data using *PROC UNIVARIATE* procedure in SAS before being used for further statistical analyses (Shapiro *et al*., 1965). It has an assumption that a sample comes from a normally distributed population. The null hypothesis to be tested is that the population is normally distributed.

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$$ ……………………………………………………………………Equation 8

where a_i is constant generated from the means, variance and covariance of order statistics, n is the sample size, $x_{(i)}$is the ordered sample values.

SAS Procedure.

```
TITLE 'Wheat';
DATA Tillage system;
INPUT Location $ Rep $ Tillage $ Cultivar $ Germination
Earemergence FLS Flowering Maturity Height Yield TKW Spikelength
HI nseed/spike nspikelets NDVI Smoist Stemp EC Bdensity;
Datalines;
;
PROC PRINT;
PROC UNIVARIATE NORMAL PLOT;
RUN;
```

The effects of the 2 tillage systems were determined by combined analysis of variance (ANOVA) using *PROC GLM* procedure from the SAS software version 9.4 (SAS Institute Inc. 2018) using the followin statistical modl and SAS procedure.

$Y_{ijklm} = \mu + L_i + R_{j(i)} + T_k + C_l + LT_{ik} + LC_{il} + RT_{jk(i)} + RC_{jl(i)} + LRT_{ijk}\ LTC_{ikl} + RTC_{jkl(i)} + LTC_{ikl} + RTC_{jkl} + \varepsilon_{ijklm}$ ……………………………………………Equation 9

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 and i^{th} location; LC_{il} = Effect of interaction due to l^{th} cultivar and i^{th} location; $RT_{jk(i)}$ = Effect of k^{th} tillage in the j^{th} replicate nested in the i^{th} location; $RC_{jl_{(i)}}$ = Effect of l^{th} cultivar in the j^{th} replicate nested in the i^{th} location; LTC_{ikl} = Effect of interaction due to k^{th} tillage and l^{th} cultivar in the i^{th} location; $RTC_{jkl(i)}$ = interaction of the lth cultivar and k^{th} tillage in the j^{th} replicate nested in the i^{th} location; $(LTCN)_{iklm}$ = main plot interaction effect; $(RTCN)_{jklm}$= sub-plot interaction effect and ε_{ijklm} = Random error component. The analysis considered cultivars as fixed factors, replicates nested in location and cultivar × location interaction as random factors.

```
SAS PROCEDURE
Title 'Wheat';
Data Tillage;
Input Location $ Rep $ Tillage $ Cultivar $ Germination
     Earemergence FLS Flowering    Maturity  Height    Yield
     TKW  Spikelength    Biomass   nseedspke nspikelets
     Chloro    ndvi smoist    stemp     EC   Bdensity Rlength
     RSA  RDiameter RVolume;
Yieldt=log(Yield+5);
HI=Yield/Biomass;
HIt=log(HI+5);
Biomasst=log(Biomass+5);
/*Rlengtht=log(Rlength+5);
```

```
RSAt=log(RSA+5);
RDiametert=log(RDiameter+5);*/
RVolumet=log(RVolume+5);
Datalines;
;
Proc glm;
Class Location Rep Tillage Cultivar;
Model Germination   Earemergence FLS Flowering    Maturity
Height    Yield Yieldt TKW Spikelength Biomass Biomasst HI HIt
nseedspke nspikelets Chloro ndvi smoist stemp EC Bdensity
Rlength RSA RDiameter RVolume = Location Rep Location*Rep
Tillage Location*Tillage Rep*Tillage Rep*Location*Tillage
Cultivar Location*Cultivar Cultivar*Tillage
Location*Tillage*Cultivar/ss4;
Random Rep Location*Rep Rep*Tillage Rep*Location*Tillage;
Test H=Cultivar E=Rep*Tillage;
```

Means were compared by use of Fischer's protected list significance difference (LSD) test at $p \leq 0.05$ probability level whenever the main effects are significant using the following formulae (Gomez & Gomez, 1984).

$$LSD = t_{\frac{\alpha}{2}} \times \sqrt{\frac{2MSE}{r}} \quad \text{Equation 10}$$

where *LSD* is the least significant difference, $t_{\frac{\alpha}{2}}$ is *t*-critical value from the t-distribution table at a given confidence level, *MSE* is the mean square error and *r* is the number of replications.
Standard error (SE) of the mean was determined by the following formulae;

$$SE = \frac{sd}{\sqrt{n}} \quad \text{Equation 11}$$

where *SE* is the standard error of the sample, *sd* is the sample standard deviation and *n* is the number of samples.

Pearson's correlation coefficient was employed to determine the relationship between the agronomic traits using the following equation described by Cohen and Aiken, (2014).

$$r = \frac{n(\sum x_i y_i) - (\sum x_i)(\sum y_i)}{\sqrt{[n\sum x^2 - (\sum x_i)^2]\,[n\sum y_i - (\sum y_i)^2]}} \quad \text{.. Equation 12}$$

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. SAS procedure was used to correlate agronomic parameters evaluated in this study.

3.5 Results

3.5.1 Weather conditions

In both locations weather parameters including rainfall, temperature and humidity were determined. Egerton received more rainfall amount (1043 mm) than Njoro (820 mm) site during the evaluation of the wheat cultivars. In both locations rainfall amount was high towards the end of the cropping seasons. The minimum and maximum temperatures of 10 °C and 26.7 °C in KALRO and 12.6 and 28 ºC at Egerton, respectively were experienced during the cropping season. The site in Egerton seemed to have high humidity than site in Njoro during the entire cropping season. Egerton University site was 1.3 °C (maximum), 2.6 °C (minimum) and 1.6 °C (mean) warmer than KALRO, Njoro (Table 3.1). Growth of crops is sometimes confounded by external factors which are out of reach by the researcher. Therefore, growing degree days was calculated o simulate the development of wheat crop in this study. The Egerton site had lower growth rate than Njoro site (Figure 3.1).

Table 3.1 Mean monthly Rainfall and temperature at KALRO, Njoro and Egerton University

Njoro		March	April	May	June	July	August
Precipitation (mm)		68.84	87.15	146.82	233.3	157.56	125.90
Temperature (°C)	Maximum	26.73	24.64	23.00	24.40	21.27	24.62
	Minimum	13.36	11.00	11.47	10.00	10.54	13.63
Egerton							
Precipitation (mm)		83.60	128.85	114.52	242.70	226.10	246.71
Temperature (°C)	Maximum	28.00	25.75	25.39	24.27	22.61	24.67
	Minimum	15.69	14.25	13.94	13.30	12.58	13.13

Source: Egerton University Weather Station, 2020 and KALRO, Njoro Weather Station, 2020

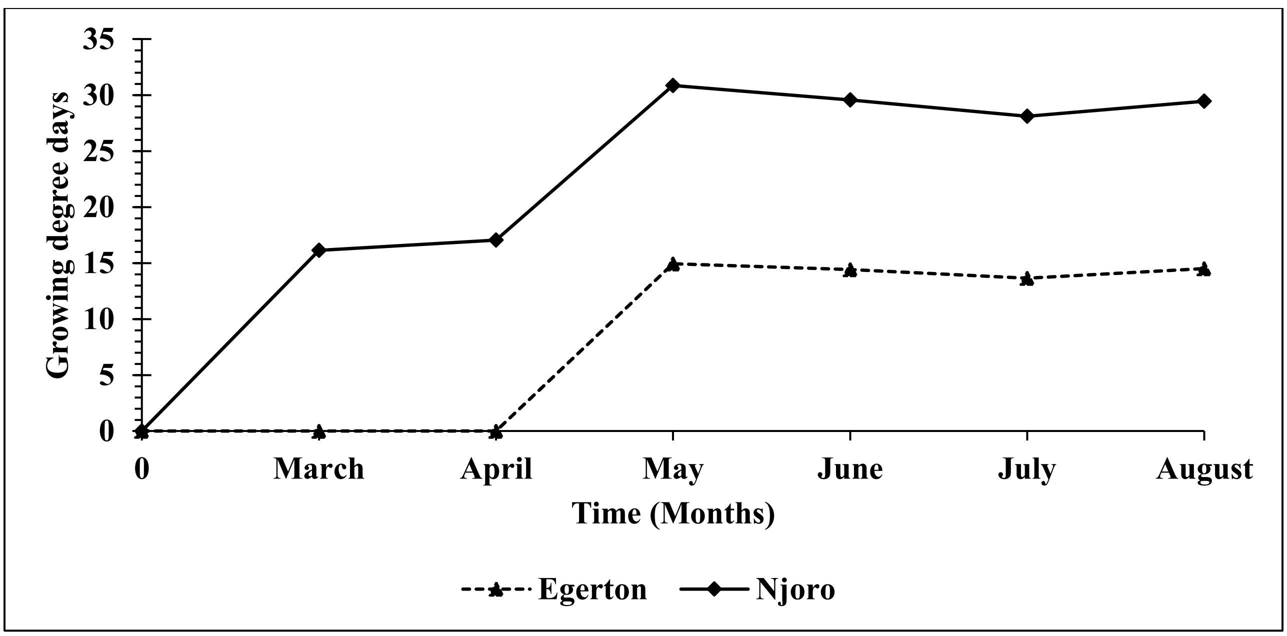

Figure 3.1 Change in phenology of wheat in the two field sites at different months in the growing season as a function of growing degree days

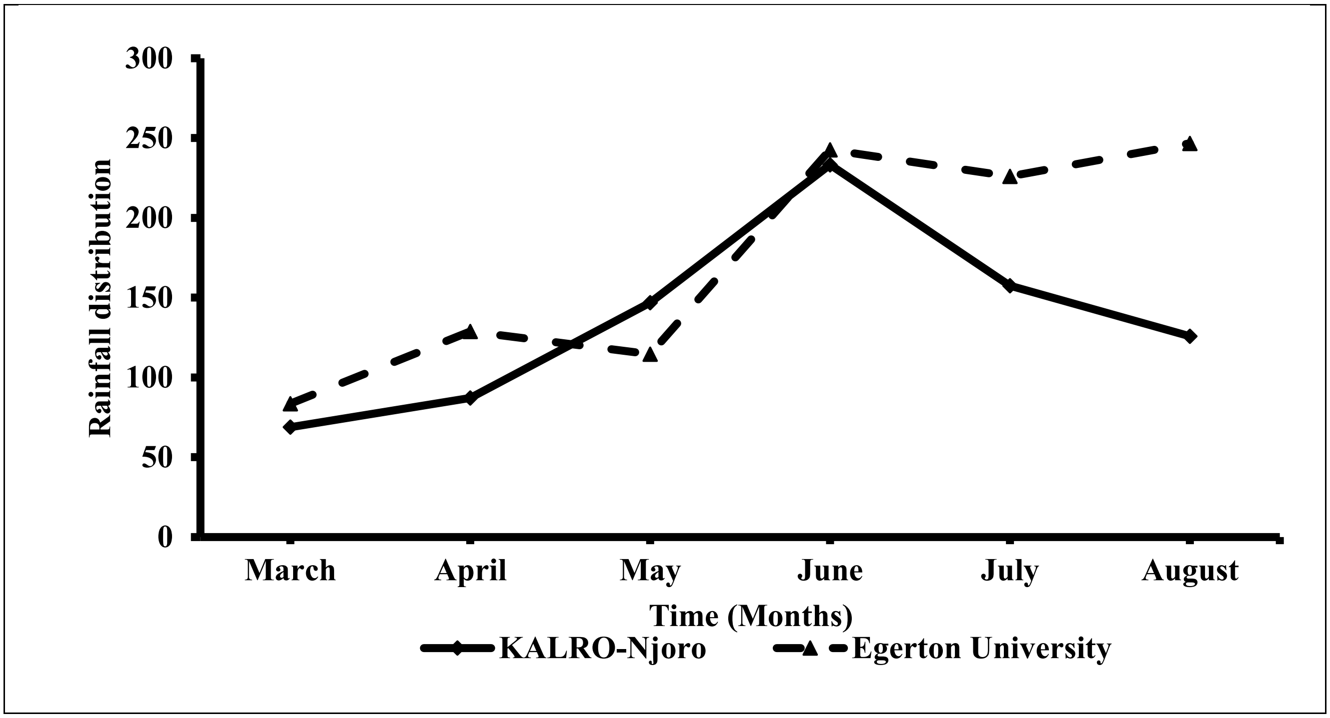

Figure 3.2 Monthly rainfall distribution in Egerton and KALRO (March – August 2020)

The *Shapiro - wilk* tests conducted showed that the distributions were significantly normal for the variables ear emergence ($W = 0.913$, $p < 0.001$), flowering ($W = 0.874$, $p < 0.001$), maturity ($W = 0.957$, $p < 0.05$), yield ($W = 0.933$, $p < 0.01$), a thousand kernel weight ($W = 0.954$, $p < 0.05$), spike length ($W = 0.963$, $p < 0.05$) (Table 3.2)

3.5.2 Analysis of variance for agronomic and yield components

The combined analysis of variance revealed that location and tillage system were the largest source of variation. Location was significant ($p \leq 0.001$) for ear emergence, days to flowering, days to maturity, flag leaf senescence, plant height, kernel yield, thousand kernel weight, spike length, number of spikelets spike^{-1}, chlorophyll concentration and normalised difference vegetation index. Tillage system significantly *($p \leq 0.001$)* affected all the evaluated agronomic traits except biomass. Location × tillage interaction significantly *($p \leq 0.001$)* influenced ear emergence, days to maturity, spike length and biomass. Further, location × tillage effect was significant *($p \leq 0.05$)* for anthesis, plant height, number of spikelets and NDVI. There was also a significant effect *($p \leq 0.01$)* of the location × tillage interaction for kernels spike^{-1}. Location × tillage × cultivar significantly ($p \leq 0.001$) influenced TKW and spike length. It also had an effect on yield and harvest index (Table 3.2).

Table 3.2 Effects of location, tillage and cultivar on yield, yield components, physiology and growth of spring wheat

Source of variation	df	Ear emergence (Days)	Days to flowering	Days to maturity	Flag leaf senescence (Days)	Plant Height (cm)	Yield (tha^{-1})	1000 kernel weight (g)	Spike length (cm)
Location (L)	1	1501.563***	1453.516***	576.000***	529.000***	364.810***	0.162***	1859.766***	21.623***
Replicate (R)	3	3.500	22.266	54.625	56.104	68.789	0.011	4.557	4.018
L× R	3	2.729	15.859*	43.875	26.541	67.287	0.017	0.724	1.808
Tillage (T)	1	225.00***	276.391***	812.250***	756.250***	359.103***	0.264***	102.516***	48.303***
L× T	1	105.063***	23.766*	441.000***	52.563	153.760*	0.031	3.516	5.523***
R × T	3	0.917	13.641*	18.625	31.792	6.623	0.003	2.724	0.248
L×R×T (Error a)	3	1.396	14.432*	87.542*	46.271	15.950	0.013	1.141	0.018
CV_a (%)		1.792	4.951	7.713	17.262	4.753	5.985	3.363	1.671
Cultivar (C)	1	7965.563***	13253.766***	6280.563***	552.250***	5041.000	0.011	50.766*	115.563***
L × C	1	4.00	346.891***	14.063	370.563**	122.103	0.188***	301.891***	1.563*
T × C	1	0.563	4.516	3.063	18.063	28.090	0.0004	37.516*	0.303
L× T × C	1	1.00	15.016	45.563	9.000	0.063	0.068**	112.891***	4.203***
Error	44	1.486	4.001	27.574	41.628	29.004	0.008	9.345	0.263
Mean		65.938	76.734	121.313	39.406	84.031	1.905	31.766	8.031
CV (%)		1.849	2.607	4.329	16.373	6.409	4.735	9.624	6.379
R^2		0.993	0.989	0.879	0.602	0.837	0.706	0.859	0.949
W		0.913***	0.874***	0.957*	0.979	0.968	0.933**	0.954*	0.963*

Table 3.2. ***Continued…***

Source of variation	df	Biomass (tonne ha^{-1})	Harvest index	Kernels $spike^{-1}$	Number of spikelets	Chlorophyll ($umolsm^{-2}S^{-1}$)	NDVI
Location (L)	1	0.005	0.001	108.160	100.501***	27.327***	0.348***
Replicate (R)	3	0.060	0.01	22.351	0.149	2.864	0.004
L× R (Error a)	3	0.113	0.002*	43.852	5.944*	0.021	0.016**
Tillage (T)	1	0.001	0.007***	2485.023***	122.656***	6.943***	0.019*
L × Tillage	1	0.703***	0.0006	256.000**	7.981*	0.056	0.014*
Rep × Tillage	3	0.050***	0.0009	23.894	1.019	0.413**	0.001
L×R×T(Error a)	3	0.052	0.002*	9.295	3.397	0.003	0.002
CV_a (%)		8.541	2.710	8.845	11.490	2.235	9.278
Cultivar (C)	1	1.209***	0.001	759.003***	174.901***	0.273	0.006
L × C	1	0.721***	0.0002	1568.160***	19.581**	0.003	0.002
T × C	1	0.145	0.0001	66.423	3.151	0.305	0.003
L× T × C	1	0.002	0.002*	7.290	5.641	0.003	0.011
Error	44	0.042	0.0004	38.116	1.660	0.089	0.003
Mean		2.670	1.650	34.469	16.041	7.749	0.482
CV (%)		7.640	1.185	18.367	8.032	3.847	11.886
R^2		0.663	0.633	0.759	0.864	0.920	0.765
W		0.979	0.923*	0.973	0.977	0.975	0.968

*, **, *** indicates significance at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$ level of probabilities respectively. CV=coefficient of variation, R^2 = coefficient of determination, NDVI=normalised difference vegetative index, TKW=Thousand kernel weight, W = Shapiro wilk statistic. Yield, Harvest index and Biomass were log transformed prior to analysis of variance.

3.5.3 Effects of location, tillage and cultivar on soil properties

Tillage system significantly affected the soil moisture conditions in the 2 sites (Figure 3.3). The combined analysis of variance for the two locations also showed significant ($p \leq 0.001$) interactions for soil temperature and electrical conductivity. Furthermore, tillage system significantly ($p \leq 0.05$) affected the electrical conductivity and had significant effect ($p \leq 0.001$) on soil temperature and soil bulk density. The interactions of location × tillage was significant ($p \leq 0.001$) for soil temperature(Table 3.3).

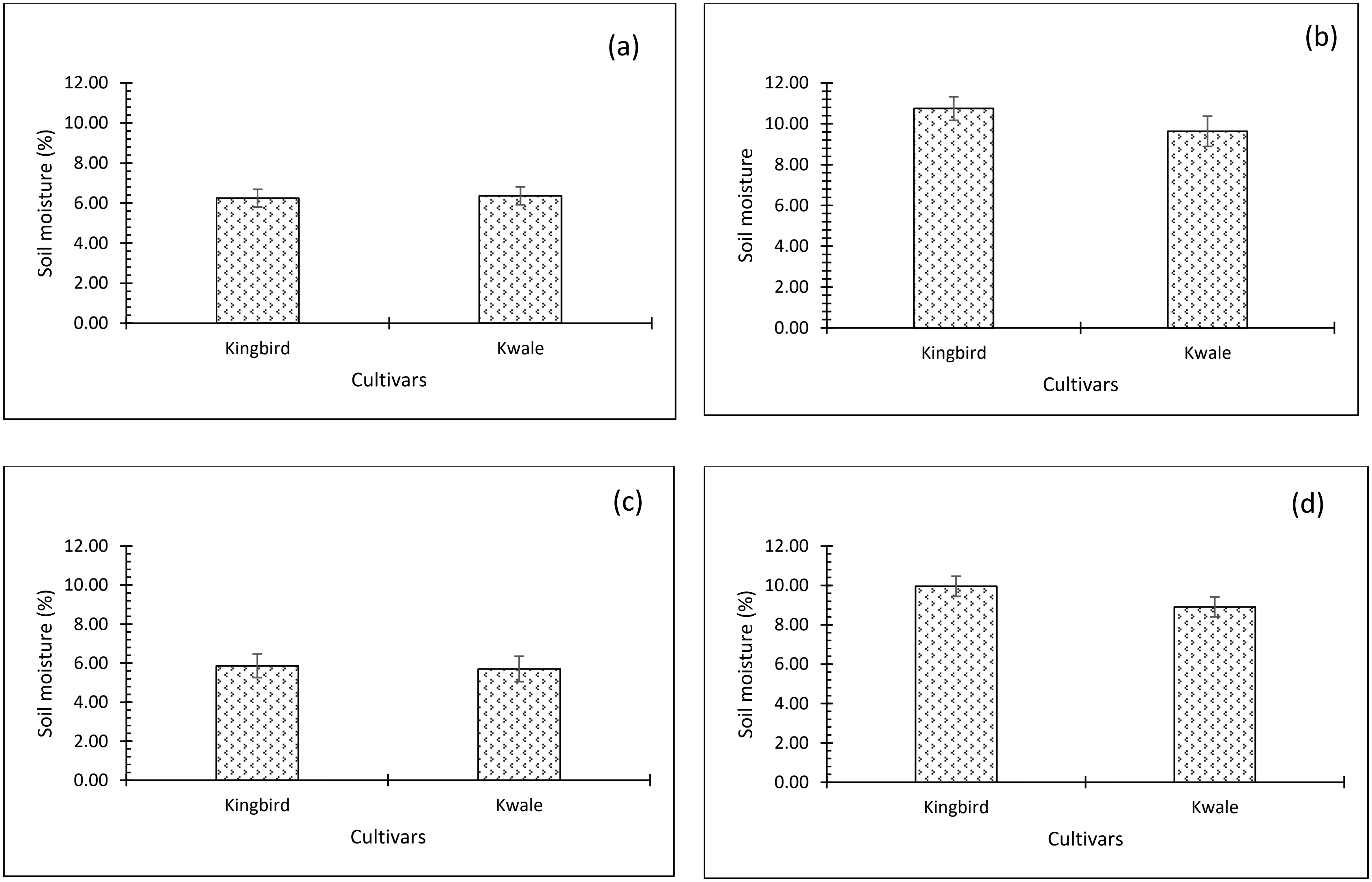

Figure 3.3. Effects of flat (a) and ridge (b) tillage system on soil moisture for spring wheat cultivars in Njoro and Effects of flat (c) and ridge (d) tillage system on soil moisture for spring wheat cultivars in Egerton.

Table 3.3. Analysis of variance for 2 wheat varieties evaluated at 2 locations under 2 tillage systems for soil temp, EC and soil bulk density.

Source of variation	df	Soil temperature (°C)	Electrical conductivity (dSm^{-1})	Soil bulk density (gcm^{-3})
Location (L)	1	734.749***	0.929***	0.026
Replicate (R)	3	3.716***	0.078	0.014
L× R (Error a)	3	3.615***	0.098	0.049*
Tillage (T)	1	0.755***	0.213*	3.106***
L× T	1	1.473***	0.017	0.011
R × T	3	0.129*	0.074	0.008
L×R×T(Error a)	3	0.114*	0.087	0.019
CV_a (%)		1.622	23.262	10.241
Cultivar (C)	1	0.005	0.044	0.001
L × C	1	0.039	0.027	0.003
T × C	1	0.019	0.116	0.010
L× T × C	1	0.106	0.047	0.021
Error	44	0.036	0.045	0.016
Mean		20.811	1.268	1.346
CV (%)		0.911	16.790	9.440
R^2		0.998	0.546	0.290

*, **, *** indicates significance at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$ level of probabilities respectively. CV=coefficient of variation, R^2 = coefficient of determination, Values shown are mean squares.

3.5.4 Effects of environment, tillage and cultivar on growth and physiology of two spring wheat cultivars

The means comparison between Egerton and Njoro sites showed that, ear emergence, flag leaf senescence, flowering, maturity, plant height, yield, TKW, chlorophyll concentration, number of kernels spikelets^{-1}, NDVI and spike length were significantly ($p \leq 0.05$) different between the sites (Table 3.5). Soil temperature, electrical conductivity and spike length varied significantly ($p \leq 0.05$) different in the two sites (Table 3.6). The tillage systems showed a significant effect ($p \leq 0.05$) for all the agronomic and soil variables. However, ridge system had higher mean than conventional flat tillage for all the test variables (Table 3.7 & 3.8). The mean performance of the cultivars varied among the traits. Cultivar *Kwale* and *Kingbird* were found to be significantly different 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 (Table 3.9).

Table 3.5. Effects of environments on 2 wheat cultivars on yield and yield components.

Environment	Ear emergence	Flag Leaf Senescence	Flowering	Maturity	Plant height	Yield	1000 kernel weight	Chlorophyll
	(Days)				Cm	tonne ha^{-1}	g	$umolsm^{-2}s^{-1}$
Njoro	61.09b	42.28a	71.97b	124.31a	86.42a	1.42b	26.38b	8.40a
Egerton	70.78a	36.53b	81.50a	118.31b	81.64b	2.15a	37.16a	7.10b
LSD $_{(0.05)}$	0.61	3.26	1.09	2.82	2.67	0.33	1.49	0.15

Environment	Biomass	Harvest index	kernels $spike^{-1}$	kernels $spikelets^{-1}$	NDVI	Spike length
	Tonne ha^{-1}		No.	No.		cm
Njoro	10.04a	0.57a	33.17a	17.29a	0.56a	8.61a
Egerton	10.06a	0.60a	35.77a	14.79b	0.41b	7.45b
LSD $_{(0.05)}$	1.60	0.11	3.11	0.67	0.03	0.25

Means followed by the same letters in the columns are not significantly different at $p \leq 0.05$. NDVI=normalised difference vegetative index

Table 3.6. Effect of environment on soil properties evaluated across environments.

Environment	Soil moisture (%)	Soil Temperature (°C)	Electrical conductivity (dSm^{-1})	Bulk Density (gcm^{-3})
Njoro	8.25a	24.20a	1.15b	1.33a
Egerton	7.61a	17.42b	1.39a	1.37a
LSD $_{(0.05)}$	0.72	0.10	0.11	0.06

Means followed by the same letters in the columns are not significantly different at $p \leq 0.05$

Table 3.7. Effect of tillage systems for yield and agronomic components

Tillage	Ear emergence	FLS	Days to flowering	Days to maturity	Plant height	Yield	TKW	Chlorophyll
	Days				cm	Tonne ha^{-1}	g	µmols m^{-2} s^{-1}
Ridge	67.81a	42.84a	78.81a	124.88a	86.40a	2.22a	33.03a	8.08a
Flat	64.06b	35.97b	74.66b	117.75b	81.66b	1.35b	30.50b	7.42b
LSD $_{(0.05)}$	0.61	3.26	1.09	2.82	2.67	0.33	1.49	0.15

Tillage	Biomass	Harvest index	Kernels $spike^{-1}$	Kernels $spikelets^{-1}$	NDVI	Spike length
	Tonne ha^{-1}		No.	No.		Cm
Ridge	9.99a	0.65a	40.70a	17.43a	0.50a	8.90a
Flat	10.11a	0.52b	28.24b	14.66b	0.46b	7.16b
LSD $_{(0.05)}$	1.60	0.11	3.11	0.67	0.03	0.25

Means followed by the same letters down the column are not significantly different $p \leq 0.05$.
FLS=Flag leaf senescence, TKW=thousand kernel weight, NDVI=Normalised difference vegetative index

Table 3.8 Effects of tillage systems on soil properties

Tillage	Soil moisture	Soil Temperature	Electrical conductivity	Bulk Density
	%	°C	d Sm^{-1}	gcm^{-3}
Ridge	9.81a	20.70b	1.33a	1.13b
Flat	6.04b	20.92a	1.21b	1.57a
LSD $_{(0.05)}$	0.72	0.10	0.11	0.06

Means followed by the same letters down the column are not significantly different $p \leq 0.05$

Table 3.9. Means of spring wheat cultivars for yield, agronomic components, soil moisture, soil temperature, bulk density and NDVI for cultivar *Kwale* and *Kingbird* evaluated across two environments.

Cultivar	Ear emergence	FLS	Flowering	Maturity	Plant height	Yield	1000-kernel weight
	Days			.	cm	Tonne ha^{-1}	g
Kwale	77.09a	36.47b	91.13a	131.22a	92.91a	1.90a	30.88b
King Bird	54.78b	42.34a	62.34b	111.41b	75.16b	1.67a	32.66a
LSD $_{(0.05)}$	0.61	3.26	1.09	2.82	2.67	0.33	1.49

Cultivar	Chlorophyll	Biomass	Harvest index	No. of kernels $spike^{-1}$	No.of kernels $spikelets^{-1}$	NDVI	Spike length
	$Umols^{-2}s^{-1}$	tha-1					cm
Kwale	7.68a	12.11a	0.52b	31.03b	17.69a	0.49a	9.38a
King Bird	7.81a	7.99b	0.64a	37.91a	14.39b	0.47a	6.69b
LSD $_{(0.05)}$	0.15	1.60	0.11	3.11	0.67	0.03	0.25

Means followed by the same letters in a column are not significantly different at $p \leq 0.05$

3.5.5 Effects of tillage system on growth of two spring wheat cultivars

The mean days to heading, flag leaf senescence, flowering, maturity, plant height, spike length, yield, TKW, harvest index, number of seeds spike^{-1}, number of kernel spikelets^{-1} and NDVI were higher in ridge tillage than flat tillage system (Table 3.10). Further, the means of soil moisture and electrical conductivity were also higher in the ridge system than flat system. However, the flat system had higher soil temperature and bulk density than the ridge system in both locations (Table 3.11).

Table 3.10 Effects of 2 tillage systems on yield and yield components of 2 spring wheat cultivars

Tillage	Cultivar	Days to heading (Days)			Flag leaf senescence (Days)			Days to flowering			Days to Maturity			Plant height (cm)		
Flat	*Kingbird*	52.81	±	0.86	39.44	±	1.81	60.00	±	1.67	108.06	±	2.13	72.13	±	1.71
	Kwale	75.31	±	1.07	32.50	±	1.77	89.31	±	0.83	127.44	±	2.31	91.20	±	1.63
Ridge	*Kingbird*	56.75	±	1.57	45.25	±	2.15	64.69	±	2.21	114.75	±	0.98	78.19	±	1.13
	Kwale	78.88	±	1.66	40.44	±	1.61	92.94	±	0.94	135.00	±	1.13	94.61	±	1.77

Tillage	Cultivar	Yield (tonne ha^{-1})			Thousand-kernel weight (g)			Spike length (cm)			Harvest index			Number of kernels spike^{-1}		
Flat	*Kingbird*	1.23	±	0.14	30.63	±	1.06	5.89	±	0.19	0.56	±	0.06	30.66	±	1.89
	Kwale	1.48	±	0.27	30.38	±	2.39	8.44	±	0.37	0.47	±	0.04	25.81	±	1.81
Ridge	*Kingbird*	2.12	±	0.17	34.69	±	1.21	7.49	±	0.20	0.73	±	0.07	45.16	±	1.94
	Kwale	2.32	±	0.27	31.38	±	1.74	10.31	±	0.22	0.57	±	0.05	36.24	±	2.47

Tillage	Cultivar	Number of spikelets^{-1}			NDVI		
Flat	*Kingbird*	13.23	±	0.42	0.45	±	0.03
	Kwale	16.09	±	0.67	0.48	±	0.03
Ridge	*Kingbird*	15.55	±	0.25	0.50	±	0.02
	Kwale	19.30	±	0.55	0.50	±	0.02

Means presented are from 16 plots. Data are represented as means ± standard error (S.E). NDVI=normalised vegetative index

Table 3.11 Effects of tillage system on cultivars soil properties (moisture, electrical conductivity, bulk density and temperature) properties for 2 wheat cultivars.

Tillage	Cultivar	Soil moisture (%)	Soil temperature (^{O}C)	Electrical Conductivity (dSm^{-1})	Soil bulk density (gcm^{-3})
Flat	*Kingbird*	6.05 ± 0.37	20.95 ± 0.92	1.19 ± 0.04	1.58 ± 0.04
	Kwale	6.03 ± 0.39	20.89 ± 0.93	1.23 ± 0.04	1.55 ± 0.04
Ridge	*Kingbird*	10.35 ± 0.39	20.69 ± 0.87	1.39 ± 0.11	1.12 ± 0.03
	Kwale	9.27 ± 0.44	20.71 ± 0.84	1.26 ± 0.03	1.13 ± 0.02

Means presented are from 16 plots. Data are represented as means ± standard error (S.E).

In both ridge tillage system and locations, cultivar *Kingbird* took less time to attain heading, anthesis, maturity, were short, had short spike length, low yield, TKW, harvest index, number of seeds spike^{-1} and number of seeds spikelets^{-1}. However, *Kingbird* had higher NDVI than *Kwale* in in the flat tillage system while *Kwale* in the ridge tillage had higher NDVI than the flat in Njoro (Table 3.12). In Njoro the flat tillage system had a mean grain yield of 1.58 tonnes ha^{-1} for *Kingbird* and 0.70 tonnes ha^{-1} for *Kwale* while in the ridge system, the mean grain yield was 1.75 for *kingbird* and 1.66 tonnes ha^{-1} for *Kwale*. In contrast, mean grain yield in flat tillage system for *Kingbird* (0.87 tonnes ha^{-1}) and Kwale (2.25 tonnes ha^{-1}) was lower than *Kingbird* (2.49 tonnes ha^{-1}) and *Kwale* (2.98 tonnes ha^{-1}) in the ridge system at Egerton. The average yield in both sites showed that ridge system had 61% higher yield than the conventional flat tillage system (Table 3.12). The difference was also seen in the TKW between the 2 environments and flat tillage systems. The differences in grain yield and TKW between the two tillage systems might be related to soil moisture content and bulk densities in the flat and ridge tillage system (Table 3.13).

Table 3.12 Effects of Location and Tillage system for 2 wheat cultivars on agronomic and physiological components of spring wheat

Location	Tillage system	Cultivar	Days to heading			Flag leaf senescence (Days)			Days to flowering			Days to maturity			Plant height (cm)		
Njoro	Flat	*Kingbird*	49.63	±	0.18	45.25	±	1.56	54	±	0.19	112.38	±	2.49	74.65	±	2.45
	Flat	*Kwale*	71.38	±	0.46	34.25	±	3.06	87	±	0.53	134.38	±	2.07	96.55	±	0.93
	Ridge	*Kingbird*	50.75	±	0.31	50	±	2.73	56.5	±	0.19	115.5	±	1.05	77.68	±	2.11
	Ridge	*Kwale*	72.63	±	0.32	39.63	±	2.65	90.38	±	0.62	135	±	2.1	96.8	±	2.97
Egerton	Flat	*Kingbird*	56	±	0.46	33.63	±	1.39	66	±	1.27	103.75	±	2.81	69.6	±	2.16
	Flat	*Kwale*	79.25	±	0.49	30.75	±	1.8	91.63	±	1.05	120.5	±	2.2	85.85	±	1.52
	Ridge	*Kingbird*	62.75	±	0.45	40.5	±	2.44	72.88	±	1.3	114	±	1.69	78.7	±	0.97
	Ridge	*Kwale*	85.13	±	0.72	41.25	±	1.99	95.5	±	1.24	135	±	1	92.43	±	1.79

Location	Tillage system	Cultivar	Spike length (cm)			Yield (tonnes ha^{-1})			TKW (g)			Harvest index			Number of kernels $spike^{-1}$		
Njoro	Flat	Kingbird	6.35	±	0.14	1.58	±	0.11	28.5	±	0.65	0.51	±	0.07	35.98	±	0.99
	Flat	*Kwale*	9.73	±	0.19	0.7	±	0.04	21.25	±	0.41	0.46	±	0.05	21.9	±	2.3
	Ridge	Kingbird	7.88	±	0.24	1.75	±	0.13	30.38	±	0.42	0.7	±	0.09	47.15	±	2.36
	Ridge	*Kwale*	10.5	±	0.18	1.66	±	0.35	25.38	±	0.75	0.6	±	0.08	27.65	±	1.19
Egerton	Flat	Kingbird	5.43	±	0.29	0.87	±	0.18	32.75	±	1.75	0.61	±	0.09	25.35	±	2.49
	Flat	*Kwale*	7.15	±	0.26	2.25	±	0.37	39.5	±	0.76	0.49	±	0.06	29.73	±	2.08
	Ridge	Kingbird	7.1	±	0.26	2.49	±	0.25	39	±	0.89	0.76	±	0.12	43.18	±	3.06
	Ridge	*Kwale*	10.13	±	0.41	2.98	±	0.24	37.38	±	1.44	0.55	±	0.08	44.83	±	1.92

Table 3.12 ***Continued…***

Location	Tillage System	Cultivar	Number of spikelets spike^{-1}	Normalised difference vegetative index
Njoro	Flat	Kingbird	14.58 ± 0.34	0.56 ± 0.02
	Flat	*Kwale*	17.95 ± 0.77	0.55 ± 0.03
	Ridge	Kingbird	15.60 ± 0.25	0.55 ± 0.02
	Ridge	*Kwale*	21.05 ± 0.56	0.57 ± 0.02
Egerton	Flat	Kingbird	11.88 ± 0.36	0.34 ± 0.02
	Flat	*Kwale*	14.23 ± 0.58	0.41 ± 0.03
	Ridge	Kingbird	15.50 ± 0.45	0.45 ± 0.02
	Ridge	*Kwale*	17.55 ± 0.34	0.44 ± 0.02

Means presented are from 16 plots. Data are represented as means ± standard error (S.E).

Table 3.13. Effects of location and cultivar on soil moisture, temperature, electrical conductivity and bulk density under wheat grown on 2 tillage systems.

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

Means presented are from 16 plots. Data are represented as means ± standard error (S.E).

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

Flag leaf senescence significantly correlated with chlorophyll content (*r*=0.71*) and number of seeds spike^{-1} (*r*=0.76*). Days to flowering had an effect on duration of plant maturity (0.79*) and plant height (0.83*). Days to maturity was highly correlated with plant height (*r*=0.98***), spike length (*r*=0.97***) and number of seeds spikelets^{-1} (0.88**) Plant height affected spike length (*r*=0.94***) and number of seeds spikelets^{-1} (*r*=0.87**). Thousand kernel weight (*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 3.14).

3.5.7 Effect of soil properties on yield of cultivar *Kingbird* and *Kwale*.

Soil moisture content correlated with grain yield (*r*=0.46) and equally, increase in electrical conductivity resulted to increase in grain yield production (*r*=0.63) of the test cultivars. Soil bulk density negatively affected growth and production the spring wheat cultivars. Similarly, high soil temperature reduced grain yield of the test cultivars. (Figure 3.4.).

Table 3.14 Pearson correlation coefficients for yield and yield components of *Kingbird* and *Kwale* wheat cultivars

Traits	Flowering	Maturity	Height	Bioma-ss	Chlorop-hyll	Yield	1000-KW	Spike length	HI	NSP	NSPK
FLS	-0.58	-0.10	-0.23	-0.10	0.71*	0.24	-0.12	0.07	0.35	0.76*	0.16
Flowering		0.79*	0.83**	0.59	-0.30	0.32	0.12	0.69	-0.10	-0.29	0.55
Maturity			0.98***	0.69	0.29	0.20	-0.33	0.97***	-0.21	-0.13	0.88**
Height				0.65	0.24	0.13	-0.34	0.94***	-0.22	-0.25	0.87**
Biomass						0.43	0.07	0.55	-0.45	0.12	0.37
Chlorophyll							-0.65	0.44	0.09	0.22	0.59
Yield							0.76*	0.20	0.55	0.73*	0.13
TKW								-0.37	0.49	0.51	-0.47
SPL										-0.01	0.94***
HI										0.53	0.10
NSP											-0.05

*, **, ***, indicate significance at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively. Chloro=chlorophyll content, SPL=spike length, NSP=number of seeds per spike, NSPK=number of seeds per spikelets

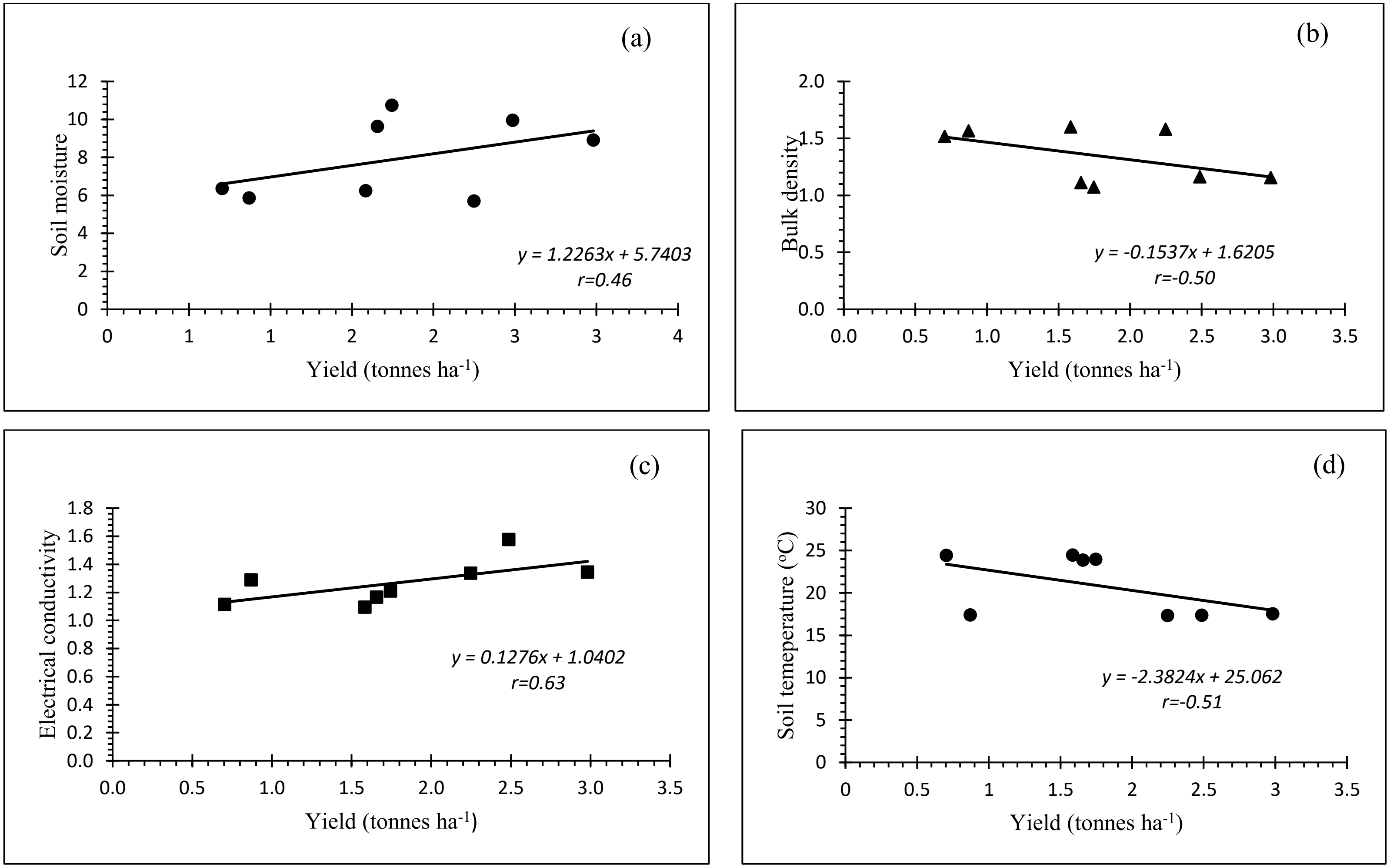

Figure 3.4 Relationship between yield and a) soil moisture, b) soil bulk density, c) electrical conductivity, d) soil temperature

3.6 Discussion

The study investigated how soil tillage system affects the growth and yield of wheat. The following were the key results: Ridge- Furrow tillage system enhanced the physiology and growth of spring wheat and increased the kernel yield and yield components. In this analysis, cultivars planted on ridge system took long to flower, head, had longer spike length, high number of seeds per spike and spikelets, and took long to mature. This is as a result of the high moisture content and low temperatures in ridge system than the conventional flat tillage systems. This is since soil moisture and temperature often have synergistic effect on plant growth implying that, the cultivars in ridge system had longer exposure to water increasing their growth period. Previous studies conducted by LI *et al.* (1999) found that moderate hydrothermal soil conditions under mulched ridge tillage increases tiller numbers and prolongs the phenostages hence contributing to yield increase. The favourable hydrothermal soil conditions in the ridge also enabled vigorous growth of the plants. Furthermore, favourable soil moisture and temperature conditions promote root growth, development and absorption of water and nutrient resulting in high biomass accumulation and leaf area index. Adequate soil moisture increases grain filling period by delaying maturity and leaf senescence (Motzo *et al*., 2010). Therefore, in this study photosynthesis continued for a longer period as result of the delayed senescence increasing the duration of assimilate partition to the grain resulting to high yield and kernel quality. In other studies, variation in yield is positively associated with grain filling period which was also related to grain number per unit area.

In this study, rainfall distribution was high at Egerton (1043mm) compared to Njoro (820mm) site. However, in both locations' rainfall amount was high towards the end of the cropping seasons which is important during anthesis and grain filling stage of wheat crop translating to high grain yield. This agrees with earlier study conducted by Nadew (2018) and thus explaining the slow growth at Egerton. Closely related results have also been demonstrated elsewhere. Wang *et al*. (2007) and Olaerts *et al.* (2018) found that high rainfall prior to anthesis and at maturity is not recommended since it leads to pre-harvest sprouting, low protein content and high carbohydrate assimilation and translocation than protein due to prolong leaf life during grain on-genesis. Consequently, heat damage and water limitation can reduce yield if crops flower too late in warm and dry environments (Flohr *et al.,* 2017).

The growing degree days also referred as heat units is used in depicting growth process of wheat genotypes in relation to the daily minimum and maximum temperatures. In both sites, wheat cultivars had high growth rates in the first 3 months and lag phase towards maturity. This is attributed to the high amounts of rainfall towards the end of cropping season experienced in the two sites. These results concur with those of Aslam *et al*. (2017) who found that growing degree days can be used to predict phenological growth of wheat under varied temperature regimes and day lengths. These results demonstrate that for optimal seed size and number (potential yield) wheat must establish biomass and reach anthesis at a time that coincides with optimal seasonal conditions as earlier indicated by Trethowan (2014). This study also revealed that high rainfall might reduce the growth rate of wheat genotypes. This might be due to low temperatures past the cardinal temperatures that come along with high rainfall (Gawith & Porter, 1999; Nadew, 2018; Slafer & Rawson, 1995).

Wheat cultivars in Njoro took longer to mature than those grown at Egerton. This might be as a result of the delayed leaf senescence and the high NDVI indices. It is known that wheat cultivars are sensitive to photoperiod. Wand and Engel (1998) suggested that both photoperiod and temperature are critical in wheat phenology especially in days to anthesis and days to maturity. Therefore, location significantly affected all the agronomic and soil properties except for harvest index, number of seeds per spike, soil moisture and soil bulk density.

In this study, wheat grown under ridge tillage system produced the highest mean yield, TKW and HI than the conventional flat tillage system both in Njoro and Egerton sites. This indicates that tillage system influences the growth and yield of crops. This is in line with Yuan-zhi. (2015) who reported 22 % and 15 % increase in panicle number and grain yield in rice (*Oryza Sativa* L.) under ridge tillage system compared to flat tillage system. *Kwale* had the highest yield while *Kingbird* had the highest TKW. The differences in yield and yield related traits between the ridge and flat tillage system might be prompted by soil physical and electrical properties. Therefore, from this study ridge tillage system promoted 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 improved yield. The ridge tillage system also had the higher number of seeds per spike, a thousand kernel weight, long spike length and high leaf chlorophyll content. The results demonstrated that the ridge tillage system had high normalised difference vegetative index which highly correlated with leaf area index, biomass, fractional of absorbed photosynthetic active radiation and grain yield. The high NDVI in ridge system suggests that cropping in this system had higher vegetation and high red light absorbed compared to infrared reflected by the plants. This enhanced photosynthesis which translated to high yield production. Similar results have been reported by Sultan *et al*. (2014) that NDVI is highly correlated with grain filling days, days to maturity and grain yield of wheat. Similar results by Yamanura and Patil (2021) indicated that decrease in NDVI is directly proportional to the percentage and composition of soil minerals.

In this study, location had no significant effect on soil bulk density which might be attributed to almost similar soil physical properties between the two locations. However, significant difference was observed on bulk density between the two tillage systems. Ridge tillage system had lower soil bulk density than the conventional flat tillage system in this study. This might be due to hard pans and the settling of soil particles after tillage in flat system and the limitation of soil compaction in the ridge tillage system. There was rather no effect between the two cultivars due to soil bulk density. This could be one of the reasons why low yields were obtained from the conventional flat tillage indicating that soil compaction and penetration resistance uniformly influence wheat growth irrespective of their genetic makeup. This is in line with results obtained by Gill and Aulakh (1990) and Wilson *et al*. (2013) who found low yield and biomass in soils with high soil bulk density.

Njoro and Egerton site had no difference in soil moisture content. Regardless of these, the flat system, had lower soil moisture content than the ridge tillage system. 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, control of water runoff during precipitation and the ability of the ridge system to collect rainwater in between the furrows.

Ridge tillage has also been reported to control soil erosion and conserve water post precipitation which indicates that, cultivars on the ridge tillage system had more duration of exposure to water during growing stages than those in the flat tillage system. This result concurs with Lal (1990) and Ren *et al*. (2021) who suggested that a ridge tillage system promotes soil fertility, requires low labour, conserves water, ease to control weeds, controls soil erosion and facilitates multiple cropping. On the other hand, the flat tillage system seems to accumulate more heat than the ridge system. This might also be due to the reason why low moisture content was observed on flat system. The results showed that increase in soil temperature simultaneously led to decrease in soil moisture content. High soil temperature facilitates increase evapotranspiration which leads to rapid water loss in soils. This is also in agreement with the study conducted by Xie (2010) indicating that soil temperature influences root activity, grain germination, filling, and grain yield. 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 (Lu *et al*., 2019; Zi *et al*., 2018;). The high soil temperature in the conventional flat tillage system led to strong evaporation which reduced soil moisture conditions in the tillage system.

Soil temperature and moisture influence soil electrical conductivity. In the ridge system the electrical conductivity was higher than the flat system. This can be attributed to the high soil moisture and temperature in the ridge system. Ma *et al*. (2011) found that soil temperature directly influences soil electrical conductivity and suggested optimum soil temperature of 25 ^{o}C. Electrical conductivity is a measure of high salts which is an indicator of available soil nutrients, good soil texture and high activity of soil micro-organisms. Electrical conductivity in soil can be used to indirectly postulate the amount of available nitrogen, ammonium, sulphate, potassium, chloride and sodium in the soil. This study revealed that soil electrical conductivity is correlated with grain yield thus explaining the high yields obtained in the ridge systems. Similarly, Othaman *et al*. (2020) found that electrical conductivity is directly proportional to soil nutrient concentration and soil salinity which influence crop yield potential and inversely proportional to soil depth.

Soil temperature, moisture and electrical conductivity are environmental dependent in terms of location and soil physical properties (Hawkins *et al*., 2017; Ma *et al*., 2011). In this study, soil physical properties seemed to influence each other. Soil bulk density increased with decrease in soil moisture, soil temperature and electrical conductivity. This could be as a result of compaction and smearing effect. Soil temperature also influenced electrical conductivity. However, soil moisture correlated with soil temperature and electrical conductivity. In the ridge system, there was high soil moisture and electrical conductivity compared to flat system which had high soil temperature and bulk density (Ma *et al*., 2011). The two locations differed in soil temperature and electrical conductivities and were not significantly different in soil moisture content. This concurs with study conducted by Lindstrom *et al*. (1976) who found out that with adequate soil moisture in the soils, the seedling emergence is directly influenced by soil temperature in wheat growth and production. However, yield is a trait that is influenced by the environment and in this study, high yield, TKW and HI was observed in Egerton than Njoro. Thus as much as management practices and environment influences cultivar performance, the genetic yield potential of wheat cultivars greatly determines the production ability of the cultivars.

3.7 Conclusions

The two locations were distinct and provided perfect environment for evaluation of the wheat cultivars in the ridge and flat tillage system. Compared with conventional flat tillage system, ridge tillage system is an effective technique of planting wheat. This study revealed that ridge tillage system provided essential elements of water and nutrient for the physiological development and growth of spring wheat. In addition, high electrical conductivity in the ridge system made sure essential soil nutrients and salts were available for plant uptake. It facilitated improved soil conditions; aeration, conserved soil moisture, optimum soil temperature and ease of root penetration translating to increased yield, TKW and harvest index in the ridge system which is an important affirmation of effectiveness of ridge tillage system for wheat growth. The high yields obtained in the ridge system are presumably due to late leaf senescence, long grain filling period, high NDVI and maturity period which facilitated photosynthesis, chlorophyll accumulation and dry matter accumulation. The mean yield difference between cultivar *Kwale* and *Kingbird* was high in flat tillage system and very low in ridge tillage system. However, the two wheat cultivars had no significant difference in yield therefore, the ridge tillage system is suitable for diverse wheat cultivars than flat tillage system. Overall, 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.

CHAPTER FOUR

MORPHOLOGY AND ROOT GROWTH OF SPRING WHEAT UNDER FLAT AND RIDGE TILLAGE SYSTEM

Abstract

Ridge-furrow (RF) tillage system influence root growth which is one of the key components of growth and production of wheat. The objective of this study was to determine the effect of RF and conventional flat tillage system on root length, volume, diameter, and surface area of *Kingbird* and *Kwale* wheat cultivars. An experiment was conducted at Egerton (0º 22' 26'' S, 35º 56' 1.3'' E) and KALRO-Njoro (0° 22′ 47'' S, 35° 56′ 1.7'' E) in a randomized complete block design (RCBD) split-plot arrangement. The tillage systems were regarded as main plots and cultivars as sub-plots. Location had significant ($p \leq 0.001$) effect on all the root traits tested, however, had no significant ($p > 0.05$) effect due to tillage systems were observed for root diameter. The location × tillage × cultivars interaction was significant ($p \leq 0.05$) for root length. Cultivars in ridge system had longer root length (85.48 cm), larger surface area (69.12 cm^2), diameter (0.19 mm) and volume (4.39 cm^3) than those in flat system. *Kingbird* had longer roots (33.49 cm) and wider root diameter (17.62 mm) whereas *Kwale* had larger root surface area (1.62 cm^2) and larger volume (2.29 cm^3). Soil bulk density negatively affected root length, root surface area, root diameter and root volume. Electrical conductivity negatively affected root surface area, root diameter and root volume. Soil moisture significantly associated with root length (r=0.80*) and surface area (r=0.76*) whereas root volume was significantly correlated with root surface area (r=0.94***) and root diameter (r=0.75*). This study has shown that ridge tillage system promotes root growth and development of wheat cultivars thus should be adopted for wheat production.

4.1 Introduction

Root growth which as a function of tillage system is the most important component of growth and yield production in wheat. Climate change is continuing to impart pressure on agricultural production (Govaerts & Sayre, 2009). It is estimated that the global human population will increase to over 9 billion by 2050 (UN, 2015). This will further put pressure on the already limited natural resources and increase food demand (Shah & Wu, 2019). Wheat is the second most important food crop worldwide, therefore its contribution to food security is critical. It therefore, necessitates to improve the physiological growth and production of wheat through improved production systems (Shiferaw *et al*., 2013). Thus, use of tillage systems which have reduced soil disturbance while promoting soil quality and health is key to improved yield production and food security (Kuntz *et al*., 2013).

Wheat growth, yield and yield quality are determined by the tillage system. There are several tillage systems including, no-tillage, conventional tillage and reduced or minimal tillage which are widely used worldwide (Woźniak & Soroka, 2018). Agricultural production should be linked to human health through nutritional values and environmental quality. Soil quality, properties, structure and capacity to produce high yields is related to crop health and conducive environment to express its full potential (Rühlemann *et al*., 2015; Woźniak & Soroka, 2018). Tillage system determines soil aeration which enhances root development. A well aerated soil facilitates vigorous root system which is associated with increased production of harvestable above ground biomass (Guan *et al*., 2015; Klepper, 1990). Ridge tillage system has greater soil water accumulation capacity which facilitates root growth and distribution (Guan *et al*., 2015). Root length, volume, biomass and spread which are determinants of crop growth and production are influenced by the soil properties and morphogenetic factors (Clark *et al*., 2003).

The main factors influencing root growth are soil pore system, soil water content, hard pans, soil temperature, soil nutrient capacity and soil oxygen concentration (Johnson *et al*., 2006). Alvaro-Fuentes *et al.* (2007) suggested that the soil structure has a great influence on the edaphic conditions and is a function of tillage systems which directly influence soil aeration, soil moisture and root growth. Reduced soil tillage decreases the rate of mineralization of soil organic matter reducing soil nutrient leaching promoting high yields (Zhang *et al*., 2015). Ridge system reduces soil compaction which facilitates ease penetration of roots to deep soil profile increasing root mass and increase their efficiency in nutrient and water uptake (Li *et al*., 2002). In a study by Yao (2015) on rice (*Oryza sativa* L.) ridge tillage system increased root number, root absorption, gas exchange, antioxidant enzyme activity, panicle number and yield by 22.12 % and 15.18 %, respectively. Therefore, the objective of this study is to determine the effect of tillage system on root length and root mass of Kingbird and *Kwale* wheat cultivars.

4.2 Materials and methods

4.32.1 Environment

The experimental site is described in chapter 3 (Section 3.3.1)

4.2.2 Cultivars

Two wheat genotypes, *Kwale* and *Kingbird* were used in this study. They are described in Chapter 3 (Section 3.3.2)

4.2.3 Experimental procedure

Root sampling was conducted using soil-core procedure by Böhm (1979) and 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 ºC. 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 157.48 dots per centimetre (dpc). Root length analyses was 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 ºC for 72 hours to obtain the root dry weight. The program detected overlapping parts and took them into account when calculating root parameters. Roots from the ridge and conventional flat planting were analysed to test their effects on the root length and diameter. In this study only results related to the total root length and root surface area was used for comparison.

4.3 Data analysis

Data on root morphology, structure and length in flat and ridge tillage system were subjected to analysis of variance (ANOVA) using Randomised complete block design (RCBD) split plot arrangement in SAS version 9.4 (SAS Institute, Inc. 2018).

$$Y_{ijklm} = \mu + L_i + R_{j(i)} + T_k + C_l + LT_{ik} + LC_{il} + RT_{jk(i)} + RC_{jl(i)} + LTC_{ikl} + RTC_{jkl(i)} + LTC_{ikl} + RTC_{jkl} + \varepsilon_{ijklm} \text{..Equation 1}$$

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 and i^{th} location; LC_{il} = Effect of interaction due to l^{th} cultivar and i^{th} location; $RT_{jk(i)}$ = Effect of k^{th} tillage in the j^{th} replicate nested in the i^{th} location; $RC_{jl_{(i)}}$ = Effect of l^{th} cultivar in the j^{th} replicate nested in the i^{th} location; LTC_{ikl} = Effect of interaction due to k^{th} tillage and l^{th} cultivar in the i^{th} location; $RTC_{jkl(i)}$ = interaction of the lth cultivar and k^{th} tillage in the j^{th} replicate nested in the i^{th} location; $(LTCN)_{iklm}$ = main plot interaction effect; $(RTCN)_{jklm}$= sub-plot interaction effect and $\mathcal{E}_{ijklm}$ = Random error component. The analysis considered cultivars as fixed factors, replicates nested in location, while location and tillage, tillage × cultivar interaction as random factors. The analysis was done using the following SAS procedures:

```
SAS PROCEDURE

Title 'Wheat';
Data Roots;
Input Length SA Diameter volume smoist  stemp EC Bdesity;
Datalines;
proc corr;
ods rtf file='corrroot2.rtf';
run;
ods rtf close;
;
Run;
```

Means for the tillage systems were compared using least significance difference (LSD) test at $p \leq 0.05$ whenever the main effects are significant using the following formulae (Gomez & Gomez, 1984).

$LSD = t_{\frac{\alpha}{2}} \times \sqrt{\frac{2MSE}{r}}$……………………………………………………………..Equation 10

where *LSD* is the least significant difference, $t_{\frac{\alpha}{2}}$ is *t*-critical value from the t-distribution table at a given confidence level, *MSE* is the mean square error and *r* is the number of replications.

Pearson's correlation coefficient was employed to determine the relationship between the agronomic traits and the root morphology using the following equation described by Cohen and Aiken, (2014).

$$r = \frac{n(\sum x_i y_i) - (\sum x_i)(\sum y_i)}{\sqrt{[n\sum x^2 - (\sum x_i)^2]\,[n\sum y_i - (\sum y_i)^2]}} \quad \text{.......... Equation 3}$$

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.

4.4 Results

4.4.1 Analysis of variance

Root length, root surface area and root volume were significant ($p \leq 0.001$) due to location. Location also had a significant ($p \leq 0.05$) effect on root diameter. The tillage systems and the interactions of Location × Tillage were significant for all the root traits except root diameter and root volume due to their interaction. The two wheat cultivars varied in root length ($p \leq 0.05$), root diameter ($p \leq 0.01$) and root volume ($p \leq 0.001$) while the interaction of Location × Cultivar and Tillage × Cultivar was significant ($p \leq 0.001$) for root surface area and root volume. The interactions of Location × Tillage × Cultivar had significant ($p \leq 0.05$) effect on root length.

Table 4.1 Mean squares of 2 wheat varieties evaluated at 2 locations under 2 tillage systems for root length, root surface area, root diameter and root volume.

Source of variation	df	Root length (cm)	Root surface area (cm^2)	Root diameter (mm)	Root volume (cm^3)
Location (L)	1	14646.748*	19913.796***	1.317*	0.668***
Replicates (R)	3	3879.301	3771.762*	0.744	0.151
L × R (Error a)	3	547.194	1797.022	0.053	0.041
Tillage (T)	1	16915.270***	76428.058***	0.559	2.005***
L × T	1	62889.982***	18985.740***	0.394	1.148
R× T	3	6111.619	1299.763	0.817*	0.045
L×R×T(Error a)	3	5531.833	1297.737	0.038	0.023
CV_a (%)		36.478	27.854	9.314	6.231
Cultivar (C)	1	17939.588*	2038.184	2.318**	0.375**
L × C	1	2182.875	8557.869**	0.214	0.33**
T × C	1	1390.451	6992.932**	2.273**	0.602***
L × T × C	1	17861.988*	3247.148	0.033	0.058
Error	44	3262.356	982.171	0.292	0.039
Mean		203.893	129.331	2.093	2.434
C.V (%)		28.013	24.232	25.831	8.141
R^2		0.672	0.788	0.484	0.742

CV=Coefficient of Variation; R^2 =coefficient of determination, df = degree of freedom

*, **, ***, indicate significance at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

Log transformation was applied on root volume prior to analysis of variance.

Table 4.2 Effect of environment, tillage system and cultivar on root length, surface area, diameter, and root volume of two spring wheat cultivars

Environment	Root length (cm)	Root surface area (cm^2)	Root diameter (mm)	Root volume (cm^3)
Njoro	219.02a	146.97a	2.24a	8.45a
Egerton	188.77b	111.69b	1.95b	5.62b
LSD $_{(0.05)}$	29.36	15.92	0.26	1.21
Tillage	Root length (cm)	Root surface area (cm^2)	Root diameter (mm)	Root volume (cm^3)
Ridge	246.63a	163.89a	2.19a	9.23a
Flat	161.15b	94.77b	2.00b	4.84b
LSD $_{(0.05)}$	29.36	15.92	0.26	1.21
Cultivar	Root length (cm)	Root surface area (cm^2)	Root diameter (mm)	Root volume (cm^3)
Kingbird	220.64a	123.69a	19.90b	5.89b
Kwale	187.15b	134.97a	2.28a	8.18a
LSD $_{(0.05)}$	29.36	15.92	0.26	1.21

Means presented are from 16 plots. Means followed by the same letters in a column are not significantly different based on Fischer's Least Significant Different.

In the two sites, ridge tillage system had high means for root length, root surface area, root diameter and root volume (Table 4.2). However, Njoro had higher means for root surface area, root diameter, and root volume in flat tillage system compared Egerton (Table 4.3). Ridge system in the two sites showed that Njoro had higher means than Egerton in all the root traits tested (Table 4.2).

Kingbird and *Kwale* spring wheat cultivars had higher means for root length, surface area and diameter in Njoro than Egerton. *Kingbird* had higher root surface area, root diameter and root volume than *Kwale* in Njoro. In Egerton, *Kingbird* had higher root length and root surface area mean than *Kwale* whereas *Kwale* had higher root diameter and root volume than *Kingbird*. In the flat tillage system, *Kingbird* had higher mean for root length, root surface area and root volumes than *Kwale*. However, the two cultivars did not differ in root diameter. In the ridge system, *Kwale* had higher mean for all the root traits than Kingbird except for the root length. Further, the ridge tillage system had higher means than the conventional flat tillage system for all the root traits under study (Table 4.3).

Table 4.3 Effects of location and tillage system on root length, root surface area, root diameter and root volume for 2 wheat varieties.

		Root length (cm)		Root surface area (cm^2)		Root diameter (mm)		Root volume (cm^3)	
Location	Tillage	Mean	se	Mean	se	Mean	se	Mean	se
Njoro	Flat	144.93	13.49	95.19	8.28	2.22	0.19	5.38	0.66
Njoro	Ridge	293.11	19.12	198.75	12.66	2.25	0.15	11.52	1.22
Egerton	Flat	177.37	16.97	94.36	9.32	1.78	0.14	4.30	0.57
Egerton	Ridge	200.16	13.31	129.02	7.31	2.12	0.12	6.94	0.59
		Root length (cm)		Root surface area (cm^2)		Root diameter (mm)		Root volume (cm^3)	
Location	Cultivar	Mean	se	Mean	Se	Mean	se	Mean	se
Njoro	*Kingbird*	229.92	7.76	129.76	15.57	1.99	0.20	6.33	0.85
Njoro	*Kwale*	208.12	5.53	164.18	17.44	2.49	0.11	10.57	1.37
Egerton	*Kingbird*	211.35	3.83	117.61	7.61	1.82	0.11	5.46	0.53
Egerton	*Kwale*	166.18	4.61	105.77	10.85	2.08	0.15	5.78	0.78
		Root length (cm)		Root surface area (cm^2)		Root diameter (mm)		Root volume (cm^3)	
Tillage	Cultivar	Mean	se	Mean	se	Mean	se	Mean	se
Flat	*Kingbird*	173.23	16.09	99.58	7.84	2.00	0.21	5.00	0.59
Flat	*Kwale*	149.07	15.06	89.96	9.53	2.00	0.14	4.68	0.67
Ridge	*Kingbird*	268.04	22.65	147.79	12.90	1.81	0.10	6.79	0.76
Ridge	*Kwale*	225.23	16.03	179.98	13.21	2.57	0.09	11.67	1.08

Means presented are from 16 plots.

Table 4.4 The Effects of location and tillage system on wheat varieties under 2 tillage systems for root length, root surface area, root diameter and root volume

			Root length (cm)		Root surface area (cm^2)		Root diameter (mm)		Root volume (cm^3)	
Location	Tillage	Cultivar	Mean	± se	Mean	± se	Mean	± se	Mean	± se
Njoro	Flat	*Kingbird*	134.47	± 13.68	81.31	± 3.02	2.19	± 0.38	4.53	± 0.86
	Flat	*Kwale*	155.40	± 23.70	109.07	± 15.15	2.26	± 0.12	6.23	± 0.95
	Ridge	*Kingbird*	325.38	± 30.36	178.21	± 18.97	1.79	± 0.16	8.13	± 1.18
	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
	Flat	*Kwale*	142.74	± 19.98	70.86	± 7.44	1.75	± 0.23	3.13	± 0.57
	Ridge	*Kingbird*	210.70	± 18.36	117.37	± 9.45	1.82	± 0.14	5.44	± 0.74
	Ridge	*Kwale*	189.62	± 19.76	140.68	± 10.03	2.42	± 0.11	8.43	± 0.53

Means presented are from 8 plots.

4.4.2 Correlation of root and the soil characteristics of spring wheat under ridge and flat conventional tillage system over two locations

Root surface area correlated with root length (*r*=0.83**) and yield (Figure 4.1). Soil moisture, correlated with root length (*r*=0.80*) whereas soil bulk density had a negative effect on root length (Table 4.5). Root surface area increased with increase in root diameter, root volume (*r*=0.94**), soil moisture (*r*=0.76*) and soil temperature while soil bulk density had negative effect on root surface area. Root diameter correlated with soil moisture (*r*=0.75*) and soil temperature but negatively correlated with soil bulk density. Soil moisture and soil temperature favoured increase in root volume and on the other hand, soil bulk density limited root growth and development (Table 4.5).

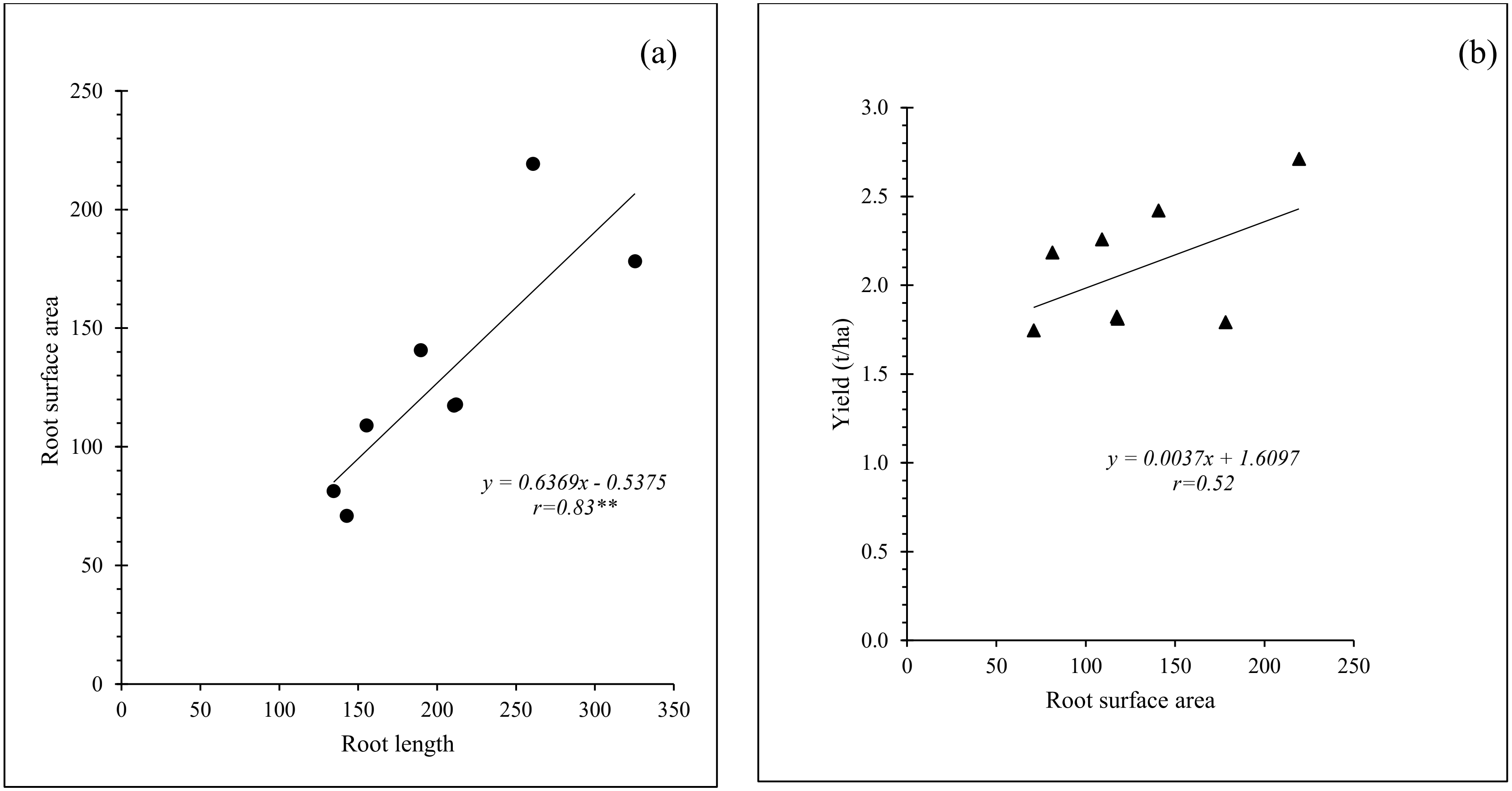

Figure 4.1 Correlation coefficients among (a) root surface area and (b) grain yield of *Kwale* and *Kingbird* spring wheat

Table 4.5 Pearson correlation coefficient of root traits and soil moisture, temperature, electrical conductivity, and soil bulk density

Traits (Root)	Surface area	Volume	Soil moisture	Soil temperature	Electrical conductivity	Soil bulk density
Length	0.83**	0.60	0.80*	0.2	0.40	-0.78*
Surface area		0.94***	0.76*	0.34	0.14	-0.81*
Diameter			0.75*	0.17	0.43	-0.44
Volume				0.61	0.38	-0.25

*, **, *** indicate significance at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

4.5 Discussion

The root system is one of the key components facilitating crop physiology through metabolic reactions and key in 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. Soil physical characteristics are location dependent which means they vary with environment (Moraes *et al.,* 2014). Njoro and Egerton sites were significantly different for root length, root surface area, root diameter and root volume. The result of this study shows that, Njoro site had higher means for root length, root surface area, root diameter and root volume. This might be influenced by the differences in soil type and properties. Njoro is predominantly *Mollic Andosols* while Egerton is predominantly covered by *Ventric Mollic Andosol* soils. These results are consistent with studies conducted by Rich *et al.* (2020) who found inconsistencies in correlation coefficients between root traits of genotypes grown in controlled and field environment. Similarly, Manschadi *et al.* (2008) found differences in root architecture of wheat grown in northern and Western Australia. Regardless of the soil physical characteristics and location, cropping system may influence the root growth. However, the effects of suitable cropping systems employed in farming are short-run and may disappear in few cropping seasons. Therefore, it is imperative to routinely practice suitable tillage systems for long term economic impact.

Ridge tillage system had higher means for root length, root surface area, root diameter and root volume. Root mass reflect the degree of root growth. According to Lynch (1995) root length, root volume, root surface area, root diameter and root density are some of the key root morphological traits facilitating crop performance. Under ridge system there is high competition for nutrients compared to conventional flat tillage system. As a result, there is high root extension and growth. Further, ridge system had well aerated soils 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 ridge tillage system in growth of wheat cultivars due to readily available soil water content and efficient nutrient supplementation. These results are in line with those of Yao (2015) which showed that, rice grown on ridge tillage system had higher stomatal conductance, photosynthesis rate, water use efficiency and root number. Wheat breeding for improved root architecture has been facing challenges and its success limited. Furthermore, glass walled rhizoboxes and soil-filled PVC has been used to determine root architecture and currently, there has been immense research on root morphology using high throughput phenotyping technology also with limited success (Chen *et al*., 2015). Therefore, using tillage systems such as ridge tillage might promote root architecture of wheat crops.

Kingbird and *Kwale* cultivars were significantly different for the root traits determined. There has been diverse genetic variation in root architecture in wheat crops worldwide (Chen *et al*., 2020; Manschadi *et al*., 2006). *Kwale* had large diameter and root volume while *Kingbird* had high greater root depth and root surface area than *Kwale.* This shows that the two cultivars are genetically different for root traits. These results are in line with those of Manschadi *et al.* (2008) and Narayanan *et al.* (2014) who found variability in root traits among spring wheat. The importance of deep and large surface area root system is maintenance of crop growth under water and nutrient limited environment. In this case roots were able to withdraw water and nutrient from deep soil layers which translated to higher yield and seed weight (Manschadi *et al*., 2006; Reynolds *et al*., 2007). 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. In wheat, shift in water availability at the pre and post anthesis stage might have great impact on grain yield and test weight. Therefore, adoption of cropping system which cushions wheat crop from water stress is vital (Kirkegaard *et al*., 2007).

The positive correlation between root traits in this study indicate that root traits are interdependent in growth of wheat crops. Root length is an important trait in determining soil moisture and soil bulk density. This study revealed a significant relationship between root length and soil moisture and a negative significant relationship with soil bulk density. Long root facilitates good crop establishment through improved photosynthesis rate, biomass production, access of water and nutrient during drought period, improved grain filling period which translated to high yields (Kirkegaard *et al*., 2007; Kulkarni *et al*., 2017). However, soil bulk density might hinder root penetration to deeper soils which might have an adverse effect on grain filling period, yield production and seed weight. In this study soil bulk density had a significant negative effect on root length and root surface area and according to Lilley *et al*. (2011) deep soil penetration of root enhances absorption of soil water and nutrients post anthesis increasing yield production in wheat. Soil profile with high soil moisture tend to have high root surface area, diameter, volume and long roots. This is due to the adventitious roots occupying the topsoil profile. However, root volume and surface area decrease with soil depth to increased soil bulk density. The root length increased with decrease in root diameter which contrasts with Narayanan *et al*. (2014) who found a positive correlation between root length and root diameter and further described large root diameter as an important trait in root penetration to deeper soil profiles. Above all, thinner roots are efficient in restriction of water and nutrient absorption at the early growth stage until anthesis and post anthesis stages. Moreover, the metabolic maintenance of thinner roots is less expensive for the plant than thicker roots. This is in line with Elazab *et al*. (2016) who found out that the ideal root structure system is a function of the metabolic cost of maintenance and production of root tissues and the ability of seizing the limited resources from the soil.

4.7 Conclusions

The results from this study showed that ridge tillage system was effective in growth and maintenance of the root morphology. Ridge tillage system improved root length, surface area, diameter and volume. Therefore, using tillage systems such as ridge tillage might promote root development and architecture of wheat crops which translates to higher yields and grain weight. Wheat genotypes have diverse root architecture which influence their growth and performance. However good the root system, tillage practice, soil physical characteristics and environment generally influence the final root structure of wheat crop.

CHAPTER FIVE

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 General discussion

From the study, ridge-furrow tillage system enhanced the physiology and growth of spring wheat. This was augmented with increase in kernel yield and yield components. The cultivars planted on the ridge system took longer to mature and had longer spike length, high TKW, HI, number kernels per spike and spikelets. This concurred with the study conducted by Yuan-Zhi (2015) who reported 22% and 15% increase in panicle number and grain yield of rice under ridge tillage system in contrast to flat tillage system. The findings can be attributed to the high soil moisture and low soil bulk density in the ridge-furrow tillage system. Similar results were recorded by LI *et al.* (1999) who discovered that favourable hydrothermal soil conditions in the ridge system increased tiller numbers and prolonged the phenostages hence contributing to increased yields. The results by Motzo *et al.* (2010) also showed that adequate soil moisture in the ridge system increased grain filling period by delaying maturity and leaf senescence. Therefore, in this study photosynthesis continued for a longer period as result of the delayed senescence increasing the duration of assimilate partitioning to the grain resulting to high yield and kernel quality.

In other studies, variation in yield is positively associated with grain filling period which was also related to grain number per unit area. The results further demonstrated that ridge tillage system had high NDVI which highly correlated with LAI, biomass, fractional of absorbed photosynthetic active radiation and grain yield. The high NDVI in ridge system suggests that cropping in this system had higher vegetation and high red light absorbed compared to infrared reflected by the plants. This enhanced photosynthesis which translated to high yield production. Similar results have been reported by Sultan *et al*. (2014) that NDVI is highly correlated with grain filling days, days to maturity and grain yield of wheat.

During the study period, growing degree days was used to depict growth processes of the two wheat cultivars in relation to the daily maximum and minimum temperatures. The findings indicated that wheat cultivars in both sites had high growth rates in the first three months and lag phase towards maturity. This was attributed to the high amounts of rainfall experienced towards the end of the cropping season in the two sites. The results demonstrated that for optimal seed size and number (potential yield) wheat must establish biomass and reach anthesis at a time that coincides with optimal seasonal conditions as earlier indicated by Trethowan (2014).

Wheat cultivars in Njoro took long to mature than those in Egerton. This might be as a result of the delayed leaf senescence, high soil moisture and high NDVI indices. It is known that wheat cultivars are sensitive to photoperiod. Therefore, location significantly affected all the agronomic and soil properties thus concurring with the findings by Wand and Engel (1998) suggesting that both photoperiod and temperature are critical in wheat phenology especially in days to anthesis and days to maturity.

Significant difference was observed on soil bulk density whereby the ridge tillage system had lower soil bulk density than the conventional flat tillage system. This might be related to high soil aeration, ease of water infiltration, control of water runoff during precipitation and the ability of ridge system to collect rainwater in between the furrows. This is further related to hard pans, settling of soil particles after tillage in the conventional system and the limitation of soil compaction in the ridge tillage system. This explains the low yields obtained from the conventional flat tillage indicating that soil compaction and penetration resistance uniformly influence wheat growth irrespective of their genetic make-up. This confirms the results obtained by Gill and Aulakh (1990) and Wilson *et al*. (2013) who found low yield and biomass in soils with high soil bulk density.

The results indicated that ridge tillage had higher means for root length, root surface area, root diameter and root volume than the conventional flat tillage system. Root mass reflect the degree of root growth. The high root extension and growth experienced in the ridges is attributed to the high competition of nutrients in the ridges in contrast to the conventional flat tillage system. Further, the ridge system had well aerated soils with reduced bulk density which increased soil permeability facilitating root growth and penetration. This supports the findings by Yao (2015) who earlier reported that rice grown on ridge tillage system had higher stomatal conductance, photosynthesis rate, water use efficiency and root number. The differences in root traits for the two wheat cultivars is attributed to the diverse genetic variation in root architecture as earlier reported by Chen *et al.* (2020) and Manschadi *et al.* (2008) who found variability in root traits among spring wheat. In this case the roots in ridge system were able to withdraw water and nutrients from deep soil layers as a result of the deep root system and large surface area translating to higher yields and seed weight concurring with results reported by Reynolds *et al.* (2007).

The study further revealed a significant relationship between root length and soil moisture and a negative significant relationship with soil bulk density. As a result of the long roots, the ridge system had a good crop establishment resulting to improved photosynthesis rate, biomass production, access of water and nutrient during drought period, improved grain filling period, yield and seed weight. The results from this study is attributed to similar results reported by Liley *et al.* (2011) that soil bulk density in conventional tillage system had a significant negative effect on root length and surface area hence deep soil penetration of roots enhanced absorption of soil water and nutrient post-anthesis increasing yield production of wheat in the ridge system. The results are in contrast with findings by Narayanan *et al.* (2014) who found a positive correlation between root length and root diameter and further described large root diameter as an important trait in root penetration to deeper soil profiles thus explaining the root behaviour experienced in our study.

5.2 Conclusions

i. Compared with the conventional flat tillage system, ridge tillage system is an effective technique for planting wheat. This study revealed that ridge tillage system provided essential elements of water and nutrient for the development and growth of spring wheat.
ii. High electrical conductivity in the ridge system made sure essential soil nutrients and salts were available for plant uptake. It facilitated improved soil conditions; aeration, conserved soil moisture, optimum soil temperature, and ease of root penetration translating to increased yield, TKW, and harvest index in the ridge system which is an important affirmation of the effectiveness of the ridge tillage system for wheat growth.
iii. Ridge tillage system improved root length, surface area, diameter, and volume. Therefore, using tillage systems such as ridge tillage might promote root development and architecture of wheat crops which translates to higher yields and grain weight.
iv. Wheat genotypes have diverse root architecture which influence their growth and performance. However good the root system, tillage practice, soil physical characteristics, and environment generally influence the final root structure of wheat crop.

5.3 Recommendations

i. Considering the changing climatic conditions, physiological growth, development, and yield performance of spring wheat cultivars across locations, the ridge tillage system ranked highly. This system can be adopted for wheat production to increase wheat productivity and curb the adverse effects of climate change.

ii. Cultivar *Kwale* which is a late maturing spring wheat cultivar produced higher yields than *Kingbird* an early maturing spring wheat cultivar. This signified the importance and suitability of ridge tillage system in production and its contribution to yield increase for late maturing spring wheat cultivars.

iii. Ridge-furrow tillage system harbors numerous benefits for wheat growth and development. These includes; increases soil moisture, by increasing water infiltration as a result of the reduced soil compaction and reduced soil penetration resistance facilitating crop development through adequate root growth and development.

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APPENDICES

Appendix A. Statistical analysis procedures

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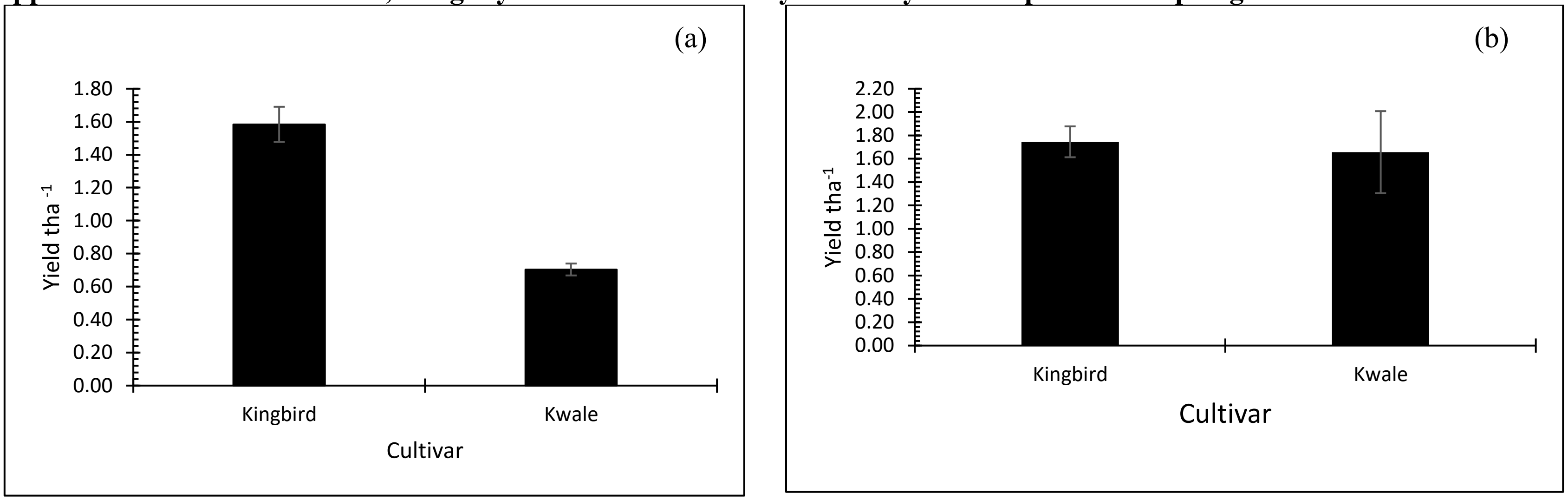
SAS PROCEDURE
Title 'Wheat';
Data Tillage;
Input Location $ Rep $ Tillage $ Cultivar $ Germination
     Earemergence FLS Flowering    Maturity  Height    Yield
     TKW  Spikelength    Biomass   nseedspke nspikelets
     Chloro    ndvi smoist    stemp     EC   Bdensity Rlength
     RSA  RDiameter RVolume;
Yieldt=log(Yield+5);
HI=Yield/Biomass;
HIt=log(HI+5);
Biomasst=log(Biomass+5);
/*Rlengtht=log(Rlength+5);
RSAt=log(RSA+5);
RDiametert=log(RDiameter+5);*/
RVolumet=log(RVolume+5);
Datalines;
;
Proc glm;
Class Location Rep Tillage Cultivar;
Model Germination   Earemergence FLS Flowering    Maturity
Height    Yield Yieldt TKW Spikelength Biomass Biomasst HI HIt
nseedspke nspikelets Chloro ndvi smoist stemp EC Bdensity
Rlength RSA RDiameter RVolume = Location Rep Location*Rep
Tillage Location*Tillage Rep*Tillage Rep*Location*Tillage
Cultivar Location*Cultivar Cultivar*Tillage
Location*Tillage*Cultivar/ss4;
Random Rep Location*Rep Rep*Tillage Rep*Location*Tillage;
Test H=Cultivar E=Rep*Tillage;
```

Appendix A. Continued…

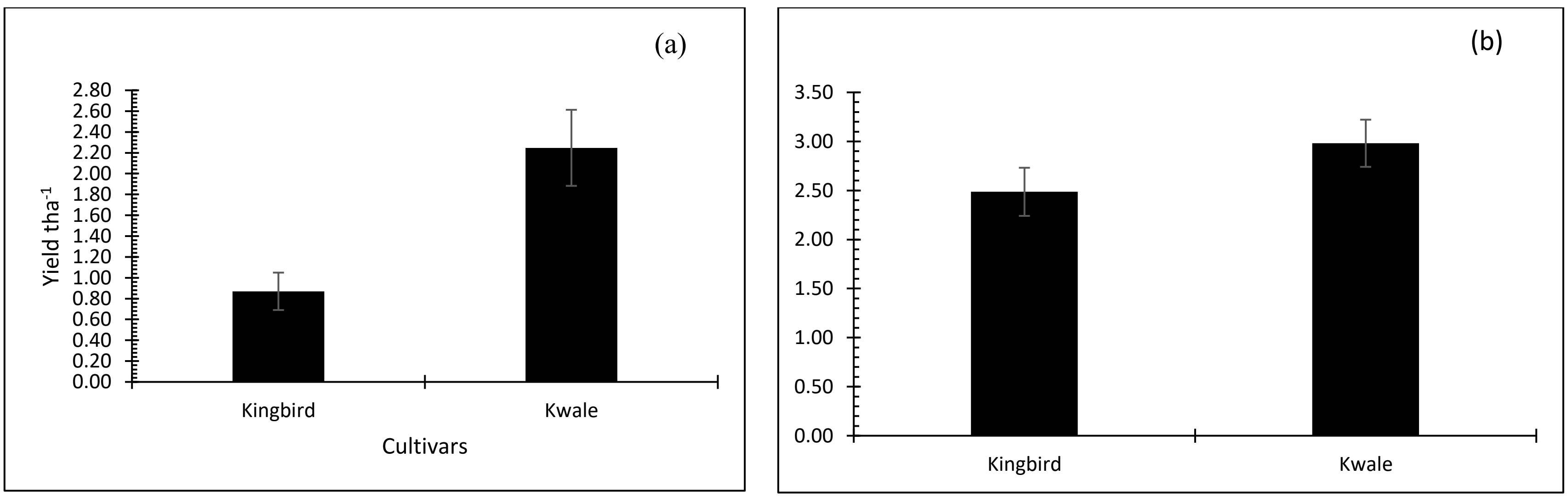
```
Test H=Tillage E=Rep*Location*Tillage;
Means Location Tillage Location*Tillage Cultivar
Location*Cultivar Cultivar*Tillage
Location*Tillage*Cultivar/lsd;
Means Tillage / dunnett ('Flt');
Ods rtf file='output. rft';
run;
ods rtf close;
;
Run;
```

```
Title 'correlation';
Data Corr;
Input;
Cards;
;
Proc corr;
Run;
```

Appendix B. Effects of location, tillage system and cultivar on yield and yield components of spring wheat

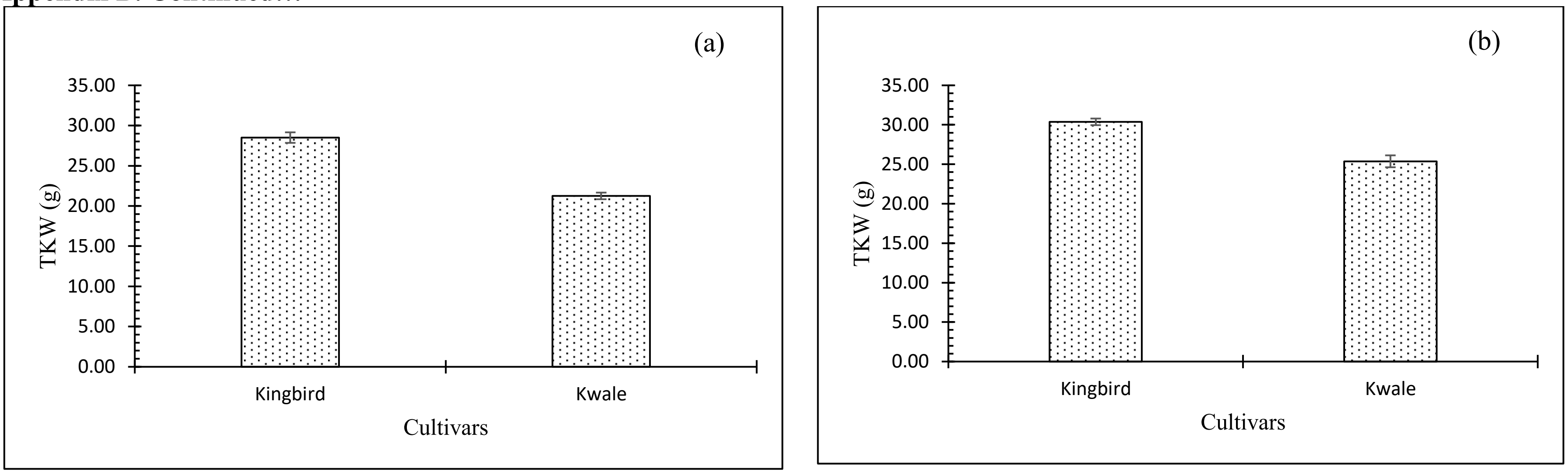


Effects of flat (a) and ridge (b) tillage system on yield of spring wheat cultivars in Njoro

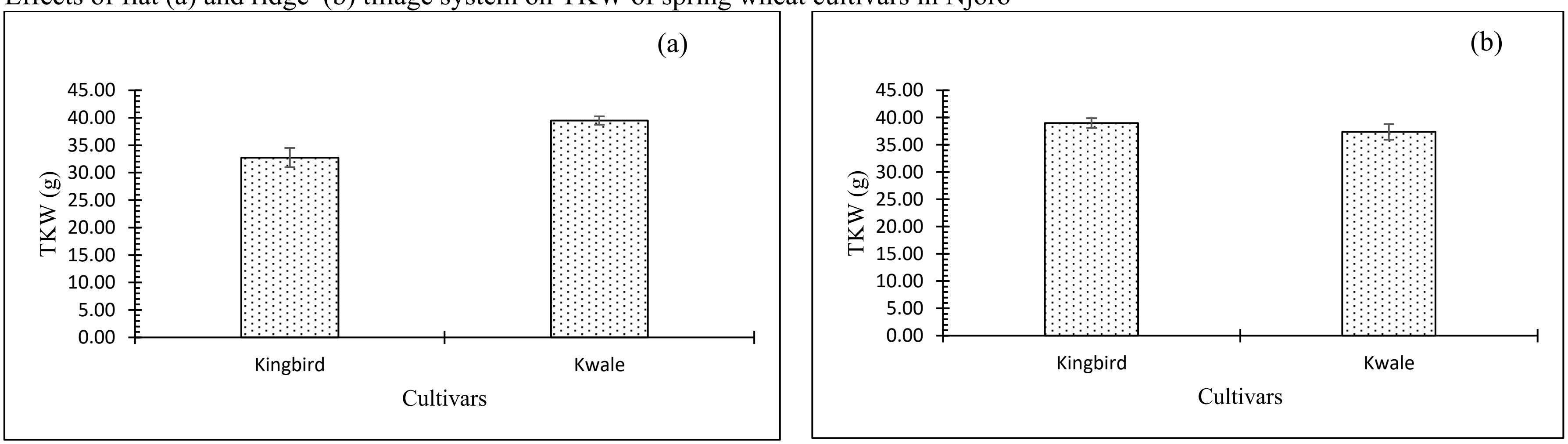


Effects of flat (a) and ridge (b) tillage system on yield of spring wheat cultivars in Egerton

Appendix B. Continued…

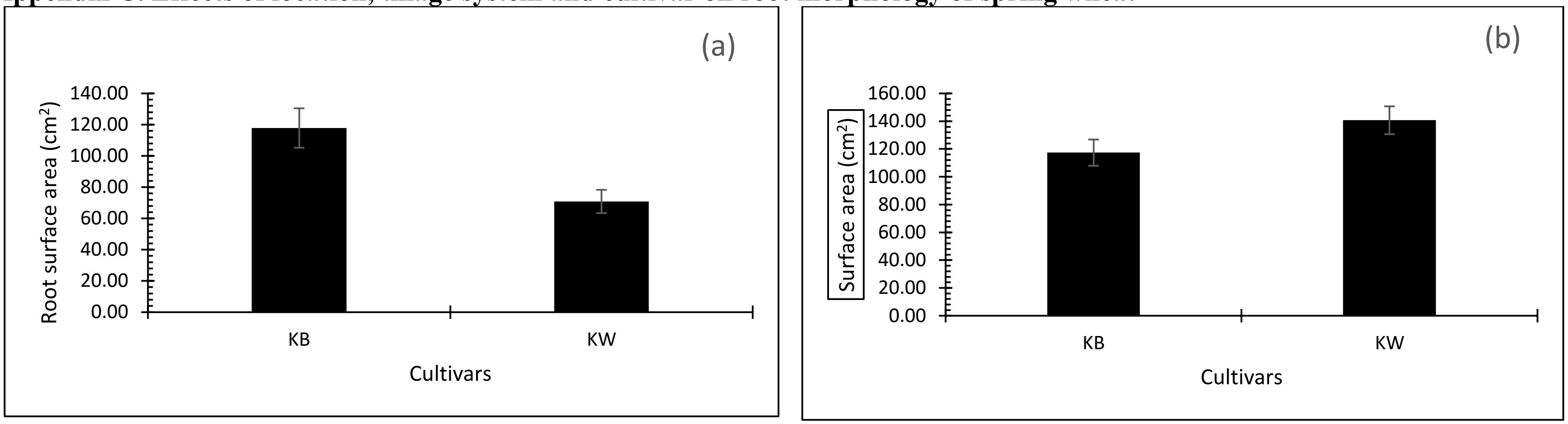


Effects of flat (a) and ridge (b) tillage system on TKW of spring wheat cultivars in Njoro

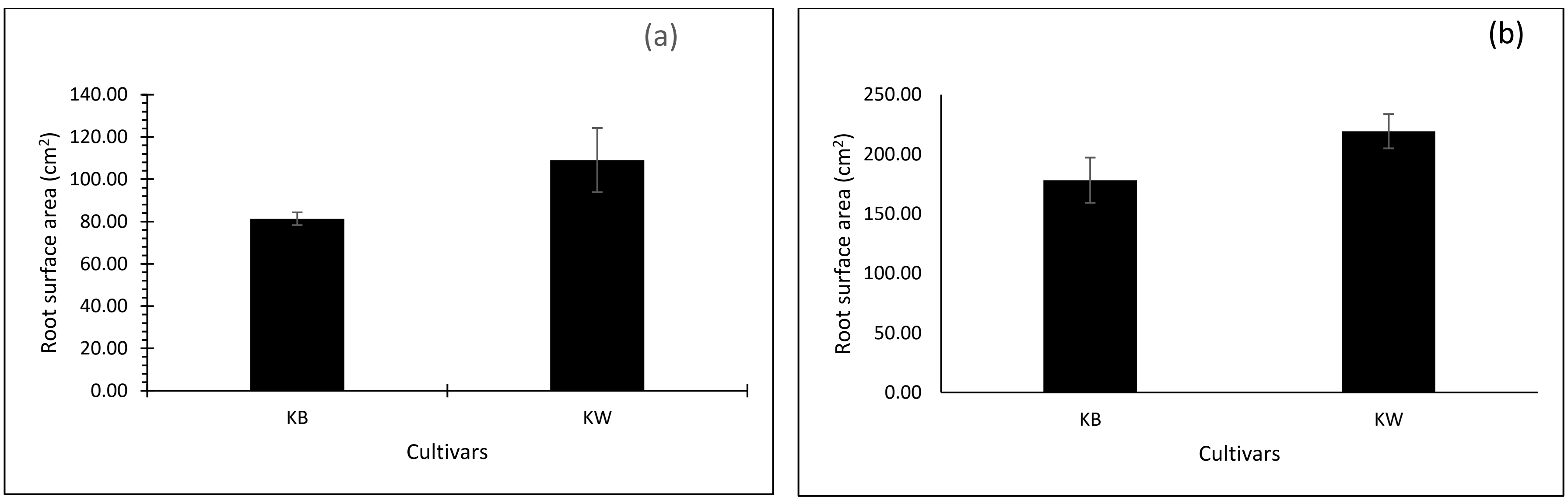


Effects of flat (a) and ridge (b) tillage system on TKW of spring wheat cultivars in Egerton

Appendix C. Effects of location, tillage system and cultivar on root morphology of spring wheat

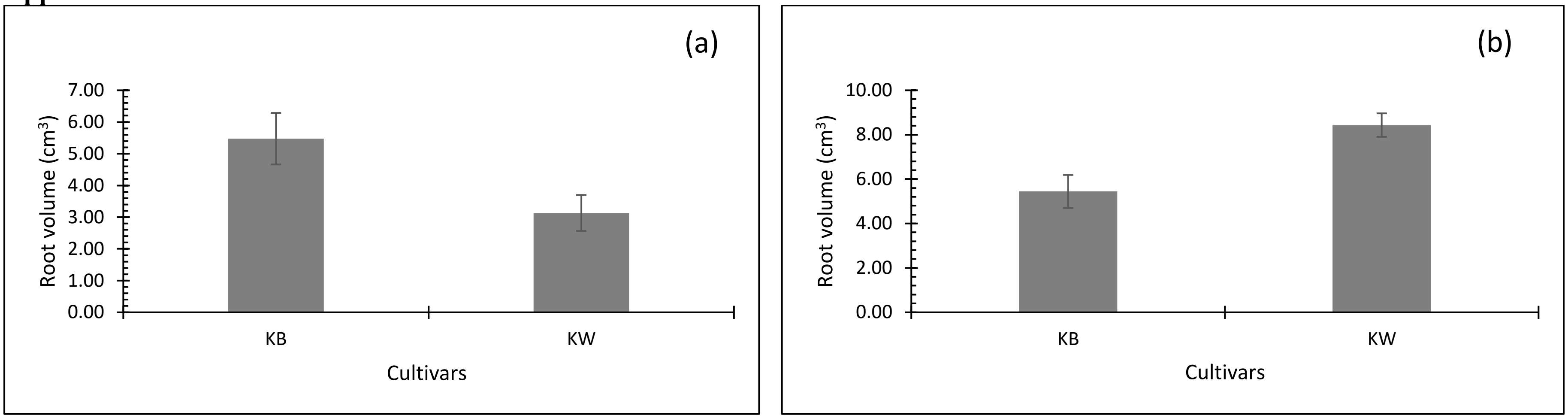


Effects of flat (a) and ridge (b) tillage system on root surface area for spring wheat cultivars in Njoro

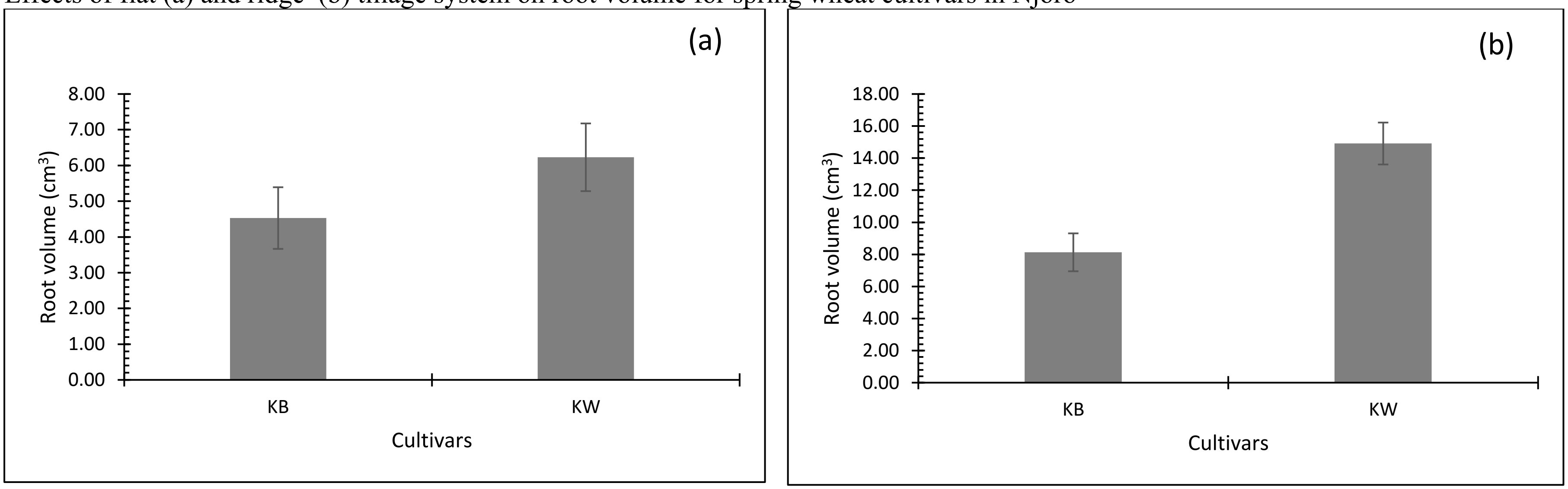


Effects of flat (a) and ridge (b) tillage system on root surface area for spring wheat cultivars in Egerton

Appendix C. Continued…



Effects of flat (a) and ridge (b) tillage system on root volume for spring wheat cultivars in Njoro



Effects of flat (a) and ridge (b) tillage system on root volume for spring wheat cultivars in Egerton

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Appendix E. Research Publication

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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.