FORIGINAL RESEARCH ARTICLE

Effect of tillage, mulching, herbicide application, intercropping and agroforestry on soil moisture maize yield and rainwater use efficiency in semi-arid Kenya: A case study of Laikipia East

Geofrey Waweru[1], *Florence Kanze Lenga*[1], *Mathew Gitau Gicheha*[2], *George Maina Ndegwa*[1]

[1]*Department of Land Resources Planning and Management, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya*

[2]*Department of Animal Science, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya*

Corresponding author email: **wajoeff@yahoo.com**

ABSTRACT

Conservation agriculture (CA) is promoted in Sub-Saharan Africa to address land degradation and low productivity among small-scale farmers. However, contrasting results have been reported from studies testing the impact of CA on land degradation and productivity. This study was conducted to investigate the effect of tillage, mulching, herbicide application, intercropping, and agroforestry on soil moisture storage, crop yield, and rainwater use efficiency (RWUE). Three main treatments consisting of conventional tillage (CT), no tillage (NT), and no tillage with herbicides (NTH) were tested. In each of the treatments, four sub-treatments, which included (a) maize and beans, (b) maize and dolichos, (c) maize, beans, and leucaena, and (d) maize, beans, and mulch (1.5 metric tonnes Ha^{-1}) replicated three times, were investigated. This implies that a split-plot design with 3 main plots and 4 subplots was used. The experiments ran for a period of three years and were characterised by two years of wetter than average. Tillage significantly affected crop yield, soil moisture, and RWUE during the dry year, with CT showing a significantly lower 33.9% and 33% maize yield and RWUE, respectively, than NT. Similarly, mulching significantly increased maize yield and RWUE by 13% and 19.8%, respectively, in the same year. Maize yield and RWUE were significantly increased in treatments that had agroforestry by 16% and 15.8%, respectively. By extension, it means that agroforestry has a positive impact on maize yield, soil moisture, and RWUE. The study showed that NT and mulch are critical aspects of CA in that they avoid drought stress on maize during dry seasons while enhancing maize yield. Agroforestry showed potential to further improve CA in semi-arid zones, resulting in higher yields in dry years. Even though the dry growing season under study corresponded with a meteorological drought, practicing two or three CA practices could avoid agricultural droughts due to the conservation of soil moisture that becomes available to crops during dry periods. The 'best' practice (no till with maize, beans, and mulch) resulted in up to 74% higher yield in the dry year and still up to 24% higher yield in the wet growing season under study, compared to the conventional practice. The study concludes that NT, mulching, and incorporating agroforestry in CA had a significant effect on soil moisture, maize yield, and RWUE, especially in seasons with rainfall below normal.

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Keywords: conservation agriculture, tillage, mulching, herbicide application, agroforestry, soil moisture

1.0 Introduction

Agriculture is key to reducing poverty and sustaining economic growth in Sub-Saharan Africa (SSA), where the majority of the population (95%) depends on rain-fed agriculture for food production (Ayanlade and Radeny, 2020). There is a strategic role played by the sector in ensuring food availability, which fosters food security (Wegren et al., 2018). The recent economic growth that has been witnessed in Sub-Saharan Africa (SSA) (Jayne et al., 2021) cannot be sustained without corresponding agricultural growth in rural areas. Researchers and policymakers agree that in order to meet future food needs and foster economic empowerment among smallholder farmers, rain-fed agricultural systems must be prioritised (Rockström et al., 2010). Compared to other regions in the world, agriculture productivity in SSA has increased impressively by roughly 4.3% annually since 2000 (Giller et al., 2021; Jayne et al., 2021). However, *per capita* food production in SSA has been declining over the last 50 years, and cereal yield remains low (Bjornlunda et al., 2020). Various factors are attributed to the large yield gaps; these include poor soil fertility because of continuous cropping and the effects of climate change (Godfrey & Tunhuma, 2020). Pozza and Field (2020) attribute major limitations to food security in SSA to poor soil health and land degradation. According to Moyo et al. (2015), the over-reliance on rain-fed agriculture and low adoption of irrigation have been the major factors contributing to low agricultural productivity in Africa. Climate change poses a threat to agricultural growth, and extreme weather events such as droughts and floods make the agriculture sector vulnerable in SSA (Kanu et al., 2014).

The above-described challenges are coupled with the fact that a large land area of SSA is arid and semi-arid, which is characterised by low rainfall with high intra- and inter-seasonal variability and high potential evaporation that easily exceeds the annual precipitation (Makurira, 2010). The ASAL covers about 80% of Kenya's landmass and is characterised by a hot and dry climate with low erratic rainfall (UNDP, 2012). Evapotranspiration rates are more than twice the annual rainfall, and drought is common. The trends of less and more than average rainfall events in SSA have increased in frequency during the 21st century, and these trends have led to the frequency of droughts and floods (Juana et al., 2013). Therefore, many countries on the African continent continue to be affected by climate change, resulting in a shift in the agricultural system (Müller et al., 2011). Due to climate change, the dependence on rain-fed agriculture by small-scale farmers negatively affects the economic growth of many African nations (Kutya, 2012). There is appreciable land degradation, largely driven by inappropriate land use and unsuitable farming practices (UNDP, 2012). Agriculture-related deforestation, climate change, soil erosion, water depletion, biodiversity loss, air, water, and soil pollution, and nutrient mining have led to environmental degradation, which in turn has threatened the viability of agriculture (Chartres and Noble, 2015; Pretty et al., 2011). Ngwira et al. (2012, 2013) highlighted that the combined effects of poor farming practices, poor soil fertility, and climate change led to low farm productivity. Continuous cropping and depletion of soil nutrients have been a major constraint to high crop productivity by small-scale farmers in SSA (Rusinamhodzi

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

et al., 2011). In addition, farming systems in SSA have been viewed as having negative impacts on the environment, hence aggravating the abiotic and biotic constraints on food production (Chartres and Noble 2015). Despite these conditions, agricultural production in the area is highly dependent on rainfall (Miriti et al., 2013). The combination of unpredictable rainfall and poor resource endowment makes ASALs have the greatest incidence and prevalence of food insecurity (Alila and Atieno, 2006).

Due to the aforementioned reasons, small-scale farmers in SSA face the double challenge of increasing production while at the same time preserving natural resources (Pretty, 2008). Therefore, sustainable land management practices that mitigate soil degradation are required (Guto et al., 2012). Conservation agriculture (CA) involving minimum soil disturbance, permanent soil cover, and diversified crop rotation (FAO, 2014) has the potential to adapt agriculture to these challenges (Govaerts et al., 2009). It has been shown to restore soil productivity through increased water and nutrient use efficiencies in ASAL, and it represents a low-investment strategy to increase water productivity and mitigate the effects of climatic variability (Araya et al., 2021; Mutuku et al., 2020). It is also associated with optimising and stabilising crop yields while at the same time providing environmental benefits, hence contributing to sustainable agriculture (Giller et al., 2009; Rockström et al., 2009). In periods of climate variability, the CA contributes to environmental benefits by enhancing soil fertility, reducing soil erosion, and improving soil moisture retention, thus stabilising crop yields (Pretty and Bharucha 2014). Studies have shown that the CA improves yield in dry environments compared to conventional crop production practices (Pittelkow et al., 2015; Rusinamhodzi et al., 2011) on well-drained soils (Rusinamhodzi et al., 2011). Notwithstanding those benefits, CA adoption is low among small-scale farmers in SSA due to various constraints that hinder the implementation of all three CA principles (Gowing and Palmer, 2008; Shetto and Owenya, 2007), particularly permanent soil cover (Giller et al., 2009; Rockström et al., 2009). Similarly, empirical evidence and consistency on the benefits associated with CA and which of the CA principles contribute to the desired effects are not clear (Thierfelder et al., 2013). There are concerns, including decreased yields often observed with CA, prompting the need to assess the feasibility of the individual components in mixed small-scale farming systems (Giller et al., 2009). Thierfelder et al. (2013) proposed step-wise integration of CA in smallholder farming systems to reduce constraints on CA adoption. Thus, there is a need for more research on various CA components in different zones. Furthermore, in their review of CA, Serraj and Siddique (2012) and Rusinamhodzi et al. (2011) concluded that there is a need to better understand the effect and interaction among the components of CA in order to develop site-specific CA options. Therefore, evaluation of the individual and combined effects of CA principles under rain-fed small-scale farming is needed, especially in ASALs where it can play a significant role in sustainable food production and might become an important climate-change adaptation strategy (Pittelkow et al., 2015).

Surface cover is rarely applied due to the competing use of crop residue as cover and livestock feed (Giller et al., 2009; Rockström et al., 2009), with the latter being given the first priority. The inclusion of agroforestry in CA through nitrogen-fixing fodder trees such as leucaena may play

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

the role of improving soil fertility and providing feed for the animals, hence reducing the competition of residue for cover and feeding livestock (Kassam et al., 2009). In agroforestry systems, improvement of the soil has been linked to various soil biological processes such as nitrogen fixation, increased soil microbial activity, recycling of nutrients, buildup of soil organic matter, and increased soil enzyme activity (Dollinger and Jose 2018). However, the inclusion of agroforestry in CA requires an evaluation of its effect on crop yield and soil moisture to avoid unhealthy competition with crops. To optimally use the land and diversify risk in case of crop failure, small-scale farmers in Kenya practice intercropping, where maize (*Zea mays* L), which is usually the main crop, is intercropped with legumes. Legumes suppress pests and diseases, enhancing the yield of other crops by offering the potential for intensification and diversification of cropping systems (Franke et al., 2018). The legumes used include common beans (*Phaseolus vulgaris* L.), pigeon peas (*Cajanus cajan* L.), dolichos beans (*Lablab purpureus* L.), and green grammes (*Vigna radiata* L.), among others. Due to the small land size, farmers practice intercropping (diversified cropping) as a CA principle instead of crop rotation (Kinyumu, 2012). Weed control is also a major challenge during the initial stages of CA adoption due to the absence of tillage. To overcome the weed control challenge, there is the general recommendation of applying herbicides (Muoni et al., 2014; Panettieri et al., 2013). However, to what extent the use of herbicides affects crop yield and soil moisture as compared to manual weed control has hardly been studied.

Pradhan et al. (2018) noted that the success of conservation agriculture depends on tailoring and adapting it to the local context. Therefore, this study aims to bring to light the effects of tillage, mulching, herbicide application, intercropping, and agroforestry on soil moisture storage, maize yield, and rainwater use efficiency in rain-fed small-scale farming in a semi-arid setting. The study hypothesised that the application of these practices has a significant effect on soil moisture storage, which in turn has an impact on yield and water use efficiency, particularly under dry weather conditions.

2.0 Material and Method

2.1 Study area

The research was carried out in a farmer's field in Muchuiri, Laikipia County, Kenya. The area lies between latitudes 0°17'S and 0°45'N and longitudes 36°15'E and 37°20'E (Fig. 1) on a semi-arid plateau (Ojwang' et al., 2010). The field plots were at an elevation of 1962 m. The field had been under conventional tillage for over twenty years, and the maize and bean intercropping system was the main practice in the field over the years.

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

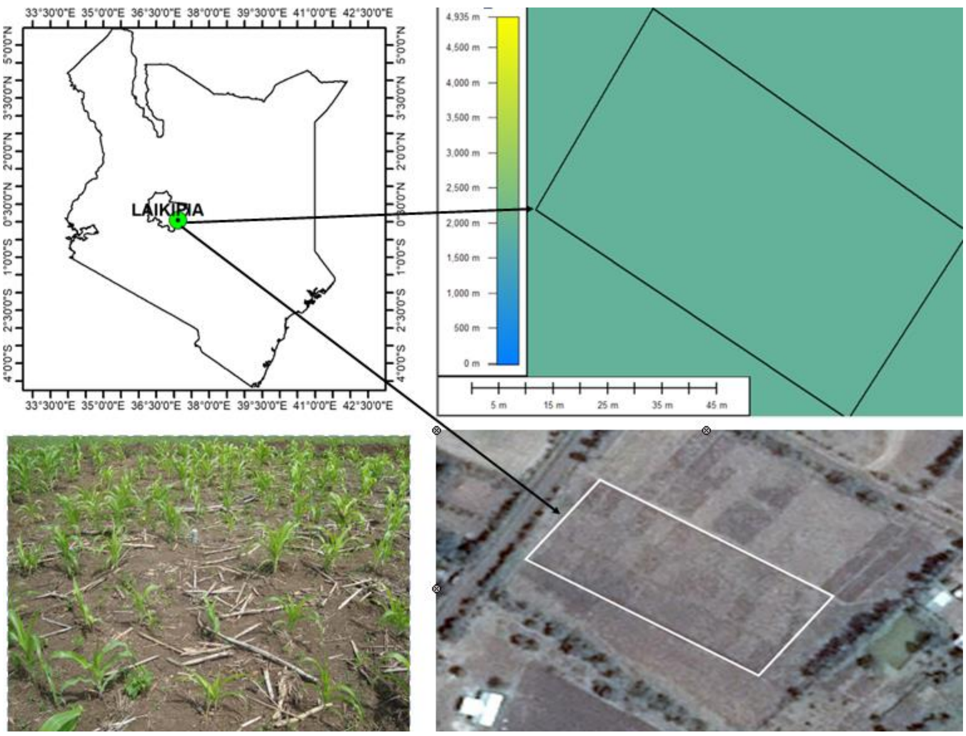

Figure 1: The geographical location of the study area, digital elevation map and research plots.

The study area is semi-arid, with a high frequency of extended dry spells and meteorological droughts. The mean annual temperatures and reference evaporation lie between 16°C and 20°C and 1700 mm, respectively (Notter, 2003). The mean annual rainfall in the area is 750 mm and has a bimodal pattern, with long rains occurring between March and June and short rains from October to January. Despite the constancy of the seasonality, the rainfall is very unreliable in amounts and patterns (Kaumbutho and Kienzle, 2007), and the variability has been on the rise. The soil is classified as vertice phaeozem according to FAO, and its textural class is clay in the top 0.3 m (Ojwang' et al., 2010). Prior to the field trials, soil had a near-neutral pH ideal for crop production, but nitrogen (N) and soil organic carbon (SOC) were low (Table 1).

Table 1 Soil characteristics at the research site prior to the field trials

Soil characteristic[1]	Depth	
	0-15cm	15-30cm
pH	6.4	6.3
N (%)	0.14	0.10
OC (g kg^{-1})	14	13
P (ppm)	74.7	62.9
K (ppm)	322	281
EC$_e$ (dS m^{-1})	0.15	0.16
CEC (cmol kg^{-1})	12.4	13.7
BD (Mg m^{-3})	1.24	1.29
Clay (g kg^{-1})	600	610
Silt (g kg^{-1})	170	180
Sand (g kg^{-1})	230	210

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

[1]N is nitrogen, OC is organic carbon content, P is phosphorous, K is potassium, EC_e is electrical conductivity of a saturated paste, CEC is cation exchange capacity, and BD is bulk density

The soil had no salinity problem, but its cation exchange capacity (CEC) was low, indicating a low capacity of the soil to retain nutrients. The bulk density of the soil was optimal for crop production (Reynolds et al., 2009). Most of the land is individually owned, and agriculture is the predominant occupation (Ojwang' et al., 2010). The area has small farm sizes, averaging 0.3 to 1.4 ha per farmer or household (Ronner, 2011), on which most farmers practice rain-fed subsistence mixed farming (Kinyumu, 2012). The main crops grown are maize (*Zea may* L.; about 51% of the cultivated area), common beans (*Phaseolus vulgaris L.*), potatoes (*Solanum tuberosum* L.), wheat (*Triticum aestivum* L.), and barley (*Hordeum vulgare* L.). Intercropping maize and common beans is a major cropping system in the area (Kaumbutho and Kienzle, 2007). The average maize yield in the county is about 1.8 Mg ha^{-1}. A major challenge in the area is reliance on rain-fed agriculture since it is very vulnerable to droughts, which result in food insecurity and the loss of livelihoods. Notable in the area is soil degradation, which is also common due to unsustainable agricultural practices such as intensive tillage (Ojwang' et al., 2010). Farm operations among these farmers are done manually (Kaumbutho and Kienzle, 2007).

Conventional tillage is practiced by tilling the land using a hoe and weeding by use of machete or hoe by the majority of the farmers. However, some farmers who practice CT use herbicides to control weeds. The majority of the farmers practicing CA under no-till prepare and clear the land for planting by using machetes or herbicides. Planting is done by opening a hole for placing the seed using a hoe, and a few farmers have jab planters for direct seeding. To control the weed, machetes and scrape weeders are used to superficially scrape the soil surface, though herbicides are also applied by a few farmers.

2.2 Experimental design and management

The experiment was set up in a split-plot design with three main plots (treatments) and four sub-plots, all of which were replicated three times. The plots measured 5 m wide and 10 m long, separated by a 1 m buffer (Fig. 2a). The main crop was maize (*Zea mays* L.), which was intercropped with common beans and dolichos beans. The main treatment was tillage: conventional tillage (CT) and no tillage (NT). The plots under CT were tilled just before planting by using a hoe at a depth of 0.15 m, while for the NT, the soil was minimally disturbed for placing the seed. In addition, there were no till plots with herbicide (NTH) laid out as well. In each of the treatments, the following sub-treatments were included: (a) maize and beans (MB), (b) maize and dolichos (MD), (c) maize, beans, and leucaena (MBL), and (d) maize, beans, and mulch (1.5 tonnes Ha^{-1}) (MBMu).

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

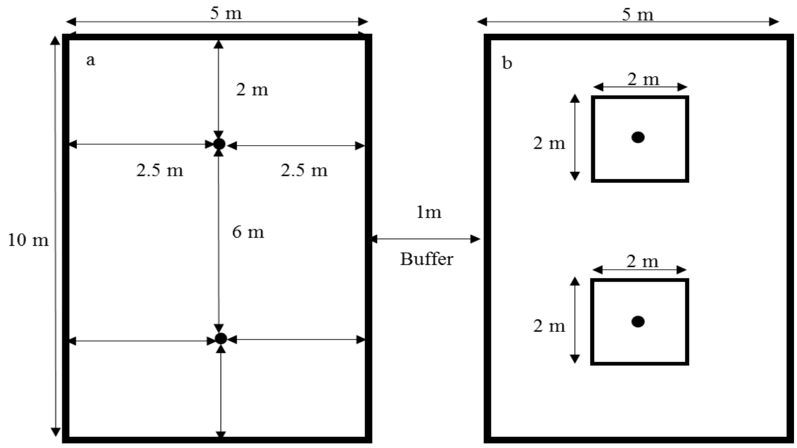

Figure 2: a) Research plot dimensions and position of neutron probe access tubes shown by the two black dots; and b) sampling grid for maize harvesting

The setup resulted in 12 combinations, as shown in Table 2, which also shows the practice being tested in each treatment.

Table 2: Research treatment showing practices being tested

Treatment	Number of CA principles applied			Specific practice tested		
	One	Two	three	herbicide	Agroforestry	mulch
CTMB	X					
CTMD	X					
CTMBL	X				+	
CTMBMu		X				+
NTMB		X				
NTMD		X				
NTMBL		X			+	
NTMBMu			x			+
NTHMB		X		+		
NTHMD		X		+		
NTHMBL		X		+	+	
NTHMBMu			x	+		+

The hybrid maize variety SC Duma 43 was planted in the experimental plots in this study. The variety was selected due to its early maturing, drought-tolerant, disease-tolerant, and intercropping-friendly characteristics. The maize was sown at the onset of the rains at a spacing of 0.75 m between the rows and 0.30 m within the rows. Sowing was done manually by placing two maize seeds per planting hole dug at a depth of 0.04 m. Dolichos beans and common bean seeds were sown in between the maize rows at a spacing of 0.75 m between the rows and 0.30 m within the rows. Seed gapping was done after emergence. Common beans and dolichos beans were sown at the same time as maize. After harvesting the mature dry dolichos pods, the plants were left to continue growing in the field as it is a perennial crop. Fertiliser was applied

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

at the rate of 50 kg ha^{-1} NPK fertilizer (17-17-17, N: P_2O_5:K_2O) at planting and was applied to all treatments by placing it next to plants. Top dressing was done when the maize crop was at knee-high height using calcium ammonium nitrate (27% N) at the rate of 50 kg ha^{-1} with the placement method. Weeds were controlled by the use of a superficial shallow scrape weeder for the NT treatment and a paraquat herbicide (Gramaxone®) at an application rate of 2 litres ha^{-1} in the NTH treatment. The herbicide was applied three times per growing season, that is, at the beginning of the season before emergence and two other times in between, depending on the weed population. The herbicide was applied using a zam-wipe to avoid crop damage.

2.3 Soil-water content

Soil-water content (SWC) was measured at depths of 0.15, 0.30, 0.45, 0.60, 0.75, 0.90, 1.05, 1.20, 1.35, and 1.50 m using a neutron probe (Hydroprobe® model 503, CPN Corporation, Martinez, CA, USA). Two access tubes were installed in each of the experimental plots at a distance of 2 m from the edge of the plot and 6 m between plots (see Fig. 2a). The SWC was measured every week and after a rainfall event, up to 120 days after planting. The neutron probe was calibrated by installing three external access tubes adjacent to the experimental plots. To have a wide range of moisture conditions, the soil surrounding the access tubes was wetted differently (wetting to field capacity, intermediate wetting, no wetting) in dry weather (Evett et al., 2003). As the neutron probe readings were taken, both disturbed and undisturbed soil samples were also taken at the corresponding depths. Gravimetric water content was determined from the disturbed samples and bulk density from the undisturbed (Grossman and Reinsch, 2002).

$$BD = \frac{M_s}{V_b} \tag{1}$$

Where BD is bulk density, M_s (Mg) is oven-dry soil mass, and V_b (m^{-3}) is the corresponding bulk (undisturbed) soil volume. Gravimetric soil-water content was multiplied by the measured bulk density (from the undisturbed samples) to obtain volumetric SWC, which was then regressed against the count ratio (CR) to get the calibration equation. The count ratio is the count rate in the soil divided by the count rate in the standard material.

$$CR = \frac{\text{count rate in soil}}{\text{count rate in standard}} = \frac{N}{N_S} \tag{2}$$

Where N is the count rate in the soil (count per minute; cpm) and Ns is the count rate in the standard material (cpm). Standard counts are taken when the detector or source tube is locked in the polypropylene shielding positioned at the top of the transport case. The calibration equation is given below.

$$SWC = 0.386CR - 0.193 \tag{3}$$

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Where SWC is soil water content and CR is count ratio.

To determine the critical moisture storage at which maize starts to experience drought stress, a matric potential of-500 kPa was taken during the vegetative period and-800 kPa during the reproductive period, which includes ripening, the latter value being the upper limit in case of a high evaporative demand (Taylor and Ashcroft, 1972) as in the study location. Water retention curves measured per treatment on undisturbed 100 cm^3 soil cores taken using a combination of sandbox and pressure plates following the procedure (Cornelis et al. 2005) were used to convert critical matric potential to critical SWC. The latter was multiplied by the depth of interest to get the critical soil moisture storage. Likewise, soil moisture storage at-33 kPa and-2400 kPa was calculated to assist in the interpretation of the results. Soil moisture storage at matric potentials above-500 kPa during the vegetative period and-800 kPa during the reproductive period could be considered readily available, while that above-2400 kPa is totally available at the dates of measurements. Taylor and Ashcroft (1972) suggested permanent wilting of maize at-2400 kPa rather than the more commonly used value of-1500 kPa. However, given the very small changes in SWC between-1500 kPa and-2400 kPa, the choice of that value hardly affected the corresponding S value.

The rainfall amount was measured using a manual rain gauge installed at the research site. The rainwater use efficiency (RWUE, kg ha^{-1} mm^{-1}) was calculated by dividing the total grain yield (GY, in kg ha^{-1}) by the total rainfall (mm) from planting to harvest.

$$\text{RWUE (kg ha}^{-1}\text{mm}^{-1}) = \frac{\text{Grain yield(kg ha}^{-1})}{\text{Total rainfall (mm)}} \qquad (4)$$

2.4 Maize yield

Yield data was collected for three years, with the maize being harvested at physiological maturity when it had a water content of about 13% measured using a digital moisture metre (GMK-303**,** G-Won Hitech Co. Ltd., Korea). Two grids of 2 m by 2 m next to the access tubes were sampled for harvesting the maize (Figure 2b). The harvesting was done manually, after which it was threshed and the grain weight taken. To examine the maize yield stability of the different treatments' an analysis was done using linear regression of treatment yield on the environment means. The environmental mean was obtained by averaging the yield of all treatments for each year (Grover et al., 2009). The treatments with a smaller slope (R^2) indicate greater yield stability (Guertal et al., 1994; Sileshi et al., 2011).

2.5 Data analysis

The data was analysed using IBM SPSS Statistics 22.0 (SPSS Inc., Chicago, IL). Data was tested for normality, and analyses of variances (ANOVA) were conducted following the General Linear Model (GLM). The significant difference between the treatments was tested using the least significant difference (LSD) at a 5% probability level. To check the effect of tillage, herbicide application, intercropping, agroforestry, and mulch, a t-test was applied at a 5% probability level. Data was pooled following the categories shown in Table 2. The effect of tillage was tested by

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

comparing CT treatments with NT treatments. When testing the effect of agroforestry, the data from all treatments with maize, common beans, and leucaena were compared against the data from treatments with maize and common beans but without leucaena. Similarly, the effect of herbicides was tested by comparing all no-till combinations with herbicides against those without. To test the effect of mulching, comparisons were made between all treatments of maize and common beans with and without mulch. To compare the effect of the bean species used in intercropping, all treatments of maize with common beans were compared to those with dolichos bean.

3.0 Results and Discussion

3.1 Rainfall

The variation in the amount of rainfall received in the different growing seasons was substantial. In total, rainfall for the three years' seasons amounted to 685, 538, and 270 mm, respectively (Fig. 3). For comparison, the average seasonal rainfall at the Kenya Meteorological Department, Laikipia County office, is 470 mm. Frequency analysis of the data shows that the 1st and 2nd growing seasons were wet, while that of the 3rd year was dry. The return period and probability of exceedance for the three-year seasons were 6.4 years and 15%, 5.3 years and 18%, and 1.1 years and 92%, respectively. Not only did rainfall vary with seasons, but the difference in rain during each season was also very substantial. Figure 3 shows the variation in daily rainfall for the three seasons of study. Periods with continuous rainy days with high rainfall amounts were followed by extended periods of dry days, resulting in meteorological and agricultural dry spells. Meteorological drought is a reduction in seasonal rainfall below normal or crop water requirements over a certain period of time and region, while agricultural drought is a soil moisture deficiency for crop production (Alam et al., 2014). Dry spells are prolonged periods of dry weather (10 days or more) during critical crop growth stages (Barron et al., 2003). Given that the crop water requirements were met during the first two years of the experiment but not in the third, the latter was facing a meteorological drought. The estimated crop water requirement (ETc) for the local maize variety under the local climate conditions was calculated with FAO's AquaCrop model and amounted to 391 mm. Periods with 10 days or more without rain occurred once in the first year, once in the second year, and three times in the third or final year.

Maize growth has been classified into three growth stages: vegetative, flowering, and reproductive. The vegetative growth is usually the first 60 days, the flowering stage is from the 60th to the 80th day, and the reproductive stage is normally from the 80th to the 120th day (Colless, 1992). The effect of moisture stress during different stages has been documented by various authors (Cakir, 2004; Setter et al., 2001). Varying results have been found on the effect of moisture stress on maize yield during different stages, but it has generally been concluded that maize is most sensitive to water stress during the flowering stage, that is, the tasselling and silking stages (Doorenbos and Kassam, 1979; NeSmith and Ritchie, 1992). The tasselling and silking stages are the period between the 60th and 80th days during maize growth. In a study by Kyei-Mensah et al. (2019), the effects of rainfall variability on crop yields in Ghana were evaluated, and results showed that in major seasons, the variability of rainfall was lower

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

compared to the minor seasons, and crop yield was reduced over the period. For instance, Amikuzino and Donkoh (2012) revealed that there was a strong relationship between the total rainfall encountered during the planting season and the inter-annual yields of crops.

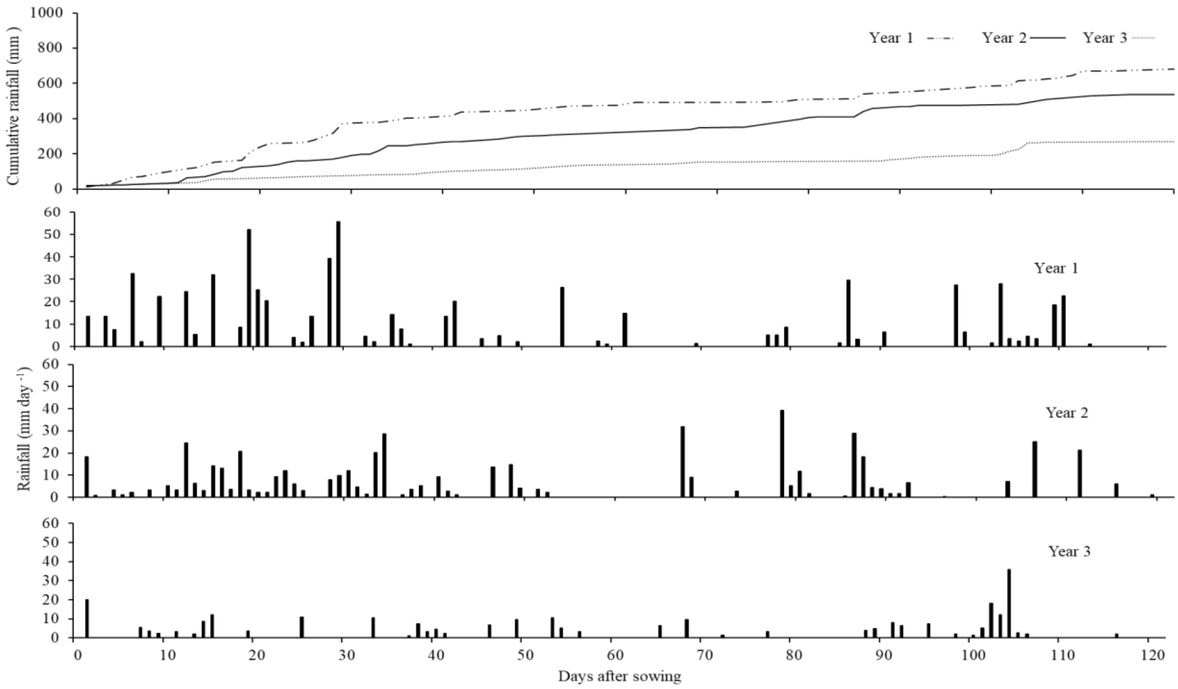

Figure 2: Cumulative rainfall distribution and daily rainfall during research period

3.2 Soil moisture

Soil moisture storage was monitored in two seasons (2nd and 3rd years) of the three seasons under study. Season one (1st year) was omitted because the data set was incomplete. The soil water profile for different treatments for two selected days, i.e., a day during the rainy period of the season (wet day), which was 50 days of the year (DOY), and a day during the extended dry period of the season (dry day), which was DOY 80 of the 3rd year growing season, is shown in Figures 4 and 5. Soil water content generally increased with depth up to 60 cm and then started decreasing with depth up to 105 cm, after which it remained almost constant. There was no positive water content during the dry and wet days of the year, as well as in any of the treatments, indicating that there was no drainage below the root zone. Based on soil water content along the soil profile, the CA based on components such as mulching showed higher soil water content in both dry and wet seasons. This concurs with the previous finding of Araya *et. al*. (2015). Tittonel et al. (2012) highlighted the need to evaluate the effect of CA technologies on the seasonal water balance with the goal of identifying those practices that can maximise the soil moisture buffer capacity. The findings on the effects of tillage, mulch, and the type of bean used for intercropping are shown in Figure 4. Tillage had no significant effect on soil water content, though CT had a slightly higher soil water content than NT. Mulching significantly affected soil water content during the selected dry and wet days in the 3rd year. Mulching had a significantly higher soil water content compared to no mulch treatments in all the depths. Soil

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

water content along the soil profile was significantly higher when dolichos was intercropped with maize compared to the scenario in which beans were intercropped with maize, whether it was during dry or wet days of the year. Though herbicide application had no significant effect on soil water content along the various soil depth profiles during the wet days of the year, it had a significant effect during the dry days of the year. Soil water content along the soil profile was not significantly affected in treatments with and without incorporation of agroforestry in the farm system, either during the dry or wet days of the year (see Fig. 5). However, soil water content was slightly lower in systems that integrated agroforestry technology during the dry days of the year. The number of CA principles applied had no significant effect on soil water content during the wet season. However, during the dry season, soil water content was lower when only one principle was applied compared to when two or three principles of CA were applied.

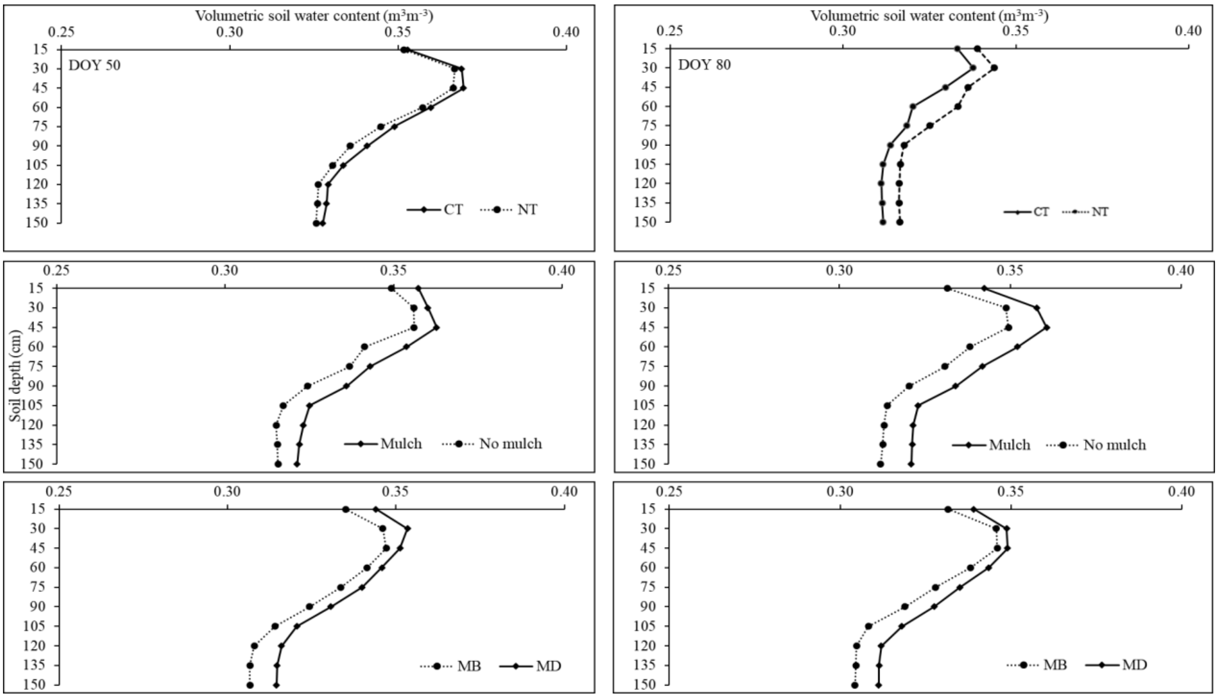

Figure 4: Root zone volumetric water content comparison on two dates, wet day (DOY 50) and dry day (DOY 80), during the growing season versus soil depth (cm) in year 3. CT, conventional tillage; NT, no till; MB, intercropping maize with common beans; MD, intercropping maize with dolichos beans.

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

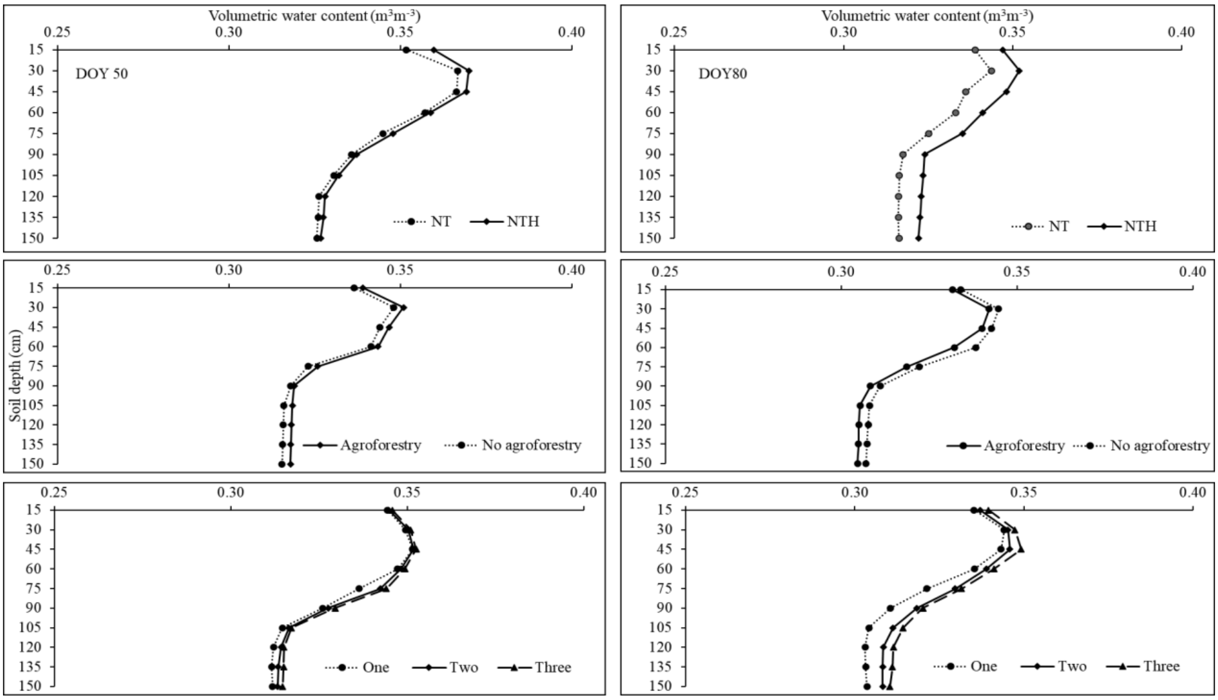

Figure 5: Root zone volumetric water content comparison on two dates, wet day (DOY 50) and dry day (DOY 80), during the growing season versus soil depth (cm) in year 3. NT, no tillage; NTH, no till with herbicide.

Figures 6 to 11 show the temporal variation in soil moisture storage to 1 m depth as affected by tillage, herbicides, mulch, agroforestry, and the number of CA principles applied during the 2nd year wet growing season and the dry growing season of the 3rd year. The soil moisture storage followed the patterns of rainfall rather well in both seasons. Generally, during the 2nd year wet season, soil moisture storage was above the critical drought stress value for vegetative, flowering, and yield formation stages for maize, while in the dry 3rd year season, only some treatments had soil moisture that remained readily available. The effect of tillage alone was not strong enough to cause a significant effect on soil moisture storage in both seasons (Figs. 6b and 7b). Higher soil moisture storage in CT than in NT, as found in the wet season in the current study, was previously reported by Obalum et al. (2011). They attributed this higher soil moisture storage in CT than NT to a temporal improvement in porosity that increases rainfall infiltration and retention in the soil. In agreement with this study, Jin et al. (2007) found that differences in soil moisture storage between conventional and no-till practices were most pronounced in drier years, with relatively higher values in no-till systems. Franzluebbers (2002) noted that no till led to greater soil organic material stratification and less evaporation, thus increasing the surface soil water content. Figure 6c shows that intercropping maize with common beans resulted in significantly lower soil moisture storage compared to intercropping maize with dolichos beans throughout the growing season during both the wet and dry years. The better surface cover by dolichos could be the reason for higher moisture when maize was intercropped with the dolichos. Thus, reducing water loss from the soil. The use of herbicides in NT did not result in a significant difference in soil moisture storage in the

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

wet 2nd year growing season; the observed higher values from 70 days after sowing in the dry 3rd year of the experiment were not significant (see Fig. 9b). The positive effect of herbicides on soil moisture, especially during the dry season, may be attributed to weed control by the herbicides. The fewer weeds, the less water is used, thus contributing to soil moisture conservation. This is in agreement with Dalley et al. (2006), who found that soil moisture where herbicide was applied was similar to the weed's free treatment.

Mulching resulted in significantly higher soil moisture storage throughout the growing period of the dry season (Fig. 9c). Changes in soil moisture storage were more pronounced under mulch, indicating a better response to rain events and more water being taken up by the crop. The higher soil moisture storage in treatments with mulch during the year with lower rainfall may be attributed to the surface cover that may contribute to higher infiltration rates and reduced evaporation (Kader et al., 2017; Thierfelder et al., 2013). This is also well illustrated by the soil water along the soil profile. The effect of mulch on soil moisture follows trends observed by Rockström et al. (2009) in the savannah agro-ecosystems of East and Southern Africa and Hitimana et al. (2021) in Rwanda. Under the rain-fed conditions of the semi-arid and arid ecosystems, conservation of soil moisture by mulching becomes profitable for the crops. In addition to conserving soil moisture, mulching also suppresses extreme temperature fluctuations and reduces water loss through evaporation, resulting in more retention of soil moisture (Shirugure et al., 2003), suppresses the growth of weeds (Ramakrishna et al., 2006), enhances and maintains soil fertility (Slathia and Paul, 2012), and improves the growth and yield of crops (Ban et al., 2009). Mulching also protects topsoil stability, hence improving soil physical conditions (De Silva and Cook, 2003). Mulching can greatly influence maize yield as it results in higher soil moisture storage during silking, tasselling, and grain filling, which are critical stages during maize growth. This higher soil moisture storage in the mulching treatment even during dry periods resulted in a higher maize yield (Table 3) compared to treatments that did not have mulch. However, the competing use of crop residue for livestock feeding hampers the application of mulch, hence the need for alternative surface cover.

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

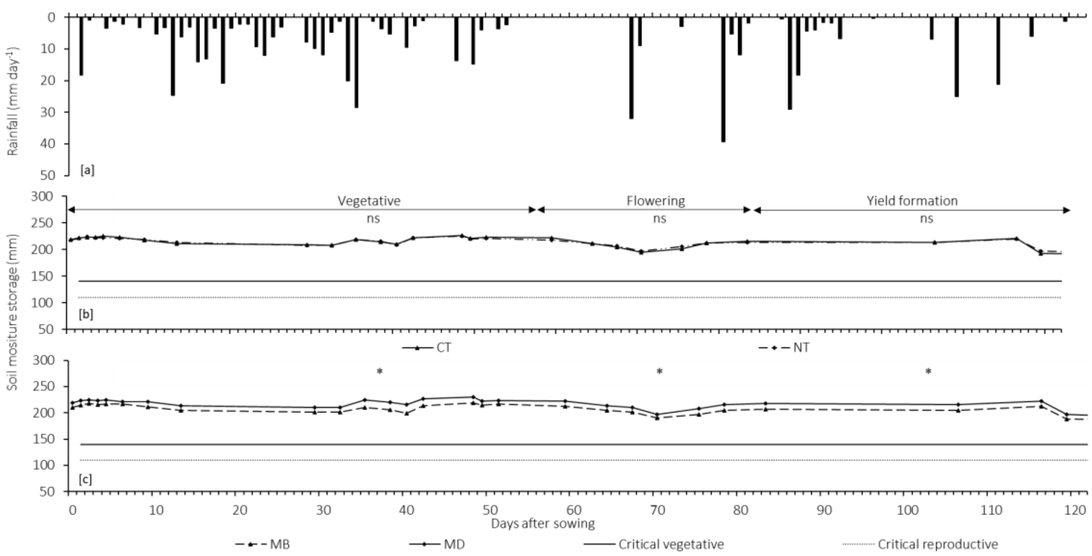

Figure 6: Daily rainfall (a) and soil moisture storage as affected by tillage (b) and intercropping (c) at various maize growing stages in year 2. CT, conventional tillage; NT, no till; intercropping maize with common beans; MB, intercropping maize with dolichos beans; MD. Significance levels of differences in soil moisture storage during the growing season are indicated, with '' indicating a significant difference (p < 0.05) and 'ns' no significant difference values across all measurements*

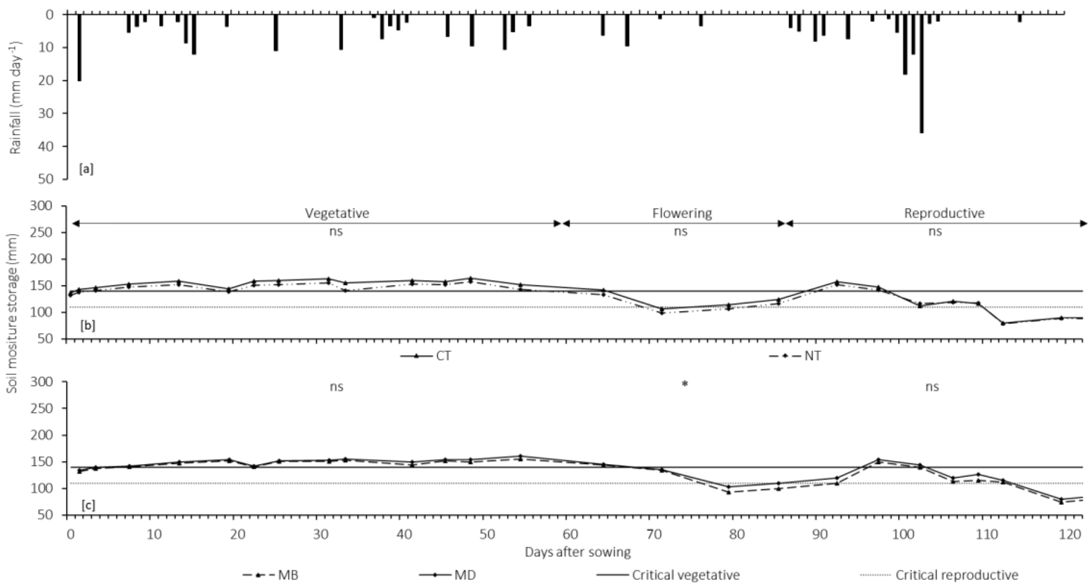

Figure 7: Daily rainfall (a) and soil moisture storage as affected by tillage (b) and intercropping (c) at various maize growing stages in year 3. CT, conventional tillage; NT, no till, intercropping maize with common beans; MB, intercropping maize with dolichos beans; MD. Significance levels of differences in soil moisture storage during the growing season are indicated, with '' indicating a significant difference (p < 0.05) and 'ns' no significant difference values across all measurements*

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Practicing agroforestry in CA had no significant effect on soil moisture storage during the wet season in year 2, but it was significantly higher during the flowering stage in the drier than average year season. Soil moisture was lower in agroforestry treatment during the wet year; however, it was higher during the dry year. During the dry year, i.e., year 3, treatments with agroforestry similar to treatments without agroforestry showed drought stress during the flowering stage (Fig. 11b). Higher soil moisture storage in soils with leucaena has previously been determined by Kang et al. (1990). The higher soil moisture storage under leucaena can be attributed to the improvement of soil physical properties, which enhance water infiltration and reduce water run-off (Dalzel et al., 2006). This may be through leucaena roots that can improve soil structure and create macro-pores, thus increasing water infiltration and reducing surface runoff (Sanginga et al., 1992; Van Noordwijk et al., 1991). This study found more soil water content along the profile in treatments with agroforestry systems. Agroforestry has previously been found to positively influence microclimates that improve soil moisture by Souza et al. (2019) and Baliscei et al. (2013) and improve productivity.

An analysis of the data on the number of CA principles applied to a farm system is presented in Fig. 10c. Generally, no significant effect on soil moisture was detected during the second year of the research (wet) season. However, during the dry-year season, applying one principle resulted in significantly lower soil moisture storage compared to applying two or three principles (Fig. 11c). The latter supported soil moisture storage to remain above the critical value for maize for most of the growing period, in contrast with applying only one principle that affected drought stress throughout the dry season. The higher soil moisture storage in the treatment with mulch and when all three CA principles were applied is important in rain-fed agriculture as it allows buffering of short dry periods (Govaerts et al., 2005; Verhulst et al., 2011). This in turn leads to better and more stable yields, which make maize farming resilient to climate change.

While in the wet season, soil moisture never dropped below critical values for maize during dry spells, it did in the dry year for several treatments. In the dry-year season, there were two major dry spells in the first 120 days after sowing. Mulching kept soil moisture above the critical values during both dry periods of the growing season. Applying two or three CA principles also maintained optimal soil moisture conditions during the two dry spells. Also worth noting is that under those treatments, soil moisture storage was already significantly higher at the onset of the growing season, indicating that they could conserve more rain from the previous wet season and from the rain showers preceding sowing in the 3rd year of the experiments. Higher soil moisture storage was found when all three principles of CA were applied, namely minimal soil disturbance (NT), surface cover (mulching with maize residues), and crop diversification and rotation (intercropping maize, beans, and leucaena), which concurs with previous findings by Obalum et al. (2011). The higher soil moisture storage, especially during dry spells, is crucial as it will protect the plant against agricultural droughts (Barron et al., 2003), which affect plant growth and yield. The surface cover conserves soil water, which is provided to the crop during dry spells, resulting in a higher and more stable crop yield. The higher soil moisture storage in the treatment with mulch as a cover crop throughout the growing season during the dry year

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

may be a clear manifestation of the critical role of residue cover among CA components. This may indicate that mulching (surface cover) is a key principle in CA. The study found that CA-associated practices considered in this work resulted in higher soil moisture at the beginning of the dry season when the preceding season was wet. This is expected to avoid drought stress during a meteorologically dry growing season, at least when the preceding season was wet, as in our study, resulting in improved yield.

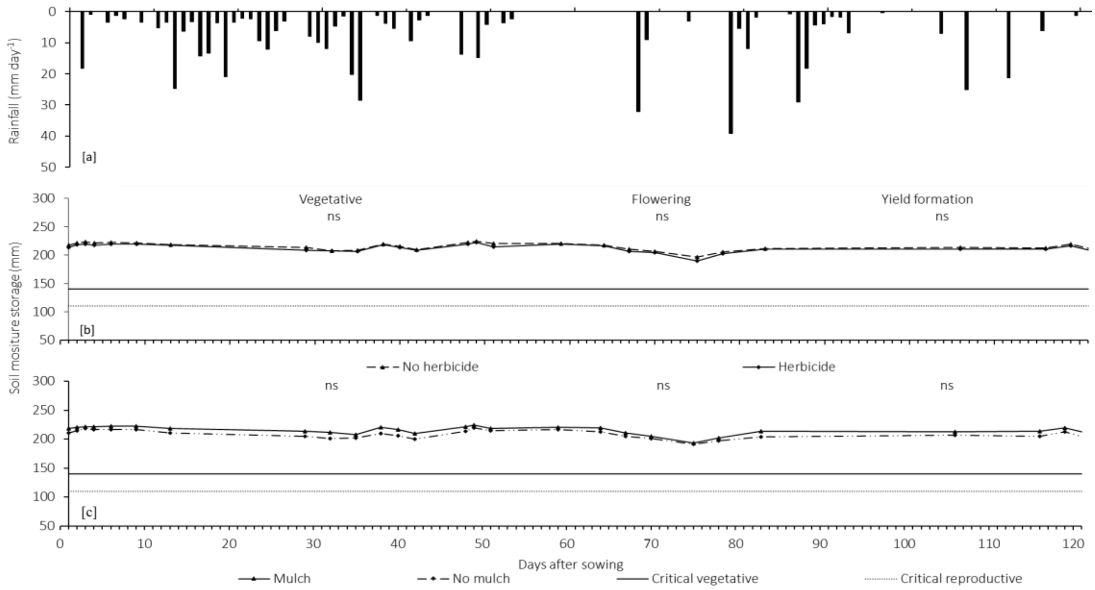

Figure 8: Daily rainfall (a) and soil moisture storage as affected by herbicide (b) and mulching (c) at various maize growing stages in year 2. Intercropping maize with common beans; MB; intercropping maize with dolichos beans; MD. Significance levels of differences in soil moisture storage during the growing season are indicated, with '' indicating a significant difference (p < 0.05) and 'ns' no significant difference values across all measurements*

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

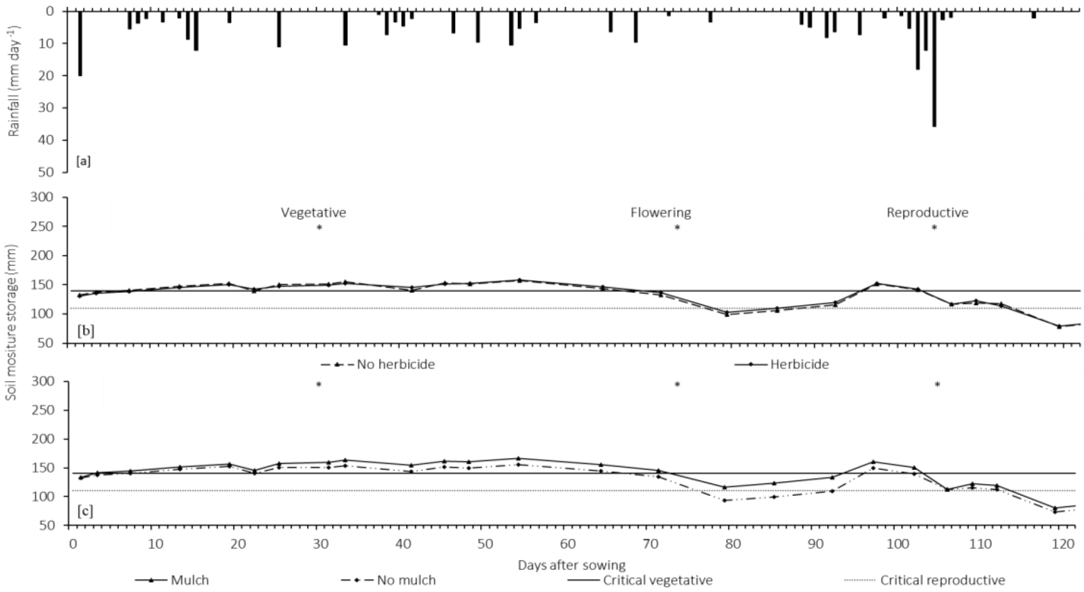

Figure 9: Daily rainfall (a) and soil moisture storage as affected by herbicide (b) and mulching (c) at various maize growing stages in year 3. Significance levels of differences in soil moisture storage during the growing season are indicated, with '' indicating a significant difference ($p < 0.05$) and 'ns' no significant difference values across all measurements.*

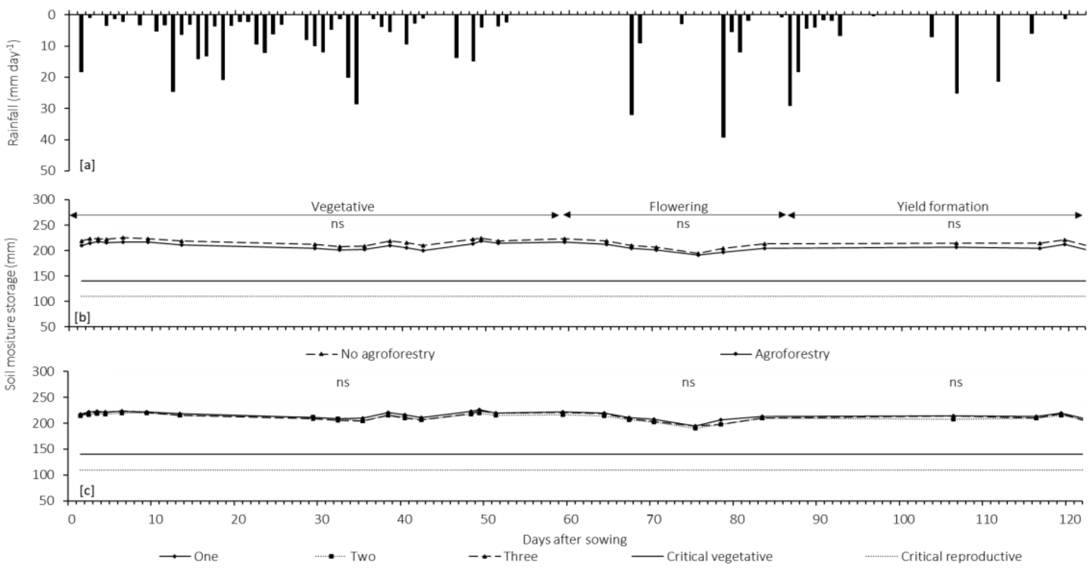

Figure 10: Daily rainfall (a), soil moisture storage as affected by agroforestry (b), and number of principles applied (c) at various maize growing stages in year 2. Significance levels of differences in soil moisture storage during the growing season are indicated, with '' indicating a significant difference ($p < 0.05$) and 'ns' no significant difference values across all measurements*

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

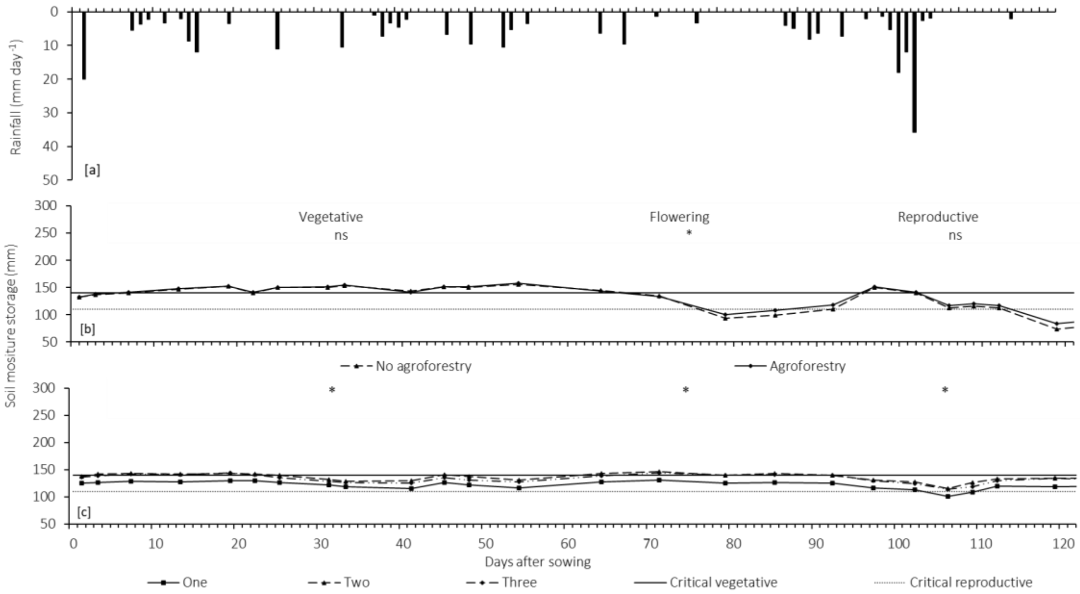

Figure 11: Daily rainfall (a), soil moisture storage as affected by agroforestry (b), and number of principles applied (c) at various maize growing stages in year 3. Significance levels of differences in soil moisture storage during the growing season are indicated, with '' indicating a significant difference ($p < 0.05$) and 'ns' no significant difference values across all measurements*

3.3 Maize grain yield

Tables 3 and 4 present maize yield and maize yield stability index for the 1st and 2nd year wet seasons and the dry 3rd year of the study for the different treatments. Tillage significantly affected maize grain yield only in the dry year season in year three, with CT showing significantly lower yield than NT by 33.9%. Over the years, NT had a more stable yield, with a CV of 62.16% compared to a CT of 93.87%. This is in line with previous findings that showed that during wet years, CT performs better than CA (Jin et al., 2007; Lenssen et al., 2014). This is affirmed by several studies in Africa, including those of Rusinamhodzi et al. (2011) and

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Table 3 Impact of tillage, agroforestry, herbicide application, mulching and their interaction on maize grain yield (kg ha^{-1})

	Year 1	Year 2	Year 3
Number of principles			
One	2896a	2803a	1640a
Two	2607a	2876a	2173b
Three	2228a	2657a	2592b
P	0.25	0.80	0.00
Interaction between tillage, intercropping and mulching			
Conventional tillage maize, beans and leucaena	2716a	2504a	1883ab
Conventional tillage, maize and beans	3292a	2438a	1523a
Conventional tillage, maize, beans and mulch	3123a	3346a	1829ab
Conventional tillage, maize and dolichos	2682a	3468a	1517a
No till, maize, beans and leucaena	2408a	1859a	2317ab
No till, maize and beans	2080a	3270a	1787ab
No till, maize, beans and mulch	2242a	3042a	2633b
No till, maize and dolichos	2648a	3042a	2305ab
No till with herbicide maize, beans and leucaena	2775a	3030a	2453ab
No till with herbicide, maize and beans	3093a	2577a	2270ab
No till with herbicide, maize, beans and mulch	2214a	2273a	2551ab
No till with herbicide, maize and dolichos	2127a	3013a	2249ab
P	0.59	0.11	0.00
Tillage			
CT	2953	2939	1688*
NT	2345	2803	2261*
Intercropping			
Common beans	2767	2920	1838
Dolichos beans	2562	3007	2026
Herbicide			
Yes	2552	2723	2381*
No	2649	2871	1974*
Agroforestry			
Yes	2632	2464	2217*
No	2821	2762	1860*
Mulch			
Yes	2526	2887	2338*
No	2821	2762	2033*

NT No Till, CT Conventional Tillage, NTH No till with herbicides. The means followed by a lowercase letter in the column were not significantly different at P≤ 0.05. * Show a significant difference from the t-test.

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Thierfelder et al. (2015), all of whose study findings found that NT significantly affected maize yield during seasons with low rainfall. In another study where similar conditions were tested, findings indicated that yields from fields that were not tilled and with plant residues retained on the farm were more productive in terms of nutrients and water use when compared with those from tilled fields and with crop residue removed (Baumhardt et al., 2013). Therefore, the improvement of crop yields from 20% to 120% has been realised through sustainable agriculture (Kassam et al., 2009; Derpsch et al., 2010).

Table 4: Impact of tillage, agroforestry, herbicide application, mulching and their interaction on maize grain yield stability

	R^2
Number of principles	
One	0.8637
Two	0.9941
Three	0.4800
Interaction between tillage, intercropping and mulching	
Conventional tillage maize, beans and leucaena	0.7435
Conventional tillage, maize and beans	0.4980
Conventional tillage, maize, beans and mulch	0.9785
Conventional tillage, maize and dolichos	0.9837
No till, maize, beans and leucaena	0.3678
No till, maize and beans	0.7035
No till, maize, beans and mulch	0.0857
No till, maize and dolichos	0.9239
No till with herbicide maize, beans and leucaena	0.9705
No till with herbicide, maize and beans	0.3355
No till with herbicide, maize, beans and mulch	0.8110
No till with herbicide, maize and dolichos	0.3949
Tillage	
CT	0.9387
NT	0.6216
Intercropping	
Common beans	0.4998
Dolichos beans	0.1557
Herbicide	
Yes	0.9435
No	0.9806
Agroforestry	
Yes	0.6061
No	0.9339

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Mulch	
Yes	0.7663
No	0.8979

NT No Till, CT Conventional Tillage, NTH No Till with herbicide

Most of the CA benefits, in terms of yield when compared to CT, have been realised in regions with moisture deficiency or during dry years (Farooq et al., 2011; Mupangwa et al., 2012). This is in agreement with this study, where the NT treatments had a higher yield during the dry season compared to CT. Higher yields in systems utilising NT technology compared to those using CT during dry years have also been demonstrated in findings by Ngwira et al. (2012) and Sun et al. (2018), and similar conclusions were made by Rusinamhodzi et al. (2011) in a meta-analysis of CA on maize yield under raid-fed conditions. The higher yield in NT-based systems compared to CT in the dry year is attributable to better capture and storage of plant-available water (Lenssen et al., 2014; Rusinamhodzi et al., 2011), particularly when water is limited. This may be due to improved soil properties, which increase soil water retention in rain-fed farming (Tebrügge and Düring, 1999). Thus, better rainwater capture and retention in the soil associated with NT would be expected to result in higher yields compared to CT-based systems, especially in dry seasons. The benefits of conservation tillage include plant water availability, soil aggregation, improved soil organic matter, and the transmission capacity of soil water, thus outweighing conventional tillage and enhancing the infiltration features of the soil (Bhattacharyya et al., 2008). Lowering or minimising tillage activities raises soil organic carbon (Nyamadzawo et al., 2008), promoting the efficient utilisation of nutrients (Tittonell et al., 2012), resulting in higher crop yields (Ngigi et al., 2006). A negative effect of tillage during dry years has also been found by Abdullah (2014) and Liu et al. (2017). Furthermore, no till is expected to have a positive effect on yield stability, as documented by Macholdt and Honermeier (2017). This is important in regard to climate change, with rainfall becoming more erratic, with more and longer dry spells and fewer rainy days.

Findings from this study indicated that there was no significant difference between intercropping maize with common beans and intercropping maize with dolichos beans during the three years of the study. However, intercropping maize with dolichos beans resulted in 3% and 10% higher maize yields in the 2nd and 3rd years, respectively, compared to intercropping maize with common beans. Intercropping maize with dolichos beans resulted in a stable yield compared to intercropping maize with common beans, with CV values of 15.57% and 49.98%, respectively. This may be explained by the better soil moisture storage determined through this study and previous studies (example, Ngenga et al., 2022) when dolichos was intercropped with maize compared to the maize and common beans intercrop. Effect of better surface cover by the dolichos that continue growing in the field even after maize is harvested compared to beans, a short-growing crop that is harvested even before maize is harvested.

Mulching played an important role, especially during the drier than average year, as evidenced by a significant 13% higher maize yield (P = 0.01). The positive effect of surface cover during the

URL: https://ojs.jkuat.ac.ke/index.php/JAGST
ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

drier than average year is in agreement with Biamah et al. (1993). They associated higher yields with the presence of mulch, which improves rainwater partitioning. Liu et al. (2017) argue that as water is most limited in dry years and since a crop is more sensitive to changes in soil moisture below critical water stress, any soil management practice that improves soil moisture retention will have a positive impact on yield. It has been reported that permanent soil cover reduces soil water loss through evaporation (Dahiya et al., 2007), modifies soil temperature (Cook et al., 2006), decreases soil erosion leading to high rainfall infiltration (Rockström et al., 2009), as well as suppressing weeds and improving soil microbial activity (Chilimba, 2002). Other benefits of mulch include surface cover that reduces evaporation, which improves water use efficiency (Snyder et al., 2015). Furthermore, mulching with organic material has been associated with improved soil fertility, which leads to better plant nutrient supply and has a positive effect on crop yield (Adekiya et al., 2019; Jagadeesh et al., 2018). Mulching in the present study had soil moisture above the critical value for maize, especially during critical stages of maize growth, and thus a positive impact of mulch on maize yield. Similar observations were made by Cakir (2004), who concluded that the short-term positive effect of mulching on maize yield is critical in that farmers will be attracted to adopting this practice as one of the CA components. Besides, Abdullah (2014) also found higher crop yields due to soil surface covering with crop residues. In Japan, Kader et al. (2017) found similar results of higher crop yield in treatments with mulch compared to no mulching. The higher yield as a result of mulching has been attributed to higher soil moisture, which enhances plant nutrient availability and root growth (Sarkar and Singh, 2007). The role played by such conservation agriculture practices in managing soil productivity, retaining and conserving soil water, and decreasing production costs has aided in achieving higher crop yields (Hossain et al., 2015).

Considering the competing uses of the crop residues, the current study incorporated agroforestry in CA in the form of the establishment of leucaena in the farm system. This technology resulted in significantly higher maize yield during the drier than average year by 16%, but no significant effect during the 1st and 2nd years (wet seasons). The yield was more stable in agroforestry with a CV of 60.61% compared to treatments with no agroforestry with a CV of 93.39%. This study found that leucaena species, if used in CA, are beneficial, as evidenced by the higher maize yield during the dry season. This is in agreement with the findings of this study, where intercropping maize with leucaena had a higher maize yield, especially during the dry season. Tree-based intercropping helps in climate regulation and enhances agriculture through improved soil quality, water quality, nutrient mineralization, biological control, and pollination (Alam et al. 2014). Considering that drier seasons are likely to occur in this area, practicing agroforestry in CA will enhance a more stable yield, contributing to food security in the area. Furthermore, Leucaena is a nitrogen-fixing plant that may improve soil fertility, resulting in better yields. The higher and more stable maize yield as a result of cropping maize together with leucaena is explained by Chintu et al. (2004) and Chirwa et al. (2003). They attribute the positive effect of leucaena to improving the soil structure, rainfall storage, and the enhancement of nutrient recycling. Mugendi et al. (1999) found a higher N uptake of 105–110 kg ha^{-1} in maize leucaena compared with 96–105 kg ha^{-1} in maize monocultures.

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Herbicide use is common in farm systems practicing CA. (Hassan et al., 2010), which underlined the importance of testing it in this study. Results from the analysis of the data indicated that there was a significant effect of the use of herbicides in controlling weeds from the third year of the experiments, with applying herbicide having a higher maize yield of 17%. Previous studies that agree with this study of higher maize yield with the application of herbicides include those by Bibi et al. (2020) and Ibade and Mohammed (2020) in Iraq. The positive effect of herbicides on maize yield, especially during the dry season, is associated with a reduced weed population, which results in a reduction in competition for water and nutrients between the maize and weeds. This results in better nutrients and water use efficiency, translating into higher yields (Hassan et al., 2010).

Applying all three principles of CA considered in this study resulted in significantly higher yield compared to applying one or two principles during the season drier than average year ($P = 0.03$), with applying one principle showing 33.0% and 58.0% lower maize yield compared to two and three principles, respectively. When considering the total maize yield of the wet seasons in the 1st and 2nd years of the experiments, as well as the 3rd year, which was drier than average growing seasons, applying two or three principles resulted in higher and more stable values than applying only one principle (6.9% and 8.6% higher, respectively). The stability is shown by the lower CV of 48% in three principles compared to 86.37% and 99.41% in one and two principles, respectively. In addition to the higher maize yield realised in this study when all three CA principles were practiced, it also contributed to yield stability, which agrees with what was reported by Govaerts et al. (2005) in a semi-arid zone in Mexico. Yield stability is an important aspect of crop production under rain-fed and more adverse conditions. A stable system shows a small change in response to changes in the environment (Lightfoot et al., 1987). During the 3rd year, which was a dry year, the two conventional practices of conventional tillage with maize and beans or dolichos had the lowest maize yield, compared to no till with maize, beans, and mulch. However, in the 2nd year wet season, no till with maize, beans, and mulch had a 12.3% lower yield than the conventional practices with dolichos, but still 24.8% higher than the conventional practice with beans. Further, the no-till method with maize, beans, and mulch in the form of maize residue had a more stable yield compared to the other treatments, as evidenced by the lowest CV of 8.6% during the dry-year season. Practicing no till combined with intercropping maize with beans and leucaena or applying maize residue mulch at a rate of 1.5 Mg ha^{-1} showed the highest yield during the dry year season. These practices showed an increase in maize yield of up to 63.0% and 73.0%, respectively, as compared to the most conventional system of CT with maize and beans. This may be attributed to the higher soil moisture in farm systems using the CA, especially during the critical dry period of flowering (tasselling) and grain filling. Another reason could be the improved nutrient uptake, especially nitrogen, when maize is intercropped with leucaena, which is likely to result in a higher maize yield than when maize is grown alone (Sileshi et al., 2011; Mugendi et al., 1999). The positive effect of no till combined with intercropping maize with bean and leucaena and covering the soil surface with maize residue is in agreement with the findings of Pittelkow et al. (2015).

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

3.4 Rainwater use efficiency

The effect of tillage on rainwater use efficiency (RWUE) is shown in Table 5. Rainwater use efficiency was significantly affected by tillage during the dry season. The CT had 33.0% significantly lower RWUE than the NT. Better RWUE in NT compared to CT has previously been found by other authors such as Peng et al. (2020) and Oduor et al. (2023). They attributed the higher RWUE in NT compared to CT to no-till decreased evaporation, thus optimising rainfall use. There was no significant effect of intercropping maize with either common bean or dolichos bean during the three years of study. During the wet season intercropping maize with beans had a higher RWUE of 7.5% compared to intercropping maize with dolichos beans. During the dry year (year 3), intercropping maize with dolichos beans had a 10% higher RWUE in comparison with common beans. The higher RWUE found when dolichos beans were intercropped with maize compared to intercropping common beans with maize during the dry season may be due to more coverage of the ground area, thus reducing water loss through evaporation (Maitra et al., 2021; Nyawande et al., 2019).

The incorporation of agroforestry in CA using leucaena trees increased RWUE by 16.0%, while covering the soil surface with maize residue mulch significantly increased RWUE during the dry season by 19.8% (P values for agroforestry and mulch were 0.04 and 0.01, respectively). Sileshi et al. (2011) found higher water use efficiency (RWUE) when maize was intercropped with leucaena compared to maize monoculture. Higher water use efficiency in combining NT with crop residue has been reported for sorghum in Nigeria by Obalum et al. (2011) and by Zhang et al. (2014) in China. Cantero-Martinez et al. (2003) also found better water use efficiency with no tillage in the driest years in Spain. Better water use efficiency under mulching is congruent with the findings of Kader et al. (2017) in Japan and Qin et al. (2015) in China. They also attributed higher water use efficiency to better soil structure due to the buildup of biological microflora and fauna. This leads to increased infiltration and a reduction in water losses through evaporation and runoff. The higher RWUE found in this study may be due to the effect of agroforestry on microclimate. This microclimate reduces water loss through evaporation, making the water available to the plant. The different root depths of the tree (agroforestry) and annual crops ensure different exploitation of water and nutrient resources, with tree components accessing deeper soil layers than the annual crops, thus avoiding competition and resulting in better RWUE (Hatfield and Dold, 2019). Sileshi et al. (2011) also attribute higher RWUE to the role leucaena plays in mitigating soil degradation and agricultural drought. The finding of higher RWUE in systems using agroforestry technology is in agreement with what Droppelmann et al. (2000) found in monocrop annuals, which had lower water use efficiency compared to alley cropping systems in semi-arid Kenya.

.

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Table 5: Rainfall water use efficiency (kg ha^{-1} mm^{-1}) as affected by tillage, agroforestry, herbicide application, mulching and their interaction

	Year 1	Year 2	Year 3
Number of principles			
One	4.2a	5.2a	6.1a
Two	3.8a	5.3a	8.0b
Three	3.3a	5.0a	9.6b
P	0.27	0.81	0.00
Interaction between tillage, intercropping and mulching			
Conventional tillage, maize, beans and leucaena	3.9a	4.6a	7.0ab
Conventional tillage, maize and beans	4.8a	4.5a	5.6a
Conventional tillage, maize, beans and mulch	4.5a	6.2a	6.8ab
Conventional tillage, maize, beans and dolichos	3.9a	6.4a	8.5ab
No till, maize, beans and leucaena	3.5a	3.4a	8.6ab
No till, maize and beans	3.0a	6.1a	6.6ab
No till, maize beans and mulch	3.3a	5.7a	9.7b
No till, maize, beans and dolichos	3.9a	5.7a	5.3ab
No till with herbicide, maize, beans and leucaena	4.0a	5.9a	9.1ab
No till with herbicide, maize and beans	4.5a	4.8a	8.4ab
No till with herbicide, maize, beans and mulch	3.2a	4.2a	9.4ab
No till with herbicide, maize, beans and dolichos	3.1a	5.6a	8.3ab
P	0.61	0.11	0.00
Tillage			
CT	4.3	5.5	6.3*
NT	3.4	5.3	8.4*
Intercropping			
Common beans	4.0	5.4	6.8
Dolichos beans	3.7	5.6	7.5
Herbicide			
Yes	3.7	5.1	8.8*
No	3.9	5.3	7.3*
Agroforestry			
Yes	3.8	4.6	8.2*
No	4.1	5.1	6.9*
Mulch			
Yes	3.7	5.3	8.6*
No	4.1	5.1	6.9*

NT No till, CT Conventional Tillage, and NTH No till with herbicide. The means followed by a lowercase letter in the column were not significantly different at P≤ 0.05. Show a significant difference from the t-test.

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

The RWUE was significantly higher (17.0%) in systems utilising herbicide applications in the drier year. Applying all three principles of CA resulted in significantly (P<0.05) higher RWUE compared to applying one or two principles during the dry-year season by 36.5% and 16.7%, respectively. The better RWUE in treatments with herbicides may be due to the reduced weeds, resulting in reduced competition for water, nutrients, and light between the maize crop and the weeds (Thimmegowda et al., 2016). The positive effect of herbicide application on RWUE has previously been reported by Singh et al. (2015).

5.0 Conclusion

The study found that surface cover is an important aspect of CA, resulting from its association with higher soil moisture, yield, and water use efficiency. An interesting finding was the positive effect of incorporating agroforestry into crop production systems, especially when the trees used have other benefits. The study concludes that NT, mulching, and inclusions of agroforestry in CA have a positive and significant effect on soil moisture, maize yield, and rainwater use efficiency in the season with rainfall below normal. It is important to apply all three principles of CA to realise more benefits compared to applying one or two principles. Further, there is a need for long-term studies to investigate the effect of leucaena on sustainable yield, soil moisture, and soil health.

6.0 Acknowledgement

6.1 Funding

None

6.2 General acknowledgement

The author would like to acknowledge and thank the Flemish Interuniversity Council-University Development Cooperation (VLIR UOS) in Belgium for funding this work. We are also greatly indebted to Jomo Kenyatta University of Agriculture and Technology and the Kenya Agricultural and Livestock Research Organisation (KALRO) for their support and to the farmer who provided his land for this research

6.3 Ethical consideration

None

6.4 Conflict of interest

None.

7.0 References

Abdullah, A.S., 2014. Minimum tillage and residue management increase soil water content, soil organic matter and canola seed yield and seed oil content in the semiarid areas of Northern Iraq. *Soil and Tillage Research*, *144*, pp.150-155. http://dx.doi.org/10.1016/j.still.2014.07.017

Adekiya, A.O., Agbede, T.M., Aboyeji, C.M., Dunsin, O. and Ugbe, J.O., 2019. Green manures and NPK fertilizer effects on soil properties, growth, yield, mineral and vitamin C composition of okra (Abelmoschus esculentus (L.) Moench). *Journal of the Saudi Society of Agricultural*

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Sciences, *18*(2), pp.218-223. https://doi.org/10.1016/j.jssas.2017.05.005

Alam, M., Olivier, A., Paquette, A., Dupras, J., Revéret, J.P. and Messier, C., 2014. A general framework for the quantification and valuation of ecosystem services of tree-based intercropping systems. *Agroforestry systems*, *88*, pp.679-691. https://doi.org/10.1007/s10457-014-9681-x%20

Alila, P.O., Atieno, R., 2006. Agricultural Policy in Kenya: Issues and Processes. A paper for the Future Agricultures Consortium workshop, Institute of Development Studies, 20-22 March 2006. https://www.future-agricultures.org/wp-content/uploads/pdf-archive/Ag_policy_Kenya.pdf

Amikuzino, J. and Donkoh, S.A., 2012. Climate variability and yields of major staple food crops in Northern Ghana. *African Crop Science Journal*, *20*, pp.349-360. http://www.bioline.org.br/pdf?cs12050

Araya, T., Gebremedhin, A., Baudron, F., Hailemariam, M., Birhane, E., Nyssen, J., Govaerts, B. and Cornelis, W., 2021. Influence of 9 years of permanent raised beds and contour furrowing on soil health in conservation agriculture based systems in Tigray region, Ethiopia. *Land Degradation & Development*, *32*(3), pp.1525-1539. http://hdl.handle.net/1854/LU-8691996

Araya, T., Nyssen, J., Govaerts, B., Baudron, F., Carpentier, L., Bauer, H., Lanckriet, S., Deckers, J. and Cornelis, W.M., 2015. Restoring cropland productivity and profitability in northern Ethiopian drylands after nine years of resource-conserving agriculture. *Experimental Agriculture*, *52*(2), pp.165-187. https://doi.org/10.1017/S001447971400060X

Ayanlade, A. and Radeny, M., 2020. COVID-19 and food security in Sub-Saharan Africa: implications of lockdown during agricultural planting seasons. npj Science of Food, 4(1), p.13. https://www.nature.com/articles/s41538-020-00073-0.pdf. Accessed on 24th June 2021

Baliscei, M. A., Barbosa, O. R., Souza, W., Costa, M. A. T., Krutzmann, A., Queiroz, E. O. (2013). Microclimate without shade and silvopastoral system during summer and winter. Acta Scientiarum. Animal Sciences, 35, 49-56. https://doi.org/10.4025/actascianimsci.v35i1.15155

Ban, D., Zanic, K., Dumicic, G., Culjak, T.G. and Ban, S.G., 2009. The type of polyethylene mulch impacts vegetative growth, yield, and aphid populations in watermelon production. *Journal of Food, Agriculture & Environment*, *7*(3&4), pp.543-550. https://www.researchgate.net/publication/285931924

Barron, J., Rockström, J., Gichuki, F. and Hatibu, N., 2003. Dry spell analysis and maize yields for two semi-arid locations in east Africa. *Agricultural and forest meteorology*, *117*(1-2), pp.23-37. https://doi.org/10.1016/S0168-1923(03)00037-6

Baumhardt, R.L., Schwartz, R., Howell, T., Evett, S.R. and Colaizzi, P., 2013. Residue management effects on water use and yield of deficit irrigated corn. *Agronomy Journal*, *105*(4), pp.1035-1044. https://doi.org/10.2134/agronj2012.0362

Biamah, E.K., Gichuki, F.N. and Kaumbutho, P.G., 1993. Tillage methods and soil and water conservation in eastern Africa. *Soil and Tillage Research*, *27*(1-4), pp.105-123. https://core.ac.uk/download/pdf/29281333.pdf#page=46

Bibi, S., Khan, I.A., Hussain, Z. 2020. Effect of herbicides and intercropping on weeds and yields of maize and the associated intercrops. Pakistan Journal of Botany, 3, 1113-1120. https://doi.org/10.30848/PJB2019-3(45)

Bhattacharyya, R., Kundu, S., Pandey, S.C., Singh, K.P. and Gupta, H.S., 2008. Tillage and irrigation effects on crop yields and soil properties under the rice–wheat system in the Indian

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Himalayas. *Agricultural water management*, *95*(9), pp.993-1002. https://doi.org/10.1016/j.agwat.2008.03.007

Bjornlunda, V., Bjornlundaand, H., Van Rooyen, A.F. 2020. Why agricultural production in sub-Saharan Africa remains low compared to the rest of the world a historical perspective. International Journal of Water Resources Development, 36, S20–S53. https://doi.org/10.1080/07900627.2020.1739512

Cakir, R., 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. Field Crops. Research. 89, 1–16. https://doi.org/10.1016/j.fcr.2004.01.005

Cantero-Martınez, C., Angas, P. and Lampurlanés, J., 2003. Growth, yield and water productivity of barley (Hordeum vulgare L.) affected by tillage and N fertilization in Mediterranean semiarid, rainfed conditions of Spain. *Field Crops Research*, *84*(3), pp. 341-357. https://doi.org/10.1016/S0378-4290(03)00101-1

Chartres, C.J., Noble, A. 2015. Sustainable intensification: Overcoming land and water constraints on food production. Food Security, 7 (2), pp. 235-245. https://link.springer.com/article/10.1007/s12571-015-0425-1

Chintu, R., Mafongoya, P.L., Chirwa, T.S., Mwale, M. and Matibini, J., 2004. Subsoil nitrogen dynamics as affected by planted coppicing tree legume fallows in eastern Zambia. Experimental Agriculture, 40(3), pp.327-340. https://doi.org/10.1017/S0014479704001826

Chilimba, A.D.C., 2002. Beneficial effects of microbes in nutrient recycling in cropping systems of Malawi. *Journal of Tropical Microbiology and Biotechnology*, *1*(1), pp.47-53. https://doi.org/10.4314/jtmb.v1i1.35411

Chirwa, T.S., Mafongoya, P.L. and Chintu, R., 2003. Mixed planted-fallows using coppicing and non-coppicing tree species for degraded Acrisols in eastern Zambia. *Agroforestry systems*, *59*(3), pp.243-251. https://doi.org/10.1023/B:AGFO.0000005225.12629.61

Colless, J.M. 1992. Maize growing, Agfact P3.3.3, second edition. NSW Department of Agriculture, Orange. https://books.google.com/books/about/Maize_growing.html?id=14dzNAAACAAJ

Cook, H.F., Valdes, G.S. and Lee, H.C., 2006. Mulch effects on rainfall interception, soil physical characteristics and temperature under Zea mays L. *Soil and tillage research*, *91*(1-2), pp.227-235. https://doi.org/10.1016/j.still.2005.12.007

Cornelis, W.M., Verplancke, H., Bonroy, J. 2005. Soil physical characteristics and processes. Practical exercises manual. Ghent University, Belgium.

Dahiya, R., Ingwersen, J. and Streck, T., 2007. The effect of mulching and tillage on the water and temperature regimes of a loess soil: Experimental findings and modeling. *Soil and Tillage Research*, *96*(1-2), pp.52-63. https://doi.org/10.1016/j.still.2007.02.004

Dalley, C.D., Bernards, M.L. and Kells, J.J., 2006. Effect of weed removal timing and row spacing on soil moisture in corn (Zea mays). *Weed Technology*, *20*(2), pp.399-409. https://www.jstor.org/stable/4495696

Dalzel, S.A., Shelton, H.M., Mullen, B.F., Larsen, P.H., McLaughlin, K.G. 2006. Leucaena: a guide to establishment and management. Meat & Livestock Australia Ltd. Sydney, Australia. https://espace.library.uq.edu.au/view/UQ:41099

Derpsch, R., Friedrich, T., Kassam, A. and Li, H., 2010. Current status of adoption of no-till

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

farming in the world and some of its main benefits. *International journal of agricultural and biological engineering*, *3*(1), pp.1-25. https://doi.org/10.3965/j.issn.1934-6344.2010.01.0-0

De Silva, S.A. and Cook, H.F., 2003. Soil physical conditions and physiological performance of cowpea following organic matter amelioration of sandy substrates. *Communications in Soil Science and Plant Analysis*, *34*(7-8), pp.1039-1058. https://doi.org/10.1081/CSS-120019108

Dollinger, J. and Jose, S., 2018. Agroforestry for soil health. Agroforestry systems, 92, pp.213-219. https://doi.org/10.1007/s10457-018-0223-9

Doorenbos, J., Kassam, A.K., 1979. Yield response to water. Irrigation and Drainage Paper 33. FAO, United Nations, Rome, p. 176. https://cir.nii.ac.jp/crid/1361137045078587776

Droppelmann, K.J., Lehmann, J., Ephrath, J.E. and Berliner, P.R., 2000. Water use efficiency and uptake patterns in a runoff agroforestry system in an arid environment. *Agroforestry systems*, *49*, pp.223-243. http://dx.doi.org/10.1023/A:1006352623333

Evett, S.R., Tolk, J.A. and Howell, T.A., 2003. A depth control stand for improved accuracy with the neutron probe. *Vadose Zone Journal*, *2*(4), pp.642-649. https://doi.org/10.2113/2.4.642

FAO. 2014. Conservation Agriculture-Implementation Guidance for Policymakers and Investors. http://www.fao.org/ag/ca/

FAO. 2016. Agricultural Sub-Saharan Africa: Prospects and challenges for the next decade. Part I Chapter 2. OECD-FAO Agricultural Outlook 2016-2025. Available at: https://doi.org/10.1787/agr_outlook-2016-en

Farooq, M., Flower, K.C., Jabran, K., Wahid, A. and Siddique, K.H., 2011. Crop yield and weed management in rainfed conservation agriculture. *Soil and tillage research*, *117*, pp.172-183. https://doi.org/10.1016/j.still.2011.10.001

Franke, A.C., Van den Brand, G.J., Vanlauwe, B. and Giller, K.E., 2018. Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. *Agriculture, ecosystems & environment*, *261*, pp.172-185. https://doi.org/10.1016/j.agee.2017.09.029

Franzluebbers, A.J., 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil and Tillage research*, *66*(2), pp.197-205. https://doi.org/10.1016/S0167-1987(02)00027-2

Giller, K.E., Delaune, T., Silva, J.V., Descheemaeker, K., van de Ven, G., Schut, A.G., van Wijk, M., Hammond, J., Hochman, Z., Taulya, G. and Chikowo, R., 2021. The future of farming: Who will produce our food?. Food Security, 13(5), pp.1073-1099. https://doi.org/10.1007/s12571-021-01184-6

Giller, K.E., Witter, E., Corbeels, M. and Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field crops research*, *114*(1), pp.23-34. https://doi.org/10.1016/j.fcr.2009.06.017

Godfrey, S. and Tunhuma, F.A., 2020. The climate crisis: climate change impacts, trends and vulnerabilities of children in Sub Sahara Africa. *Nairobi:* United Nations Children's Fund Eastern and Southern Africa Regional Office. https://www.unicef.org/esa/reports/climate-crisis

Govaerts, B., Sayre, K.D. and Deckers, J., 2005. Stable high yields with zero tillage and permanent bed planting?. *Field crops research*, *94*(1), pp.33-42.

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

https://doi.org/10.1016/j.fcr.2004.11.003

Govaerts B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K.D., Dixon, J. and Dendooven, L., 2009. Conservation agriculture and soil carbon sequestration: between myth and farmer reality. *Critical Reviews in Plant Science*, *28*(3), pp.97-122. https://doi.org/10.1080/07352680902776358

Gowing, J.W. and Palmer, M., 2008. Sustainable agricultural development in sub-Saharan Africa: the case for a paradigm shift in land husbandry. *Soil use and management*, *24*(1), pp.92-99. https://doi.org/10.1111/j.1475-2743.2007.00137.x

Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility. In Dane, J.H. and Topp, G.C. (Eds.). Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI. P.201-228. https://doi.org/10.2136/sssabookser5.4.c9

Guertal, E.A., Raun, W.R., Westerman, R.L. and Boman, R.K., 1994. Applications of stability analysis for single-site, long-term experiments. *Agronomy Journal*, *86*(6), pp.1016-1019. https://doi.org/10.2134/agronj1994.00021962008600060016x

Guto, S.N., De Ridder, N., Giller, K.E., Pypers, P. and Vanlauwe, B., 2012. Minimum tillage and vegetative barrier effects on crop yields in relation to soil water content in the Central Kenya highlands. *Field Crops Research*, *132*, pp.129-138. https://doi.org/10.1016/j.fcr.2011.10.014

Hassan, G., Tanveer, S., Khan, N.U. and Munir, M., 2010. Integrating cultivars with reduced herbicide rates for weed management in maize. *Pak. J. Bot*, *42*(3), pp.1923-1929. https://www.pakbs.org/pjbot/PDFs/42(3)/PJB42(3)1923.pdf

Hatfield, J.L., Dold, C. 2019. Water-Use Efficiency: Advances and Challenges in a Changing Climate. Frontiers in Plant Science. Frontiers in Plant Science. https://doi.org/10.3389/fpls.2019.00103

Hitimana, S., Rukangantambara, H., Nsengiyumva, J.N. 2021. Effect of mulching on soil physico-chemical properties of soil under semiarid of rain fed fersiallitic soil condition in Eastern of Rwanda. International Journal of Progressive Sciences and Technologies. 25, 468-475. http://ijpsat.ijsht-journals.org

Hossain, M.I., Sarker, M.J.U. and Haque, M.A., 2015. Status of conservation agriculture based tillage technology for crop production in Bangladesh. *Bangladesh Journal of Agricultural Research*, *40*(2), pp.235-248. https://doi.org/10.3329/bjar.v40i2.24561

Ibade, K.W., Mohammed, Y.A. 2020. Efficiency of Herbicides on Weeds and Effect on Growth and Yield of Maize (Zea mays L.). Indian Journal of Ecology, 10, 22-26. https://www.researchgate.net/publication/338571704

Jagadeesh, C., Madhavi, M., Prasad, M. S., Padmaja, V. V. 2018. Effect of organic manure on growth and yield attributes of beetroots Cv. Crimson globe. International Journal of Current Microbiology and Applied Sciences, 11, 3538-3553. https://doi.org/10.20546/ijcmas.2018.711.403

Jayne, T.S., Fox, L., Fuglie, K., Adelaja, A. 2012. Agricultural Productivity Growth, Resilience, and Economic Transformation in Sub-Saharan Africa. https://www.usaid.gov/bifad/documents/agricultural-productivity-growth-resilience-and-economic-transformation-sub-saharan-africa

Jin, K., Cornelis, W.M., Schiettecatte, W., Lu, J., Yao, Y., Wu, H., Gabriels, D., De Neve, S., Cai, D., Jin, J. Hartmann, R., 2007. Effects of different management practices on the soil–water balance and crop yield for improved dryland farming in the Chinese Loess Plateau. Soil and Tillage

Research, 96, 131-144. https://doi.org/10.1016/j.still.2007.05.002

Juana, J.S., Kahaka, Z. and Okurut, F.N., 2013. Farmers' perceptions and adaptations to climate change in sub-Sahara Africa: A synthesis of empirical studies and implications for public policy in African agriculture. *Journal of Agricultural Science*, *5*(4), p.121. http://dx.doi.org/10.5539/jas.v5n4p121

Kader, M. A., Senge, M., Mojid, M.A., Nakamura, K., 2017. Mulching type-induced soil moisture and temperature regimes and water use efficiency of soybean under rain-fed condition in central Japan. ISWC. http://dx.doi.org/10.1016/j.iswcr.2017.08.001

Kang, B.T., Reynolds, L. and Atta-Krah, A.N., 1990. Alley farming. *Advances in agronomy*, *43*, pp.315-359. https://doi.org/10.1016/S0065-2113(08)60481-2

Kanu, B.S., Salami, A.O. and Numasawa, K., 2014. Inclusive growth: An imperative for African agriculture. *Afr. J. Food Agric. Nutr. Dev*, *14*(3). https://www.academia.edu/download/40289111/24.04.2014.pdf

Kassam, A., Friedrich, T., Shaxson, F., Pretty, J., 2009. The spread of Conservation Agriculture: justification, sustainability and uptake. International Journal of Agricultural Sustainability. 7, 292–320. https://doi.org/10.3763/ijas.2009.0477

Kaumbutho, P., Kienzle, J., 2007. Conservation agriculture as practised in Kenya: two case studies. Nairobi: African Conservation Tillage Network, Food and Agriculture Organization of the United Nations. https://agritrop.cirad.fr/541158/

Kinyumu, D.M., 2012. Is Conservation Agriculture a Solution to Dry Land Rain-fed Farming? Experiences and Perceptions of Smallholder Farmers in Laikipia District, Kenya. Journal of Developments in Sustainable Agriculture.7, 134-147. https://doi.org/10.11178/jdsa.7.134

Kutya, L., 2012. Small Scale Agriculture. Summaries of Presentations Made at Seminar Hosted by Afesis-Corplan on Small Scale/Holder Agriculture. Available online: www.ngopulse.org/article/small-scale-agriculture

Kyei-Mensah, C., Kyerematen, R. and Adu-Acheampong, S., 2019. Impact of rainfall variability on crop production within the Worobong Ecological Area of Fanteakwa District, Ghana. *Advances in Agriculture*, *2019*, pp.1-7. https://doi.org/10.1155/2019/7930127

Lenssen, A.W., Sainju, U.M., Jabro, J.D., Iversen, W.M., Allen, B.L., Evans, R.G., 2014. Crop diversification, tillage, and management system influence spring wheat yield and water use. Agronomy Journal. 106, 1445–1454. https://doi.org/10.2134/agronj14.0119

Lightfoot, C.W.F., Dear, K.B.G., Mead, R., 1987. Intercropping sorghum with cowpea in dry land farming systems in Botswana. II. Comparative stability of alternative cropping systems. Experimental Agriculture. 23, 435–442. https://doi.org/10.1017/S0014479700017397

Liu, D.L., Zeleke, K.T., Wang, B., Macadam, I., Scott, F., Martin, R.J., 2017. Crop residue incorporation can mitigate negative climate change impacts on crop yield and improve water use efficiency in a semi-arid environment. European Journal of Agronomy. 85, 51–68. https://doi.org/10.1016/j.eja.2017.02.004

Macholdt, J. Honermeie, B., 2017. Yield Stability in Winter Wheat Production: A Survey on German Farmers' and Advisors' Views. Agron. 7, 1-18. https://doi.org/10.3390/agronomy7030045

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J.B., Jena, J., Bhattacharya, U., Duvvada, S.K., Sagar Lalichetti, S., Sairam, M. 2021. Intercropping a low input agricultural strategy for food and environmental security.

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Agronomy 11, 1-28. https://doi.org/10.3390/agronomy11020343

Makurira, H., 2010. Water productivity in rain-fed agriculture redrawing the rainbow of water to achieve food security in rain-fed smallholder systems. PhD. Thesis. Wageningen University, The Netherlands 169 p. https://doi.org/10.1201/b10823

Miriti, J.M., Kironchi, G., Esilaba, A.O., Gachene, C.K.K., Heng, L.K., Mwangi, D.M., 2013. The effects of tillage systems on soil physical properties and water conservation in a sandy loam soil in Eastern Kenya. Journal of Soil Science and Environmental Management. 4, 146–154. https://doi.org/10.5897/JSSEM2013.0395

Moyo, J.M., Bah, E.H.M. and Verdier-Chouchane, A., 2015. Transforming Africa's agriculture to improve competitiveness. *The Africa competitiveness report*, *2015*, pp.37-52. https://www3.weforum.org/docs/WEF_ACR_2015/ACR_Chapter2.1_2015.pdf

Mugendi, D.N., Nair, P.K.R., Mugwe, J.N., O'Neill, M.K., Swift, M.J., Woomer, P. 1999. Alley cropping of maize with Calliandra and Leucaena in the Sub-humid highlands of Kenya. Part 2: Biomass decomposition, N mineralization and N uptake by maize. Agroforestry Systems. 46, 51–64. https://doi.org/10.1023/A:1006288301044

Müller, C., Cramer, W., Hare, W.L. and Lotze-Campen, H., 2011. Climate change risks for African agriculture. *Proceedings of the national academy of sciences*, *108*(11), pp.4313-4315. https://doi.org/10.1073/pnas.1015078108

Muoni, T., Rusinamhodzi, L., Mabasa, S., Rugare, J.T., Thierfelder, C., 2014. Does the Use of Atrazine in Maize Grown Under Conservation Agriculture Adversely Affect Soybean Productivity in Maize-Soybean Rotation in Zimbabwe? Journal of Agricultural Science; 7, 294-302. http://dx.doi.org/10.5539/jas.v6n7p294

Mupangwa, W., Twomlow, S., Walker, S. 2012. Reduced tillage, mulching and rotational effects on maize (Zea mays L.), cowpea (Vigna unguiculata (Walp) L.) and sorghum (Sorghum bicolor L. (Moench)) yields under semi-arid conditions. Field Crops Research. 132, 139-148. https://doi.org/10.1016/j.fcr.2012.02.020

Mutuku E.A., Roobroeck D., Vanlauwe B., Boeckx P., Cornelis W.M. 2020. Field crops research maize production under combined conservation agriculture and integrated soil fertility management in the sub-humid and semi-arid regions of Kenya. Field Crop. Research.;254:107833. https://doi.org/10.1016/j.fcr.2020.107833

NeSmith, D.S., Ritchie, J.T. 1992. Short and long-term responses of corn to a pre-anthesis soil water deficit. Agronomy Journal. 84, 107–113. https://doi.org/10.2134/agronj1992.00021962008400010021x

Ngenga, M. E., Bastiaans,L., Anten, N.P.R., Zingore, S., Giller, K.E. 2022. Immediate and residual-effects of sole and intercropped grain legumes in maize production systems under rain-fed conditions of Northern Tanzania. Field Crops Research 287 (2022) 108656. https://doi.org/10.1016/j.fcr.2022.108656

Ngigi, S.N., Rockström, J. and Savenije, H.H., 2006. Assessment of rainwater retention in agricultural land and crop yield increase due to conservation tillage in Ewaso Ng'iro river basin, Kenya. *Physics and Chemistry of the Earth, Parts A/B/C*, *31*(15-16), pp.910-918. https://doi.org/10.1016/j.pce.2006.08.006

Ngwira, A.R., Aune, J.B. and Mkwinda, S., 2012. On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Malawi. Field crops research, 132, pp.149-157. https://doi.org/10.1016/j.fcr.2011.12.014

Ngwira, A.R., Thierfelder, C., Lambert, D.N., 2013. Conservation agriculture systems for Malawian smallholder farmers: long term effects on crop productivity, profitability and soil quality. Renewable Agriculture and Food Systems. 28, 350–363. https://doi.org/10.1017/S1742170512000257

Notter. B., 2003. Rainfall-Runoff Modeling of Meso-scale Catchments in the Upper Ewaso Ng'iro Basin Kenya. PhD. Thesis. Universität Bern 221p. http://www.secheresse.info/spip.php?article58893

Nyamadzawo, G., Nyamugafata, P., Chikowo, R. and Giller, K., 2008. Residual effects of fallows on selected soil hydraulic properties in a kaolinitic soil subjected to conventional tillage (CT) and no tillage (NT). *Agroforestry Systems*, *72*, pp.161-168. https://doi.org/10.1007/s10457-007-9057-6

Nyawade, S.O., Karanja, N.N., Gachene, C.K.K., Gitari, H.I., Schulte-Geldermann, E., Parker, M.L. 2019. Intercropping Optimizes Soil Temperature and Increases Crop Water Productivity and Radiation Use Efficiency of Rainfed Potato. American Journal of Potato Research. 96, 457–471. https://doi.org/10.1007/s12230-019-09737-4

Obalum, S.E., Amalu, U.C., Obi, M.E., Wakatsuki, T., 2011. Soil Water Balance and Grain Yield of Sorghum under No-Till Versus Conventional Tillage with Surface Mulch in the Derived Savanna Zone of South-eastern. Nigeria. Exp. Agric.47, 89–109. https://doi.org/10.1017/S0014479710000967

Oduor, O.N., Mucheru-Muna, M., Mugwe, N.J., Sijali, I., Nyabuga, G., Mugendi, N.D. 2023. Soil water use efficiency under integrated soil management practices in the drylands of Kenya. Heliyon 9 (2023) e16145. https://doi.org/10.1016/j.heliyon.2023.e16145

Ojwang, G. O., Agatsiva, J., Situma, C., 2010. Environment and natural resources management working paper. Analysis of Climate Change and Variability Risks in the Smallholder Sector: Case studies of the Laikipia and Narok Districts representing major agro-ecological zones in Kenya. FAO Rome. 84pp. http://www.fao.org/3/a-i1785e.pdf

Panettieri, M., Lazaro, L., López-Garrido, R., Murillo, J.M., Madejón, E., 2013. Glyphosate effect on soil biochemical properties under conservation tillage. Soil Tillage Research. 133, 16–24. http://dx.doi.org/10.1016/j.still.2013.05.007

Peng, Z., Wang, L., Xie, J., Li, l., Coulter, J.A., Zhang, R., Luo, Z., Cai, L., Carberry, P., Whitbread, A. 2020. Conservation tillage increases yield and precipitation use efficiency of wheat on the semi-arid Loess Plateau of China. Agricultural Water Management Volume 231, 106024. https://doi.org/10.1016/j.agwat.2020.106024

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J.,Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature. 517, 365–368. https://doi.org/10.1038/nature13809

Pozza, L.E., Damien J. Field, D.J. 2020. The science of Soil Security and Food Security. Soil Security 1 (2020) 100002. https://doi.org/10.1016/j.soisec.2020.100002

Pradhan, A., Chan, C., Roul P.K., Halbrendt, J., Sipes, B., 2018. Potential of conservation agriculture (CA) for climate change adaptation and food security under rain-fed uplands of India: A trans disciplinary approach. Agricultural Systems. 163, 27-35. https://doi.org/10.1016/j.agsy.2017.01.002

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. Philosophical Transactions of the Royal Society B: Biological Sciences. 363, 447-465. https://doi.org/10.1098/rstb.2007.2163

Pretty, J., 2011. Sustainable intensification in Africa. *International Journal of Agricultural Sustainability*, *9*(1), pp.3-4. https://doi.org/10.3763/ijas.2011.91ED

Pretty, J. and Bharucha, Z.P., 2014. Sustainable intensification in agricultural systems. *Annals of botany*, *114*(8), pp.1571-1596. https://doi.org/10.1093/aob/mcu205

Qin, W., Wang, D., Guo, X., Yang, T., Oenema, O., 2015. Productivity and sustainability of rain-fed wheat–soybean system in the North China Plain: Results from a long-term experiment and crop modelling. Sci. Rep. 5, Article number: 17514. https://doi.org/10.1038/srep17514

Ramakrishna, A., Tam, H.M., Wani, S.P. and Long, T.D., 2006. Effect of mulch on soil temperature, moisture, weed infestation and yield of groundnut in northern Vietnam. *Field crops research*, *95*(2-3), pp.115-125. https://doi.org/10.1016/j.fcr.2005.01.030

Reynolds, W.D., Drury, C.F., Tan, C.S., Fox, C.A., Yang, X.M., 2009. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma. 152, 252–263. https://doi.org/10.1016/j.geoderma.2009.06.009

Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, H., Oweis, T., Bruggeman, A., Farahani, J., Qiang, Z., 2010. Managing water in rain-fed agriculture-The need for a paradigm shift. Agric. Water Manage. 97, 543–550. https://doi.org/10.1016/j.agwat.2009.09.009

Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., Temesgen, M., Mawenya, L., Barron, J., Mutua, J., Damgaard-Larsen, S., 2009. Conservation farming strategies in East and Southern Africa: yields and rain water productivity from on-farm action research. Soil Tillage Research. 103, 23–32. https://doi.org/10.1016/j.still.2008.09.013

Ronner, E., 2011. How does conservation agriculture improve rain water use efficiency? A study on the effects of mulch and no-tillage on the seasonal water balance in Laikipia District, Kenya. M. Sc. Thesis. Wageningen University, The Netherlands. 89p.

Rusinamhodzi, L., Corbeels, M., van Wijk, M.T., Rufino, M.C., Nyamangara, J., Giller, K.E. 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agronomy Sust. Development. https://doi.org/10.1007/s13593-011-0040-2

Sanginga, N., Mulongoy, K., Swift, M.J., 1992. Contribution of soil organisms to the sustainability and productivity of cropping systems in the tropics. Agriculture, ecosystems & environment, 41, 135-152. https://doi.org/10.1016/0167-8809(92)90106-L

Sarkar, S., Singh, S. R., 2007. Interactive effect of tillage depth and mulch on soil temperature, productivity and water use pattern of rain-fed barley (*Hordium vulgare L.*). Soil Tillage Research. 92, 79–86. https://doi.org/10.1016/j.still.2006.01.014

Serraj, R., Siddique, H.M., 2012. Conservation agriculture in dry areas. Field Crops Research. 32, 1–6. https://doi.org/10.1016/j.fcr.2012.03.002

Setter, T.L., Flannigan, B., Melkonian, J. 2001. Loss of kernel set due to water deficit and shade in maize. Crop Science. 41, 1530–1540. https://doi.org/10.2135/cropsci2001.4151530x

Shetto, R., Owenya, M., 2007. Conservation Agriculture as Practised in Tanzania: Three Case Studies. African Conservation Tillage Network, Centre de Coope´ ration Internationale de Recherche Agronomique pour le De´veloppement, Food and Agriculture Organization of the United Nations, Nairobi, Kenya. https://agritrop.cirad.fr/541149/

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Shirugure, P.S., Sonkar, R.K., Singh, S. and Panighrah, P., 2003. Effect of different mulches on soil moisture, weed reduction, growth and yield of drip irrigated Nagpur mandarin (Citrus reticulata). Indian Journal of Agricultural Sciences, 73, pp.148-52. https://api.semanticscholar.org/CorpusID:81327080

Sileshi, G.W., Akinnifesi, F.K., Ajayi, O.C., Muys, B. 2011. Integration of legume trees in maize-based cropping systems improves rain use efficiency and yield stability under rain-fed agriculture. Agricultural Water Management, 98, 1364–1372. https://doi.org/10.1016/j.agwat.2011.04.002

Singh, B., Ahmed C.S., Hussain.T., Jebran, K., Manlil, S. 2015, Integrated weed management approaches to improve weed control efficiencies for sustainable rice production in dry seeded systems. Crop Protection., 71:19-24. https://doi.org/10.1016/j.cropro.2015.01.012

Slathia, P.S. and Paul, N., 2012. Traditional practices for sustainable livelihood in Kandi belt of Jammu. http://nopr.niscpr.res.in/handle/123456789/14400

Snyder, K., Grant, A., Murray, C., Wolff, B. 2015. The effect of plastic mulch systems on soil temperature and moisture in Central Ontario. American Society for Horticultural Science, 25, 162-170. https://doi.org/10.21273/HORTTECH.25.2.162

Souza, W., Barbosa, O. R., Marques, J. A., Teixeira, M. A. T., Gasparino, E., Limberger, E. (2010). Microclimate in silvipastoral systems with eucalyptus in rank with different Heights. Revista Brasileira de Zootecnia, 39, 685-694. https://doi.org/10.1590/S1516-35982010000300030

Sun, L., Wang, S, Zhang, Y., Li, J., Wang, X., Wang, R., Lyu, W., Chen, N., Wang, Q., 2018. Conservation agriculture based on crop rotation and tillage in the semi-arid Loess Plateau, China: Effects on crop yield and soil water use. Agriculture Ecosystems and Environment. 251, 67–77. https://doi.org/10.1016/j.agee.2017.09.011

Taylor, A.S., Ashcroft, G.L., 1972. Physical Edaphology: The physics of irrigated and non-irrigated soils. WH Freeman and Company, San Francisco. https://lccn.loc.gov/70094874

Tebrügge, F., Düring, R. 1999. Reducing tillage intensity–a review of results from a long-term study in Germany. Soil Tillage Research. 53, 15–28. https://doi.org/10.1016/S0167-1987(99)00073-2

Thierfelder, C., Matemba-Mutasa, R., Rusinamhodzi, L. 2015a.Yield response of maize (Zea mays L.) to conservation agriculture cropping system in southern Africa. Soil and Tillage Research. 146, 230–242. http://dx.doi.org/10.1016/j.still.2014.10.015

Thimmegowda, J.M. N., Meti, R.N., Prakash, G. 2016. Water Use Efficiency and Economics of Weed Management Practices Under Drip Irrigated Aerobic Rice. Advances in Life Sciences 8, 2016. https://www.researchgate.net/publication/328554191

Tittonell, P., Scopel, E., Andrieua, N., Posthumush, H., Mapfumo, P., Corbeels, M. van Halsema, G.E., Lahmara, R., Lugandu, S., Rakotoariso, J., Mtambanengwe, F., Pound, B., Chikowo, R., Naudina, K., Triomphe, B., Mkomwa, S., 2012. Agroecology-based Aggradation-conservation agriculture (ABACO): Targeting innovations to combat soil degradation and food insecurity in semi-arid Africa. Field Crops Research. 132, 168–174. https://doi.org/10.1016/j.fcr.2011.12.011

UNDP. 2012. Mainstreaming Sustainable Land Management in Agro pastoral Production Systems of Kenya. http://www.ke.undp.org/content/dam/kenya/docs/energy_and_environment/FINAL%20PRODOC.pdf

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3

Van Noordwijk, M., Widianto, Heinen, M., Hairiah, K., 1991.Old tree root channels in acid soils in the humid tropics: Important for crop root penetration, water infiltration and nitrogen management. Plant Soil. 134; 37-44. https://doi.org/10.1007/978-94-011-3438-5_47

Verhulst, N., Nelissen, V., Jespers, N., Haven, H., Sayre, K. D., Raes, D., Deckers, J., Govaerts, B., 2011. Soil water content, maize yield and its stability as affected by tillage and crop residue management in rain-fed semi-arid highlands. Plant Soil. 344, 73–85. https://doi.org/10.1007/s11104-011-0728-8

Wegren, S.K. and Elvestad, C., 2018. Russia's food self-sufficiency and food security: An assessment. Post-Communist Economies, 30(5), pp.565-587. https://doi.org/10.1080/14631377.2018.1470854

Zhang, P., Wei, T., Jia, Z., Han, Q., Ren, X., 2014. Soil aggregate and crop yield changes with different rates of straw incorporation in semiarid areas of northwest China. Geoderma. 230, 41–49. https://doi.org/10.1016/j.geoderma.2014.04.007

ISSN 1561-7645 (online)
doi: 10.4314/jagst.v24i1.3