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Does Conservation Agriculture Improve Soil hydrology, Soil Quality and Crop Yields? A Case of Drylands of Laikipia, Kenya.

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Dedication

This dissertation manuscript is dedicated to my lovely daughter, Fedora Mawia. Memories of me leaving you very young kept me going every minute of my stay in Belgium.

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May God bless all of you abundantly.

Last but not least, my heart is deeply grateful to God for the far He has taken me. Thanks for the protection accorded to my daughter when I was away. Your answers are Yes and Amen.

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Abbreviations

ASAL	Arid-arid lands
BD	bulk density
CA	Conservation Agriculture
CT	Convectional tillage
FAO	Food and agricultural organization
GoK	Government of Kenya
IFAD	International Fund for Agricultural Development
K	Potassium
N	Nitrogen
NT	No tillage
P	Phosphorus
PAWC	Plant available water capacity
RWC	Relative water capacity
SOC	Soil organic carbon
SPSS	Statistical analysis for social scientist
SQI	Soil quality indicator
SSA	Sub-Sahara Africa
SWRC	Soil water retention curve
UNEP	United Nations Environment Programme
USA	United states of America
VSA	Visual soil assessment

Abstract

The world's population is predicted to exceed 9 billion by 2050 raising a need for increasing food production. This extra production is expected to come from SSA where rainfall is erratic and unreliable. Majority of farmers in this area are smallholder farmers owing less than one hectare for farming, practicing mainly tillage farming and obtaining sub-optimal yields due to sub-optimal land and water management. With the need for extra production, conservation agriculture (CA) is seen as an alternative management strategy to reduce yield losses related to inter-seasonal dry spells. However, evidence whether CA improves soil conditions and hence the partitioning of the rainfall and ultimately yield is not very consistent across studies worldwide. The aim of this study was to investigate the effects of CA on soil hydrology, on soil quality and on crop yield on clay soils in Laikipia East sub county, Kenya. A field experiment was installed according to a split block design with three replicates and three main treatments: (1) conventional tillage (CT), (2) no tillage (NT) and (3) no tillage with use of herbicides (NTH) and four sub-treatments: (a) intercropping with beans (Phaseolus vulgaris L.) and leucena (*Leucaena diversifolia)* as cover crop (BM), (b) intercropping with beans (*Phaseolus vulgaris L*.) (B), (c) intercropping with dolichos (*Lablab purpureus (L.)* Sweet) as cover crop (D), and (d) intercropping with beans and application of mulch (1.5 ton of maize stover per hectare) (BM). Main treatment (2) and (3) are considered as CA-based practices converted from fields previously under CT. Soil samples were collected in the third year of the experiment at depths of 0–15 (top soil) and 10–30 cm (sub soil) from a total of 36 plots. Maize yield, rain water use efficiency, soil organic carbon, microbial biomass carbon, total nitrogen (sub soil), FC (sub soil), PWP (sub soil), structural stability index and dry water stable aggregates (top soil) were greater in CA plots. pH, total nitrogen (top soil), available phosphorus, exchangeable potassium, calcium, magnesium, sodium, BD and parameters derived from SWRC were not significantly influenced by tillage nor by intercropping and cover crops. However most of the parameters were slightly better in CA based practices as compared to CT. K_S was higher in

CTBL than other treatments. Soil water content was significantly higher in NTBM and NTHBM during a dry spell which occurred during maize yield formation stage. In addition, during yield formation, water deficit was significantly higher in CT as compared to NT and NTH and was directly linked to the observed yields.

1. Introduction

The sustainability of farming in dryland areas of Sub-Sahara Africa (SSA) depends on the capacity to develop and adopt suitable farming practices that arrest the negative effects of continuous tillage on soil quality (Araz et al., 2014). The consequence of continuous tillage is soil degradation resulting from hastened erosion, soil structure damage, accelerated organic matter loss and reduced soil fertility (Alam et al., 2014; Das et al., 2014). Soil degradation coupled with low productivity per unit water (Vohland and Barry, 2009) ultimately results in food shortage experienced by small holder farmers in SSA (Barron and Okwach, 2005).

Kenya forms part of the arid and semi-arid lands (ASAL) of SSA (Ngigi et al., 2005a) with 83% of the total land covered by arid land area (GoK, 2002). The annual overall rainfall of SSA is usually 300-900 mm (UNEP, 1992) with Kenya receiving an annual rainfall of 630 mm (Mango et al., 2011). Part of the received rainfall is lost as direct runoff or as deep drainage resulting from bypass flow through cracks (blue water), resulting in less rainwater being available for crops, the so called green water (Rockström and Falkenmark, 2015). Green water can also be lost by soil evaporation (Rockström and Falkenmark, 2015). This imbalanced soil hydrology is attributable to physical, chemical and biological deterioration of the soil quality and absence of effective field conservation practices in cropland (Reynolds et al., 2007).

In Kenya, agriculture is the dominant sector playing a big role in household food and income (Maithya et al., 2006). The country's food security depends entirely on this dominant sector with 80% of crop production been rainfed (Ngigi et al., 2005b). However, crop production is unable to cope with the increasing population growth. Drought and dry spells coupled with immense land degradation and poor soil fertility has led to decreased production. Due to these constrains facing the sector, 70% of the population is food insecure (IFAD, 2013). For Kenya to feed 38.6 million people at a growth rate of 3% per year (GoK, 2011) and considering the annual rainfall constrains and variability, efforts should be made to ensure that the farming systems are made efficient in both water and nutrient utilization (Barron and Okwach, 2005) by considering alternative farming systems. Efforts should be directed to small holder farmers who contribute 75% of Kenyan crop production and are key drivers to increase crop production and improve livelihoods (Nyoro, 2002).

The alternative farming systems arrest the negative effects of the common known convectional tillage which inverts the soil causing degradation in soil health (depletion of organic matter and other nutrients) as well as decline in crop productivity (Alam et al., 2014). The introduction of alternative land management strategies calls for efforts to assess their effects on soil quality. As reported by Schjønning et al. (2004), soil quality is a measure of a soil's capacity to deliver ecosystem services and functions, and is indicated by the interaction of its physical, chemical and biological properties influencing crop yields (Knight et al., 2013). Among the important soil properties is soil structure, which is used to asses agricultural soil quality (Moncada et al., 2014). Soil structure is an indicator of physical and biological soil quality, and its assessment can be direct or indirect. Even though there exist methods to determine this parameter, there are times when the methods cannot be used thus an alternative is Visual Soil Assessment (VSA) methods. This method is usable by both farmers, extension officers and researchers alike and gives results that are easy to interpret (Ball et al., 2007; Mueller et al., 2013). The methods have been used in the humid areas with much success but their applicability in the tropics or to which extent they should be adapted still needs to be ascertained (Moncada et al., 2014).

Conservation Agriculture (CA) is an example of an alternative approach to continuous tillage and its negative effects. CA is believed to increase water infiltration thus increasing plant available water (Kahlon et al., 2013), increase soil organic carbon (Brunel et al., 2013) and improve soil nitrogen status through the use of legumes as cover crops (Belel et al.,2014). This approach can result in improved soil properties and hence improved crop productivity in the drylands helping reduce the effect of food shortage among smallholder farmers (Corbeels et al., 2013; Chitogo, 2013). CA is based on three principles, namely no or minimum tillage, soil cover with 30% crop residues on soil surface and the use of crop rotations or associations (Hobbs, 2007; Thierfelder et al., 2013; Van Wie et al., 2013).

A common practice by farmers practising CA is intercropping with cover crops (Flower et al., 2012) due to their advantages which include provision of surface cover to reduce erosion, improve soil fertility, improve soil moisture, suppress weeds, nutrient cycling and optimise crop production (Sainju et al., 2006; Snapp et al., 2005; Flower et al., 2012; Ward et al., 2012). In Kenya legumes grown as intercrops with maize (*Zea mays L*) are mostly used as cover crops (Nakhona and Tabatabai, 2008) and kept up to maturity for harvesting. Cover crops are also used to replace the 30% residue cover on CA which is proving difficult to achieve in SSA due to the alternative uses of crop residues (Giller et al., 2011).

In Africa CA has increasingly been promoted by international organizations, donors, and non-governmental organizations as a means to overcome continuing poor profitability, food insecurity and soil degradation on smallholder farms (Corbeels et al., 2013). Similarly, in Kenya, CA is being promoted to smallholder farmers by the government, research institutions and non-governmental organisations as an in-situ water harvesting technique (Rockström et al., 2010).

Even though there is a lot of interest in CA, proof of its benefits is limited and inconsistent in SSA (Mupungwa et al., 2013; Paul et al., 2013). This is also in line with Reynolds et al. (2007) who reported that the characteristics of the effects of land management on near surface physical properties of soil are poorly understood. He also argued that diagnostic physical quality indicators of soil are not well developed. Results from comparison of CA and conventional tillage (CT) are inconsistent between socio-economic structures, crop types, tillage systems, soil types and climates in the different parts of the world (Ahuja et al., 2006). For this reason, standardized research methods based on site specific conditions are fundamental to understanding of CA (Derpsch et al., 2014). Ahuja et al. (2006) argue that physical soil properties exhibit temporal and spatial variability meaning that research on effects of CA has to be done enormously across the globe before a univocal statement about the issue can be given. Moreover, much research done in Kenya on CA so far based their focus mainly on the adoption rates of CA by smallholder farmers (Waweru et al., 2015). Others were concerned about the trade-offs that exist between residue that is used as mulch in CA and the same time as livestock feeding by mixed farmers (Jaleta et al., 2013). Few studies have been done in Kenya showing the effect of CA on soil hydrology (Gicheru et al., 2004; Ngigi et al., 2005b). Furthermore, to successfully integrate CA into Kenyan farming systems information on its effect on soil chemical, biological and physical properties is required. Farmers also need information on whether the shift from conventional tillage to reduced tillage will improve their productivity which is the main aim of farming. Therefore, this study aims to investigate the effects of CA on soil hydrology, soil quality and crop yields on a heavy clay soil in the drylands of Laikipia East sub County, Kenya. It evaluates whether CA is an appropriate alternative management strategy for smallholder farmers in the study area. We hypothesize that selected sustainable land management practices based on conservation agriculture principles with use of cover crops will increase crop yield by improving soil quality and the root zone water content.

Specific objectives are:

- To investigate the effects of CA on root zone soil water content
- To investigate the effects of CA on soil physical properties
- To investigate the effects of CA on soil chemical properties
- To investigate the effects of CA on soil biological properties
- To evaluate soil quality using VSA method
- To investigate the effects of CA on crop yield

2. Literature Review

2.1 The burning issue

Mind-sets of farmers rarely change unless there is a pressing reason to necessitate the change. So then, what are some of the pressing global and regional issues making researchers invest on changing the mind-sets of farmers towards a more sustainable farming system?

2.1.1 Growing world population

Research and predictions have projected that the world's population will exceed 9 billion by 2050 (FAO, 2015). This implies that food production has to increase to cater for the growing population. This in turn will put a lot of pressure on land and fresh water resources if the current cropping systems remain unchanged. Furthermore, it is clear that the present crop production cannot cope with the increasing world population (FAO, 2011). This calls for adjustment from the existing cropping systems to use of sustainable strategies that are able to produce enough food to feed the growing population.

2.1.2 Water resource

Currently 7% of the world's population lives in areas where water is insufficient with prediction indicating a rise to a stunning 67% by 2050 (Wallace, 2000). In order to increase food using rainfed agriculture there is a need to use the fresh water resources sustainably (Wallace, 2000). Depending on the land management practices used, this fresh water, coming from precipitation, can either become blue water or green water (Falkenmark and Rockström, 2010). Green water is defined as that fraction of rainfall that infiltrates into the soil and is available to plants (Ringersma et al., 2003; Falkenmark and Rockström, 2010). It also includes water retained in the soil by the soil matrix, depending on the soil's water holding capacity. On the other hand, they define blue water as fraction of water that reaches rivers directly as runoff or indirectly through deep drainage to ground water and stream base flow. Figure 2.1 illustrates this partitioning of blue and green water. Barron et al. (2003) reported that crops make use of only 36–64% on average of seasonal rainfall in Kenya and Tanzania indicating extensive water losses by surface runoff and deep percolation.

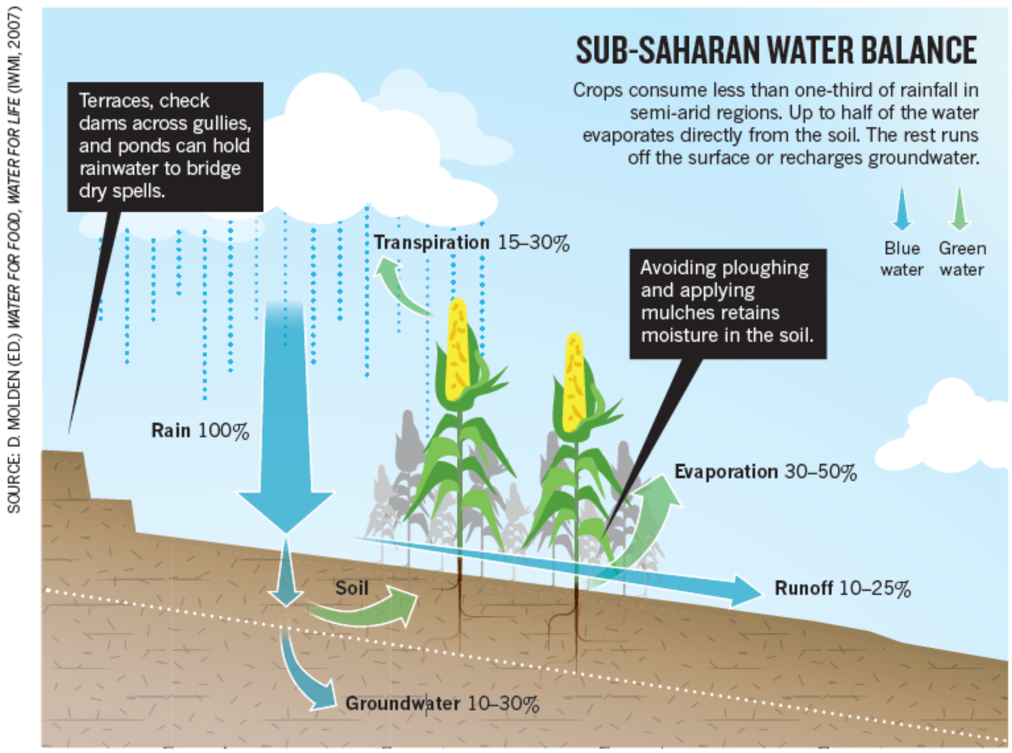

Figure 2.1: General overview of rainfall partitioning in farmer fields in semiarid savannah agro-ecosystems in SSA. Adapted from Rockström and Falkenmark, 2015.

2.1.3 Occurrence of drought and dry spell

Drought is defined as a prolonged period of abnormally low rainfall which can result in complete crop failures. Alam et al. (2014) differentiates between meteorological and agricultural drought. Meteorological drought is based on precipitation's departure from normal average over a certain period of time and region, while agricultural drought links the effects of meteorological drought to agricultural impacts and refers to lack of soil-water being available to crops. Dry spells on the other hand are short periods of drought during the growing season. Dry spells occur more common than drought (Table 2.1). It is also important to note that in semi-arid areas, amount of rainfall is not the limiting factor in crop production (Hatibu et al., 2003), but intra and off season dry spells resulting from rainfall distribution and variability (Rockström et al., 2010).

2.1.4 Food security status

Even though the growing global demand for food is expected to be met in part by rainfed cropping systems in SSA, most countries in this area are faced with persistent food insecurity accompanied by low and declining farm incomes (Lahmar et al., 2012; Thierfelder et al., 2014). World Bank (1996) attributes this food insecurity to low and declining agricultural production and productivity.

Table 2.1: Types of water stress and underlying causes in semiarid and dry sub-humid tropical environment.

	Dry spell	Drought
Meteorological		
Frequency	2 out of 3 years	1 out of 10 years
Impact	Yield reduction	Complete crop failure
Cause	Rainfall deficit of 2 to 5 weeks periods during crop growth	Seasonal rainfall below minimum plant water requirement
Agricultural		
Frequency	More than 2 out of 3 years	1 out of 10 years
Impact	Yield reduction or complete crop failure	Complete crop failure
Cause	Low plant water availability and poor plant water uptake capacity	Poor rainfall partitioning; leading to soil moisture deficit for producing harvest (where poor partitioning refers to a high proportion of runoff and non-productive evaporation relative to soil water infiltration at the surface)

Source: Falkenmark and Rockström, 2004.

Growth in agricultural sector has not been able to cope with the increasing population (FAO, 2011). Furthermore, cereal production increase observed in some areas is for 60% linked to area expansion other than improvement in cropping systems (Challinor et al., 2007).

In Kenya, agriculture is the central sector playing a big role as a source of food and household income (Maithya et al., 2006). Similar as the SSA trend, population growth rate has been considerably higher than the growth rate in the agriculture sector resulting in recurrent food crises and worsening rural poverty (Republic of Kenya, 2002). IFAD (2013) states that rural food insecurity experienced in Kenya is linked strongly to poor water management, soil erosion, decreasing soil fertility and land degradation. The food shortage can only be reduced if the agricultural sector grows at a rate that meets the growing population (Maithya et al., 2006) necessitating identification of appropriate strategies to steer agricultural productivity to higher and sustainable levels (Govaerts et al., 2009).

2.2 Conservation Agriculture (CA), an alternative strategy

2.2.1 CA origin, definition and principles

The dust bowls that were experienced in the central plains of North America in1930s caused enormous soil erosion and loss of millions of tons of soil; they are at the origin of reduced tillage (Anderson and Giller, 2012). Soil erosion resulting from deep tillage and lack of ground cover called for strategies for its control hence efforts were made towards soil conservation.

The initiative was started by the American government to ensure that dust bowls never reappeared again during years of drought. To avoid moisture competition, equipment used to spray and kill weeds while maintaining grass as the only soil cover were developed. Efforts were also dedicated to water conservation hence moisture retention in the soil. Since then, the practice has been improved to what is now called CA (Anderson and Giller, 2012).

The Food and Agricultural Organisation (FAO) defines CA as an approach to managing agro-ecosystems for improved and sustained productivity, increased profit and food security while preserving and enhancing the resource base and the environment (FAO, 2008; FAO, 2011). FAO further characterises CA by three linked principles: continuous minimum mechanical soil disturbance, permanent organic soil cover using crops and/or crop residues, and diversification of crop species grown in sequence and/or association. Van Wie et al. (2013) indicate that CA includes a variety of reduced and no till techniques that leave at least 30% crop residue on the soil surface. Thierfelder et al. (2014) argue that CA is not entirely a new approach to farming. It is an approach that changes the unsustainable practices of conventional tillage with sustainable practices. It replaces excessive tillage with minimum soil disturbance, residue removal with surface retention and mono-cropping with diversified crop rotations.

2.2.2 Conservation agriculture CA versus conventional tillage CT

The two systems, CA and CT, are differentiated mainly by the intensity of soil disturbance and surface cover (Figure 2.2). CA is believed to gradually improve soil properties and hence improve crop productivity leading to increased household incomes and food security (Mason et al., 2015). CT on the other hand loosens the soil resulting in a well tilled seedbed hence provide a good rooting medium for crops, to help in weed control and also to increase residue decomposition enabling the crops to benefit from the released nutrients. However, the negative effects of CT are very detrimental to the environment. Continuous tillage results in weakening of soil structure consequently reducing soil aggregate stability against rain drop impact, increasing compaction and crusting, rain water runoff and soil erosion, moisture loss through bringing the subsoil to the surface, oxidation of organic matter and sometimes in delayed planting due to time required for seed bed preparation (FAO, 2008; Thierfelder and Wall, 2009; Alam et al., 2014).

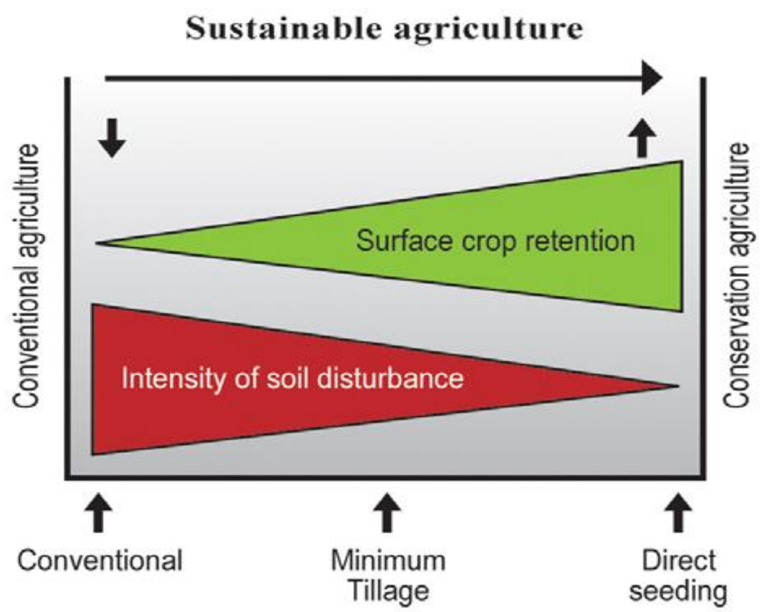

Figure 2.2: Conceptual framework of a step-by-step process to sustainable agriculture by the use of conservation agriculture. (Adapted from Govaerts, PhD thesis, 2007**).**

2.2.3 Developments in CA definition and principles

As with any other technology, CA improves continuously as research and investments continue. In SSA for example, most of the land is degraded and biomass production is not enough to cater for the required land cover. Similarly, smallholder farmers in Kenya, despite being the majority in crop production rarely achieve the 30% cover throughout the year (Rockström et al., 2010). Rockström, (2000) redefined conservation tillage with respect to small-scale farmers in semi-arid environments as any tillage system that conserves water and soil while saving labour and traction needs.

Even though CA is based on three key principles, Farooq et al. (2011) included weed management as a fourth principle since weed management was suggested by Giller et al. (2009) as a challenge to implementation of CA. Smallholders farmers in SSA, must integrate appropriate use of fertilizer as a fourth principle of CA as concluded by Vanlauwe et al. (2014) in their study in Kenya. This suggestion can be supported by the fact that fertilizer increases biomass production thus providing more residues which are inadequate for small holder farmers (Lahmar et al., 2012). In their study, Kassam and Friedrich (2011) included controlled traffic that lessens soil compaction as a fourth principle, applicable to large scale farmers that mainly use big machinery.

2.2.4 Adoption of CA

As the pressure to feed the growing population increases, farmers are increasing their interest in CA to improve crop production. This increased interest is shown by the progressive increase of hectares under CA in the world. Sanchez et al. (2014) reports that in 2011, 125 million hectares in the world were under no till (NT). Derpsch and Friedrich (2009) reported a worldwide CA estimation of around 105 million hectares, 96.1% of which is in South America, USA, Canada and Australia, 0.3% in Africa and the rest of the world accounts for 3.6%. This shows a positive increase in CA adoption compared to 72 million hectares reported in 2003 by Derpsch and Benites (2003) and 45 million hectares in 1999 reported by Sanchez et al. (2014).

CA is believed to be adopted step wise, first with implementation of reduced tillage and later with introduction of 30% residue retention (Lahmar, 2008). Corbeels et al. (2013) also reported that adoption of CA begins with one or two principles. This was recently confirmed by Waweru et al. (2015) for Laikipia East sub county, Kenya. In Africa, CA adoption is limited regardless of research and development ventures that have been done (Kassam et al., 2009). Kassam et al. (2009) reported a total area of less than 1% in Kenya, Zimbabwe and Zambia that is under CA. The reason for the low adoption is probably that CA principles are not supported well by the farming systems in Africa (Giller et al., 2009). Farmers in Africa practice mixed farming (crop-livestock) and most of the residue is used to feed livestock (Corbeels et al., 2013). In addition degraded lands may not produce enough biomass for the more than 30% residue cover needed in CA. Smallholder farmers also have an immediate need to feed their families and can only willingly adopt technologies that give short term benefits especially with yield increase which might not be so with CA (Giller et al., 2009). As reported by Thierfelder et al. (2013) yield effects under CA are variable in short term and its benefits accrue with time due to improvement in soil biological, chemical and physical properties. Giller et al. (2009) reports the main reason why farmers in SSA have difficulties adopting CA. They are highlighted as: ` "(i) concerns on initial yield decreases often observed (or perceived) with CA; (ii) lack of sufficient biomass for effective mulching due to poor crop productivity or to competing uses for crop residues in crop-livestock systems; (iii) increased labour requirements when herbicides are not used, putting an extra burden on female labour for weeding; (iv) lack of access to, and use of, external inputs such as mineral fertilizers and herbicides''.

2.2.5 Weed control in CA

Weed management has been recognized as a major challenge in CA (Giller et al., 2009). This could be the reason why Farooq et al. (2011) suggested weed management as a fourth principle in CA practices thus requiring special attention. Weed compete with crops for soil moisture, nutrients, space and act as habitats for insects and disease causing pests which can lead to yield reduction. In CT, inversion through tillage helps control weed. Several methods have been suggested by Bajwa (2014) for weed control in CA including, crop rotation, use of mulch and/or cover crops, intercropping, biological weed control, chemical weed control and allelopathy. Chemical weed control (use of herbicides) is commonly used by farmers. However, it should be noted that herbicides can become persistence in soil and contaminate ground water (Bajwa, 2014). But Ahuja et al. (2006) suggested that this negative effects becomes negligible over time as residues retained on the surface reduce weed infestation and use of herbicides reduces. Herbicides can reduce microorganisms in the rhizosphere and continued use of one herbicide can cause resistance thus becoming ineffective. Bajwa (2014) suggests use of biological weed control and allelopathy as a viable option in weed control under CA. Allelopathy is a natural, ecological phenomenon in which different organisms affect the functioning of other organisms in their vicinity, negatively or positively by releasing secondary metabolites (Bajwa, 2014).This method is advantageous because allelochemicals do not have residual or toxic effects. According to Bajwa, (2014) allelopathy can be used by introducing crops with allelopathic potential in rotation.

2.2.6 Intercropping practice in CA

Intercropping is a farming practice involving two or more crop species, or genotypes, growing together and coexisting for a time (Belel et al., 2014; Booker et al., 2014). It is mainly done by use of cereal and legumes due to the capability of legumes to improve soil fertility and increase total yields. This practice enhances water and nutrient use, reduces the risk of crop failure and increases food security (Wang et al., 2015). Intercropping is a practice that goes in line with the third principle of CA, i.e., diversification of crop species grown in sequence and / or association.

In Kenya, maize is an important food crop (Miriti et al., 2012), whose production is constrained by frequent drought and dry spells. Intercropping is a major cropping system among the smallholder farmers in Kenya which reduces the production uncertainties associated with these constrains. To improve maize production, different legumes (Midega et al., 2014), Desmodium species (Koech et al., 2012) and cowpeas (Miriti et al., 2012) have been reported to be intercropped with maize in various parts of Kenya. Results from experiments show higher maize yield when legumes and Desmodium species are used as intercrops (Koech et al., 2012; Midega et al., 2014; Miriti et al., 2012) than when maize was planted as a mono crop. Midega et al. (2014) also reported suppression of striga *(srtiga hermonthica*) weed with Desmodium species.

2.2.7 Cover crops in CA (surface cover)

Use of cover crops as soil surface cover in CA can partly replace the expected residue in drylands, where crop residues have alternative uses. Part of their benefit is soil protection and enrichment (Motta et al., 2007). They insulate the soil surface from direct sunlight thus reducing evaporation from the soil surface (Serraj and Siddiques, 2012). They help maintain porosity through protection of the surface from disruptive action of raindrop. This in turn improves soil water infiltration. Cover crops also play a role of improving soil fertility and suppressing weeds by reducing the light transmitted to the soil which affects phytochrome-mediated germination of weeds (Serraj and Siddiques, 2012).

The use of legumes as cover crops in crop production is of great importance. Legumes enhance growth and production of other crops due to their ability to prevent soil erosion, reduce evaporation, increase soil fertility (López et al., 2008), fix atmospheric nitrogen (N) and phosphorus (P), increase earthworm numbers in the soil and improve soil organic matter (Koné et al., 2012).

The focus of this dissertation is on two legumes *Leucaena diversifolia* and *Lablab purpureus* used as cover crops in CA. *Leucaena* species, which is a fast growing leguminous shrub from America and used frequently in agroforestry (López et al., 2008), is reported to fix 100 – 500 kg of N $ha^{-1}year^{-1}$ (Díaz et al., 2007). It is found to grow very well in poor soils and can increase biomass production (Goel and Behl, 2002; López et al., 2008). As a perennial legume, it has the advantage of fixing more N throughout the year and reduces cost of re-establishing again. Its ability to exploit subsoil water and nutrients which crops cannot exploit very well results in high biomass production (Rao and Mathuva, 2000). In their experiment in India, Goel and Behl (2002) reported an improvement of soil physiochemical properties by *Leucaena* species as well as increase in SOC, N and P.

Lablab purpureus species is widely grown in the tropics for its edible seeds and pods, and as a fodder for livestock. It is a N fixing green manure contributing to soil N and improving soil quality. It is tolerant to drought, low soil quality and even acid soils. Its advantages among other are weed suppression, soil erosion control and improvement of soil structure. In their study in Ivory Coast, Koné et al. (2012) reported an increase in N, P, ammonia and earthworm average numbers in fields were *Lablab* was grown. Use of *Lablab* and stover residues resulted to a high maximum moisture holding capacity (61%) compared to use of lablab only (53%) in ferrasols from Trans Nzoia district, Kenya (Medvecky et al., 2007).

2.3 Effects of CA on hydrological properties

CA plays a major role in influencing the water dynamics in the soil in drylands (Brunel et al., 2013). Tillage systems change the arrangement of soil pores reducing their ability to transport water (Kahlon et al., 2013). With CA due to crop residues and/or crop cover, positive effects of less evaporation, less runoff hence improved infiltration and improved soil water storage are evident (Falkenmark and Rockström, 2010).

2.3.1 Water infiltration and hydraulic conductivity

Water infiltration and hence hydraulic conductivity (Ks) is expected to be high in CA as compared to CT due to use of surface residue. Use of residues has been reported to reduce surface runoff thereby increasing the amount of water infiltrating into the soil (Verhulst, 2010). Moreover, residues encourage microbial biomass which can help in constructing pores for water infiltration (Henneron et al., 2014; Muchabi et al., 2014). With CA these created pores are maintained due to minimal soil disturbance. This improvement in water infiltration is believed to improve season after season (Alam et al., 2014). Studies on the effects of CA on infiltration show diverse results. In their study on CA in India on a sandy loam soil, Choudhury et al. (2014) reported increase of stable water macropores by 50%. Thierfelder et al. (2014) in Zimbabwe reports that NT and surface residue retention had significantly greater infiltration, measured by the "time to- pond" method, as compared CT. In central Ohio NT showed high infiltration rates compared to plough tillage (CT) in a silt loam soil (Kahlon et al., 2013). Similar results were observed by Thierfelder and Wall (2009) in their experiment in Zambia on CA; they recorded a 27% increase in total water infiltrating the soil plus increase in infiltration rate. Gicheru et al. (2004) in their experiment in Kenya reported high infiltration rate in all the CA treatments compared to CT in a loam sandy soil. In Malawi, Mloza-Banda et al. (2014) found Ks to be one of the few soil properties that changed after two and four years of CA adoption on sandy clay loam soil.

In contrast, an experiment in Ohio on NT and mulch showed an increase of earthworms and surprisingly no influence on water infiltration (Lal, 2007). This could have been due to less activity of earthworms so that they did not create vertical interconnection of pores. Similarly, Ferreras et al. (2000) reported only a slightly higher rate of water infiltration when using NT compared to CT in their experiment in Argentina where CT increased porosity. The observed differences in different experiments could be due to (i) the effects of the different land management strategies to abundance and number of earthworms, (ii) the different activities of the earthworms depending on their movements thus making vertical or horizontal channels, the former favouring water infiltration while the later does not, (iii) site specific characteristics and (iv) the different methods of measurements used in each experiment.

A ''critical limit'' for K_S of 8.64 cm day^{-1} for fine-textured agricultural soils was proposed by McQueen and Shepherd (2002) below which crop yield was substantially reduced due to poor root zone aeration, reduced trafficability, and increased surface runoff and erosion. K_S values significantly above this range cause rapid infiltration and drainage of water making soil devoid of water moisture and subsequently resulting in leaching of nutrients and pesticides (Reynolds et al., 2007).

2.3.2 Water content and plant available water content

Soil water content in CA is believed to be higher than in CT due to improvement of soil structure. In CA the soil surface is protected from direct sunlight by residue thereby reducing water evaporation and improving water storage in the soil. With residue organic matter also increases, which is expected to improve the water holding capacity of soils. The reported reduced runoff under CA is also of great importance in improving soil water storage. Corbeels et al. (2013) in Zimbabwe reported a higher maize grain yield under CA than under CT and attributed the difference to increased water availability resulting from decreased runoff under CA compared to CT. This improved water content can be useful in bridging dry spells and poor distributed rainfall events.

2.4 Soil quality

Soil quality (SQ) is a measure of a soil's capacity to deliver ecosystem services and functions (Schjønning et al., 2004). According to a definition given by Soil Science Society of America, SQ is concerned with biological productivity, environment and human healthy. Land managers on the other hand are interested in the capacity of the soil to increase and protract productivity for current and future generations (Shukla et al., 2006). Whether SQ is good or poor is indicated by the interaction of the soil's physical, chemical and biological properties influencing crop yields (Reynolds et al., 2007; Reynolds et al., 2009; Ling–ling et al., 2011; Knight et al., 2013). Among the three properties, physical properties are very important indicators of SQ since they affect chemical and biological properties (Ling–ling et al., 2011). The said soil properties are affected by land management either positively or negatively resulting in an increase or decrease of crop yield (Reynolds et al., 2007; Knight et al., 2013).

2.5 Effects of CA on soil physical quality

Soil physical quality is defined as the soil's strength, and fluid transmission and storage characteristics in the crop root zone (Reynolds et al., 2007). Good soil physical quality is important for the root zone and is affected by many factors among them the soil physical properties, management practices, climate and crop types.

2.5.1 Bulk density and total porosity

Normally, it is from the measurements of soil bulk density (BD) that total porosity of a soil is calculated (Verhulst, 2010). The two parameters are inversely related such that increase of BD leads to decrease in total soil porosity. Even though CA is expected to result in low BD as compared to CT due to the effect of residue which increases microbial activity, this effect is again progressive and initial years of change from CA to CT might result to small changes (Verhulst, 2010). Logsdon et al. (1999) found no differences in BD between different tillage systems. Jabro et al. (2009), in a 22 years study on a sandy loam soil found that the tillage practices NT, spring till, and fall and spring till apparently had not significantly influenced the soil BD and only slight differences were observed. Based on 8 years studies Zhang et al. (2003) reported that the mean soil BD was 0.8-1.5% lower in NT treatments than in CT. In Malawi, soils from CA fields showed significantly lower BD than corresponding ridge tillage fields after two years while after four years, soils from CA fields and corresponding ridge tillage fields did not show significant difference in BD (Mloza-Banda et al., 2014).

Ranges of the values have been elaborated in literature. BD optimum values for crop lands in fine-textured soils are 0.9–1.2 Mg m^{-3} (Reynolds et al., 2003). Values below 0.9 Mg m^{-3} may result in insufficient contact between soil and roots, poor water retention and plant anchoring, while BD values above 1.2 Mg m^{-3} may prevent root growth or reduce soil aeration (Reynolds et al., 2007).

2.5.2 Aggregate stability

Aggregate stability is a parameter that is easily affected by tillage and residue removal. With CA and especially with use of cover crops, the soil aggregates are protected from the erosive forces of raindrop hence maintaining their structure (Verhulst, 2010). In CA, decomposing crop residues produce binding agents which keep the aggregates together as well as increase in micro-organisms which through their action help stabilize the aggregates (Blanco and Lal, 2009) Reduced tillage in CA also helps in maintaining soil aggregates. Authors have shown that the use of CA improves the stability of soil aggregates (Brunel et al., 2013; Blanco and Lal, 2009; Govaerts et al., 2009).

2.6 Effects of CA on physical soil quality indicators (physical SQI)

Reynolds et al. (2007 and 2008) presented physical SQ indicators (SQI) that are directly influenced by land management. They are stated as soil macroporosity, MacPOR (m^3 m^{-3}), soil matrix porosity, MatPOR (m^3 m^{-3}), soil matrix air capacity, AC (m^3 m^{-3}), plant-available water capacity, PAWC (m^3 m^{-3}), relative water capacity, RWC (dimensionless).

The parameters and their critical values have been defined by Reynolds et al. (2007) and Reynolds et al. (2009) (Table 2.2). They can be measured from the volumetric soil water content at matric potential of -10 kPa (θ_m), volumetric soil water content at matric potential of -33 kPa (θ_{FC}), volumetric soil water content at matric potential of -1500 kPa (θ_{PWP}). SI index is calculated from structural stability.

2.6.1 MacPOR and MatPOR

MacPOR (macro-porosity) represents pore volumes compared to total pore volume with large MacPOR values indicating the potential of a soil to quickly drain excess water and allowing development of root and good aeration for microbial activity (Reynolds et al., 2009). According to Jarvis, (2007), MacPOR can be defined as pores having an equivalent cylindrical diameter larger than 0.3 to 0.5 mm, which is equivalent to a water entry pressure head of −6 to −10 cm, according to the Young–Laplace equation:

$$h = \frac{2\gamma \cos(\theta)}{\rho g R} \tag{1}$$

where h is the pressure head, γ is the surface tension, θ is the contact angle between the two fluids, ρ is the fluid density, g is the gravitational acceleration, and R is the radius of the capillary.

Minimum or optimum MacPOR and MatPOR (matric-porosity) have not yet been identified (Reynolds et al, 2007). Suggestions by Drewry et al. (2001) in Reynolds et al. (2007) are given as MacPOR ≥0.05 – 0.10 m^3 m^{-3} indicating a soil in good physical conditions and MacPOR < 0.04 m^3 m^{-3} for a soil in poor physical conditions

2.6.2 AC and PAWC

AC (air capacity) is used to show the level of soil aeration indicating microbial activity of the soil (Reynolds et al., 2007). An AC value of ≥ 0.10 m^3 m^{-3} has been suggested to indicate a good aeration in fine-textured soils (Reynolds et al., 2009). PAWC (plant available water content) indicates the amount of water available for root uptake from the soil (Reynolds et al., 2009). Critical PAWC value is suggested as 0.15 m^3 m^{-3}, with higher values indicating optimal condition.

Table 2.2: Physical SQI parameters and definitions

SQI	Definition
Bulky density	$BD = M_s/V_s$
Matric porosity	$MatPOR = \theta_m$
Macro porosity	$MacPOR = \theta_s - matPOR$
Air capacity	$AC = \theta_s - \theta_{FC}$
Plant available water capacity	$PAWC = \theta_{FC} - \theta_{PWP}$
Relative water capacity	$RWC = 1 - AC/\theta_s$
Saturated volumetric water	$\theta_s = (M_w - M_s)/(M_s * BD/WD)$
Soil structural stability index	$SI = \frac{1.724 \times SOC}{Clay + Silt} \times 100$
S index	$S = -n(w_s - w_r)x \left[\frac{2n-1}{n-1}\right]^{\left(\frac{1}{n}-2\right)}$

Source: Reynolds et al., 2007; Reynolds et al., 2009

2.6.3 RWC

RWC (relative water capacity) expresses the soil's total volume occupied by water compared to total porosity of the soil (Reynolds et al., 2007). This parameter is closely related to AC. Optimal equilibrium between RWC and AC occurs when RWC is in the range $0.6 \leq RWC \leq 0.7$ for all soil textures and indicates the capacity of the soil to have maximum microbial activity (Reynolds et al., 2007). Values below this are indicative of poor microbial activity as a result of limited soil water, while values above this are indicative of poor microbial activity as a result of limited soil air.

2.6.4 *S* index

S index was proposed by Dexter (2004a) as a parameter that can be used to indicate soil structural quality. The *S* index is defined as the slope of the soil water retention curve (SWRC) at its inflection point when the curve is expressed as gravimetric water content, θg ($kg\ kg^{-1}$) against the logarithmic matric potential scale (Dexter, 2004a). *S* index can be used to compare effects of different management practices on soil quality. The *S* index is basically based on the fact that BD can be divided into two parts, textural porosity (not affected by management), also called plasma porosity (Boivin et al., 2006), and structural porosity (affected by management). Because the S index is the slope of the SWRC, it can be calculated from van Genuchten parameters (van Genuchten, 1980). The index divides the drying curve into two parts as mentioned above. During the drying process, structural pores drain between saturation and the inflation point while textural pores drain below the inflation point. Although the values of S index are always negative, Dexter, (2004a) suggested the use of modulus of S in reporting.

Critical value for S index is proposed as 0.035 by Dexter, (2004a) below which the soils are degrade and above which the soils have good PSQ. For both temperate and tropical soils, an $S \geq 0.050$ indicates "very good" soil physical or structural quality, while $0.035 \leq S$ 0.050 is "good physical quality", $0.020 \leq S$ 0.035 is "poor physical quality", and S 0.020 is "very poor" or "degraded" physical quality (Dexter, 2004c; Dexter and Czyz, 2007). However, agricultural soils tend to fall within the range $0.007 \leq S \leq 0.14$ (Dexter and Czyz, 2007).

2.6.5 Structural stability index

StI is an indicator of structural stability of the soil, SOC is the soil organic carbon content (%) and Clay + Silt is the soil's combined clay and silt content (%). Optimal and critical values have been suggested in literature with a StI ≤ 5% indicating a structurally degraded soil due to extensive loss of organic carbon; 5% < StI ≤ 7% indicates high risk of structural degradation due to insufficient organic carbon; 7% < StI ≤ 9% indicates low risk of soil structural degradation; and StI > 9% indicates sufficient soil organic carbon to maintain structural stability (Reynolds et al., 2007).

2.7 Effects of CA on chemical quality

2.7.1 pH

Arguments on the effect of tillage on soil pH are diverse with different authors giving different reasons for their findings. Some authors report low pH in the top soil with CA linked to acidification caused by (i) decomposition of the crop residues in CA (Franzluebbers and Hons 1996), (ii) increased infiltration in this practice leading to leaching of base cations (Verhulst, 2010) and (iii) sometimes related to N and P fertilizers used mostly in CA (Duiker and Beegle (2006). However, there are claims of less acidity in CA being related to the buffering capacity of SOM (Duiker and Beegle, 2006).

2.7.2 Soil Organic Carbon (OC)

Soil organic carbon is an indicator of chemical and biological fertility of the soil and indirect physical fertility. Land management greatly affects the amount of OC in the soil. Ploughing the land under conventional tillage (CT) exposes OC and enormous oxidation takes place reducing the amount of OC (Cooper et al., 2014). Reduced tillage (RT) and no tillage (NT) on the other hand are believed to protect OC from rapid oxidation and thus enhance build up. Several studies have been done on the effects of CA on soil organic carbon. The results are inconsistence across soil types, climates and regions. Some studies indicate increase of OC with RT and NT as compared to CT; In Malawi in the top 0-15cm (Sharma et al., 2013), Mexico at 0-5cm soil depth only (Navarrete et al., 2012) and in China at 0-10cm soil layer (Liu et al., 2009) in China. Alam et al. (2014) also reported increase of OC with RT and NT as compared to CT adding that the build-up increases over time. Increase of OC in the top soil and a low amount in the sub soil was reported by Melacka et al. (2012) in their study which compared different tillage in Poland. OC also increased with time in all tillage systems tested in the 0-20cm layer of clay loam soils of Zimbabwe (Mupungwa et al., 2013). In Malawi, Mloza-Banda et al. (2014) found that mean values of OC, were significantly greater for CA fields over the ridge tillage fields.

These results contrasts with Thierfelder et al. (2013) whose experiment in Zambia did not reveal any significantly induced change at any level in total OC. Also Paul et al. (2013) did not find an increase in OC due to NT when considering the upper 30 cm soil layer irrespective of residue management, even after 11 cropping seasons in Kenya. Similarly, Corbeels et al. (2013) reported that OC remained more or less constant with CA in the first years of their experiment while CT resulted in a decrease in OC. The differences are justifiable because OC depends on (i) the different site characteristics, (ii) the measurement methods used, (iii) the number of years the experiment took which effects on OC build up in the soil, (iv) initial soil conditions, (v) climate, (vi) carbon inputs and outputs and (vii) most important, the interaction between the soil and management.
Literature shows optimal values for OC with a range of 3–5 percentage per weight (wt. %) for plant growth in compacted soils. A lower ‘‘critical limit’’ (2.3 wt. %) in crop land was proposed by Greenland (1981), below this value, loss of soil structure may be evident. He also suggested an upper ‘‘critical limit’’ (6 wt. %) after which he soil is susceptible to compaction.

2.7.3 Total Nitrogen (N) and N sources

Total N in the soil is directly linked to OC of the soil because the both N and C cycles are closely related. However, this can only be true if the source of N in the given tillage is from OC; thus with CA total N is expected to be high as compared to CT due to high OC reported under CA (Verhulst, 2010). In Malawi, Mloza-Banda et al. (2014) found higher total N values for CA fields over ridge tillage fields. In this study, the presence of leguminous cover crops might imply that the N source might be more from atmospheric N fixation than OC.

Plants can obtain N from different sources which include agricultural inorganic fertilizers, atmospheric N fixation, groundwater input among others. To distinguish the different N sources, determination of stable isotope ratios of N can be used (Mayer et al., 2002). There are two naturally occurring stable isotopes of nitrogen (N), ^{14}N and ^{15}N. Majority of N in the atmosphere is composed of ^{14}N (99.6337%) and the remainder is composed of ^{15}N (0.3663%) (Mayer et al., 2002). These ratios are expressed as delta (δ) units and per mil (‰) notation relative to certified international standards (Xue et al., 2009):

$$\delta_{sample} (‰) = [(R_{sample} - R_{standard})/R_{standard}] * 1000 \quad (2)$$

where R is the $^{15}N/^{14}N$ ratio of the sample and standard respectively.

$\delta^{15}N$ values are reported relative to atmospheric air. When δ_{sample} is positive it indicates enrichment in the heavy isotope while a negative δ_{sample} value indicates depletion in the heavy isotope (Xue et al., 2009). Different N sources can be discriminated from each other because N originating from different sources shows characteristic $\delta^{15}N$ values (Xue et al., 2009). Inorganic fertilizers show a typical $\delta^{15}N$ value range between -6‰ and 6‰. The typical $\delta^{15}N$ values for atmospheric N fixation are situated between -13‰ and 13‰. $\delta^{15}N$ values of N originating from manure are between +5‰ and +25‰ and sewage between +4‰ and +19‰. The typical $\delta^{15}N$ values of soil N range from 0‰ to +8‰. This value is related to the relative rate of mineralization and nitrification. Other factors affecting the $\delta^{15}N$ values of soil are stated as soil depth, vegetation, climate and site history (Mayer et al., 2001).

2.7.4 Available Phosphorus

Available P is expected to be high in CA as compared to CT because in CA P is not fully mixed with the soil and thus less fixation occurs. This observation has been reported by several authors

(Liu et al., 2009; Alam et al., 2014). CA fields were also reported to have higher P as compared to ridge tillage in Malawi (Mloza-Banda et al., 2014).

2.7.5 Exchangeable K^+, Ca^{2+}, Mg^{2+}, Na^+

CA increases the concentration of potassium (K^+) in the top soil due to reduced tillage activity (Franzluebbers and Hons, 1996). However, a recent study by Mloza-Banda et al. (2014) in sandy clay loam soils in Malawi showed higher K^+ concentration in ridge fields as compared to CA fields. Nevertheless, Lal et al. (2004) reported no effect of tillage or depth on available K^+. With increased infiltration rates in CA, ideally, the concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) should be less due to leaching of these elements out of the root zone. But authors have reported that Ca^{2+}, Mg^{2+} and sodium (Na^+) are less affected by tillage practice (Duiker and Beegle, 2006; Franzluebbers and Hons, 1996).

2.8 Effects of CA on soil biological quality

2.8.1 Microbial biomass

Microbial biomass is defined as the living component of soil organic matter (SOM) (Liu et al, 2009). It acts as a good indicator of changes in soil quality induced by soil management (Kujur and Patel, 2012) mainly resulting from physical and chemical changes in the soil. Microorganisms play a fundamental role in delivering key ecosystem services and soil functions which include releasing nutrients from SOM forming and maintaining soil structure (Balota et al., 2003), contributing to water storage and transfer, gas exchange and carbon sequestration.

Soil microbial biomass is affected to a great extent by conversion from one land management system to another (Balota et al., 2003). Continuous tillage leads to soil deterioration arising from rapid loss of SOM due to decline in soil microbial biomass and soil biological activity resulting in poor physical soil properties and reduced crop productivity (Balota et al., 2003). However, in CA the use of crop residues encourages fungal and bacterial growth which together with their secretion combine with soil particles to form soil aggregates (Ghimire et al., 2014). Reduced tillage also maintains shape of aggregates and continuity of pores resulting in increased water infiltration (Ahuja et al., 2006). Diversification of crops and use of legumes in rotations in the same system enable diversity of plant residue supply resulting into different microorganisms (Ghimire et al., 2014). A study done by Henneron et al. (2014) in France indicated that CA results in high biomass as compared to CT. Similarly, a study done in Zambia by Muchabi et al. (2014) also showed high microbial biomass in CA as compared with CT in all the years of the experiment but indicated significant difference only after 16 years. Aerobic microorganisms like bacteria are abundant mostly under CT while under NT fungi are the main decomposers of SOM both reporting high microbial biomass under NT as compared to CT (Spedding et al., 2004; Wang et al., 2012).

2.8.2 The V index

The V index is a measure used to show in which tillage system the micro-organisms are many (Henneron et al., 2014). The index V ranges from −1 (maximum inhibition: microbes occur only in conventional cropping system) to +1 (maximum stimulation: microbes occur only in alternative cropping system). Zero represents equal values.

2.9 Evaluation of soil quality using Visual Soil Assessment (VSA)

VSA methods provide a rapid and simple, semi-quantitative approach to assessing the overall soil structural condition of a given soil (Newell-Price et al., 2012; Mueller et al., 2013; Shepherd, 2000). Soil structure is an important aspect of agricultural soil quality used to assess the effect of different land management (Moncada et al., 2014). As indicated by Mueller et al. (2013) preservation and improvement of soil structure is key to sustaining important soil functions. Loss of soil structure leads to soil slaking and dispersion, crusting and seal formation, compaction, runoff and erosion and poor aeration which ultimately lead to poor crop productivity (Newell-Price et al., 2012). CA is expected to result in to a good soil structure given the minimum soil disturbance and also increase in microbial activity consequently loosening the soil.

Indirect methods such as OC content, BD, porosity, soil water retention curve (SWRC), soil resistance to root growth, Ks, and infiltration rate (Lal and Shukla, 2004), can be used to evaluate soil structure acting as indicators parameters for soil physical quality (Reynolds et al., 2009). These methods however are not applicable in all circumstance and especially with smallholder farmers who cannot afford to pay for laboratory tests involved in these methods (Newell-Price et al., 2012). For this reason, visual soil structural assessment methods have been developed.

The advantages of making assessment of soil structure directly in the field using VSA methods are: (i) the relatively short time consumed and the immediate availability of the results, (ii) the use of simple equipment, (iii) the observation of slight changes in physical conditions that may be difficult to determine by other means, and (iv) the flexibility to deal with a wide range of situations. On the other hand, some of the disadvantages of the visual soil examinations are: (i) they demand field training and some experience for effective use, (ii) cross-checking of the results by two or more assessors is necessary when there is an absence of confidence for accurate evaluation, and (iii) the process of sample extraction requires destruction of significant area in experimental plot (Batey, 2006).

VSA method has been used to assess soil quality in the temperate regions but information on its applicability in tropical soils is not sufficient (Moncada et al., 2014). This study in addition to the classical laboratory methods of evaluating soil structure also used VSA method to quantify soil structural quality.

2.10 Effects of CA on crop yields

Yield gain or loss in rainfed agriculture in dry areas depends mainly on water availability. Tillage systems affect plant available water with NT and RT reported to have higher water content compared to CT due to reduced erosion and evaporation (Alam et al., 2014; Brunel et al., 2013). Over time, higher yields are expected in CA due to its positive effects on soil quality provided crop rotations are well designed and include leguminous cover crops. Positive effects also result due to the improvement in soil fertility over time related mainly to the added residues. In their experiment in Malawi, Ngwira et al. (2014) report high yields in RT with residue retention, herbicide use and fertilizer application compared to CT in an experiment that tested only two principles of CA excluding rotations. A study done by Ngwira et al. (2014) in Malawi on smallholder farmers showed that CA produced higher maize yields than CT and especially when maize was intercropped with a legume compared to when maize was grown as a monocrop under CA. Liu et al. (2009) reported 20% higher yields of winter wheat under CA as compared to CT. Mupangwa et al. (2012) reported that maize grain yield increased with increased mulch cover in those seasons that had below average rainfall, although the tillage system itself had no significant effect on maize yield under semi-arid conditions in southern Zimbabwe.

CA can also result in no change or even decreasing crop yield as seen in literature (Mason et al., 2015). Yield decline can occur due to weed infestation and in some cases disease. Therefore the impacts of CA on crop yield depends on the balance between the positive effects of increased soil water content and fertility improvement, and the negative effects of frustrating weeds and disease infestations. Several studies have been done to compare yields from CA and CT showing inconsistent results. Thierfelder et al. (2013) report 80% maize yield response in CA as compared to CT in their study done in southern Africa. Mason et al. (2015) in their review in semi-arid West Africa showed that sorghum and pearl millet yields with conservation agriculture remain unchanged or decreased, especially during the first years of no-tillage, even when crop residues were applied.

Lahmar et al. (2008) report that in Europe, CA does not necessarily increase yields quoting an increase or decrease of 10% in yields. This change does not seem to convince farmers from Europe to adopt the technology. Similarly, Melecka et al. (2012) in their study in Poland indicated that CA increased soil nutrients over time but had no significant effects on crop yields. Their study showed a lower yield of winter wheat in NT as compared to CT. The inconsistent results can be explained by differences in soil types, local climate and more so on the interaction between the soil and management.

3. Materials and Methods

3.1 Study area

Kenya is located in East Africa lying between latitudes 5˚S and 5˚N and between longitudes 34˚ and 42˚E. It borders the Indian Ocean to the South East, Somalia to the East, Ethiopia to the North, Sudan to the North West, Tanzania to the South West and Uganda to the West. Kenya has an area of 587,900 km2 (58,900,000 ha), out of which 57,670,000 ha is land surface. 46,140,000 ha (83%) of the land surface is classified as arid and semi-arid, with the remaining 11,530,000 ha (17%) being classified as sub humid and humid.

This research was conducted at Muichuiri, Laikipia East Sub county in Laikipia county. The county is situated 200 km north of Nairobi between latitudes 0°17'S and 0°45'N and longitudes 36°15'E and 37°20'E. The experiment site location is 0° 02' 52.8"N and 37° 06' 57.9"E at an altitude of 1962 m above sea level and it is semi-arid with a high frequency of droughts.The mean annual rainfall is 750 mm with bimodal pattern, with long rains between March and June, and short rains from October to January (Kaumbutho and Kienzle, 2007). Mean annual temperatures range between 16 and 20 °C (Berger, 1989).

The farming system in the area is largely conventional, involving tilling land with hoe planting, first weeding and sometimes second weeding. Most of the farmers practice mixed farming (crop and livestock). Consequently, harvested crop residue is collected and stored for livestock as pasture is in short supply (Kinyumu, 2012).

3.2 Experimental design

The research was carried out in an existing experiment which has different plots installed according to a split plot design. Plot dimensions are 5 by 10 m. The field selected for this research is a field on which CA and CT has been conducted for three years (2012 - 2014) with adjustment of management practices. Before the whole field was under CT, in 2012, part of CT field was converted to CA and intercropping and cover crops introduced to both CT and CA. The main crop was maize (*Zea mais* L.) intercropped with bean, lablab and leucaena. The experiment had three main treatments: (1) conventional tillage (CT), (2) no tillage (NT) and (3) no tillage with use of herbicides (NTH).The fields under CT were tilled by use of a hoe at a depth of 20cm just before planting. Weeding was done at the same time by a scrap weeder (CT and NT) and by GRAMAXONE ® herbicide at an application rate of around three litres per hectare (NTH). The herbicide was used at all plots before planting to start on a clean field. Sub-treatments included (a) intercropping with beans (*Phaseolus vulgaris* L.) and leucaena (*Leucaena diversifolia*) as cover crop (BL), (b) intercropping with beans (*Phaseolus vulgaris* L.) (B), (c) intercropping with dolichos (*Lablab purpureus* (L.) Sweet) as cover crop (D), and (d) intercropping with beans and application of mulch (1.5 ton of maize stover per hectare) (BM). The combination of the main treatments and sub-treatments resulted into twelve treatments replicated three times giving a total of thirsty six plots. Planting and harvesting dates of the main crop and cover crops is shown in table 3.1.

The textural class of the soils under study is clay classified as Phaeozems according to FAO and also WRB soil classification.

Table 3.1: Spacing, planting and harvesting dates various crops under study.

Crop	**Crop type**	**spacing**	**Planting data**	**Harvesting date**
Maize	Main crop	75 by 60 cm	April, 22, 2014	October, 11
Bean	Intercropping and	75 by 30 cm	April, 22, 2014	August, 10
Dolichos	cover crops	75 by 30 cm	April, 22, 2014	August, 10
Leucaena		75 by 30 cm	April, 18, 2012	

3.3 Soil sampling

Undisturbed soil samples were collected from all the plots in September, 2014 at two depths, 0–15 cm and 15-30 cm, representing top and sub soil, respectively. The samples were collected near neutron probe access pipes in each plot for bulk density and water retention curve analysis. In addition two separate plots representing a virgin land and a degraded land were also sampled both for top and sub soil. The undisturbed soil samples were collected using Kopecky rings of 5 cm inner diameter and 5.1 cm height with a volume of $100cm^3$. The rings were vertically inserted into the soil by hammering gently on the top ring with a hammer after which the soil surrounding the core was removed. The rings were then closed with plastic covers and put in a special box to avoid disturbance during transportation. For other physical and chemical analysis, disturbed composite samples were collected in each plot at top and sub soil and put in plastic bag. In total three samples per plot (two undisturbed and one disturbed) were transported to the Department of Soil Management, Ghent University, Belgium for subsequent analysis.

3.4 Rainfall data

Rainfall data during the whole experiment period was collected by use of a manual metal rain gauge and recorded every morning by use of a graduated cylinder. Rainfall data outside this period was sourced from secondary sources. The software package Rainbow developed by Raes et al. (2006) was used to analyze the rainfall data for recurrence period and probability of exceedance.

3.5 Soil hydrological properties

3.5.1 Infiltration and hydraulic conductivity

Infiltration rate and hydraulic conductivity for all the 36 plots was determined in the field using tension disc infiltrometer (Model 2825K1 Soilmoisture Equipment Corp., Santa Barbara CA, USA) at four different times. Steady infiltration rates obtained at different water pressure (-6, -10 and -30 cm H_2O) were used to obtain unsaturated hydraulic properties. This method eliminated water flow in the macropores including large cracks and wormholes and water infiltration was only through soil matrix. Based on the capillary rise equation, these water potentials exclude pores of diameter or fissures of width greater than 0.50 mm, 0.30 mm and 0.10 mm, respectively, from participating in the water flow.

The unsaturated hydraulic conductivity and its relation to matric potential was obtained from tension infiltrometer measurements based on the solution of the equation of Wooding (1968):

$$\frac{q_h}{\pi R^2} = K(\psi)\left(1 + \frac{4}{\pi R k}\right) \tag{3}$$

where q_h is the steady-state flow rate ($m^3\,s^{-1}$), R is the radius of the disc (m), K(ψ) is the hydraulic conductivity ($m\,s^{-1}$) and κ (m^{-1}) is a fitting parameter. The two unknowns K(ψ) and κ were derived from tension infiltrometer measurements using the steady-state approach of Logsdon & Jaynes (1993). Their method consists of finding the two unknowns Ks and κ via regression of the data using Equation (2) while substituting Gardner's (1958) hydraulic conductivity function $K(\psi) = K_s \exp(\kappa\psi)$, where K_s is the field saturated hydraulic conductivity ($m\,s^{-1}$).

3.5.2 Soil water content

Soil water content (SWC) was measured at depths of 15, 30, 45, 60, 75, 90, 105, 120, 135, 150 cm using neutron probe (Hydroprobe® model 503, CPN Corporation, Martinez CA, USA). Two access tubes were installed in each plot 2 m from the edges of the plot and 6 m between them. Two access tubes located close to the field experiments were used for calibration. For the calibration equation, samples were taken by use of a core close to the calibration access tubes and at the same depth with the neutron probe readings. The standard count was taken by positioning the probe on top of the transport case and the detector/source locked in the polypropylene shielding repeated five times and the average calculated. This was used to get the count ratio (CR) by dividing count number with the standard count.The cores were used to determine gravimetric water content which was converted to volumetric water content using bulk density. Regression analysis was then done between volumetric water content and count ratio calculations with a R^2 = 0.94 (Figure 3.1):

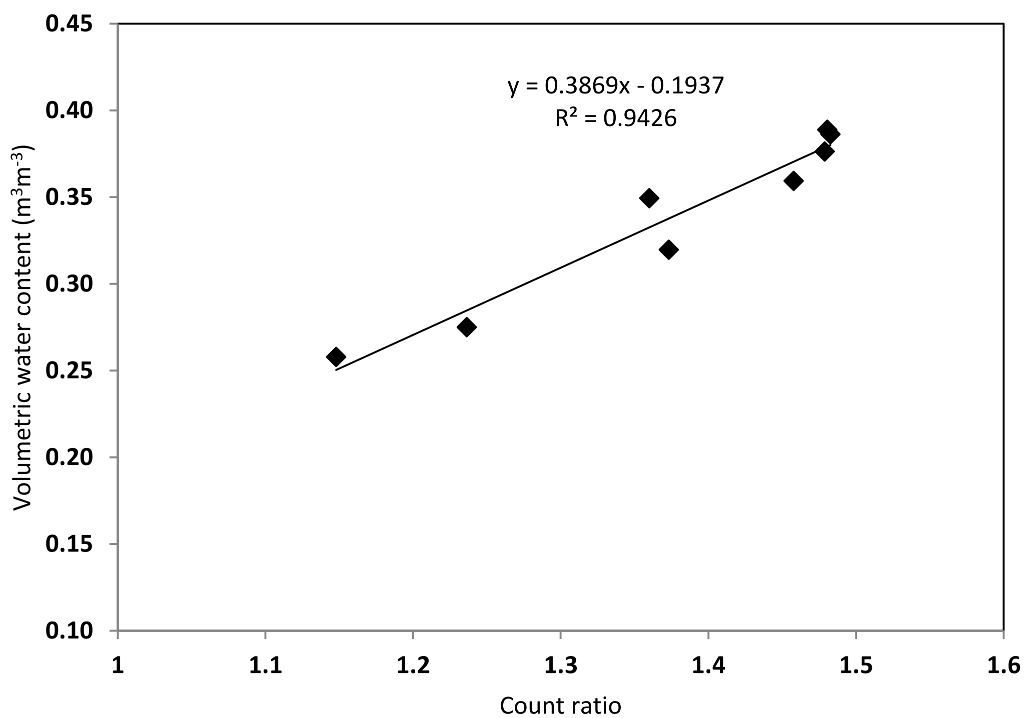

Figure 3.1: Neutron probe calibration curve used to calculate the volumetric soil water content from the count ratio.

$$SWC = 0.386CR - 0.193 \quad (4)$$

where SWC is soil water content ($m^3\ m^{-3}$) and CR count ratio.

The obtained SWC at different depths was used to calculate total soil profile water storage (mm) for the different treatments at 1m which is the limiting depth for the profile. It was also used to investigate whether maize crop got water stress as a result of dry spells which occurred during the growing season. Matric potential for maize water stress was taken as -500 cm as sugested by Taylor and Ashcroft, 1972. This information was used to calculate soil water deficit in the profile.

$$\int_0^{1000} SWC = 225 * SWC_{15cm} + 150 * SWC_{30cm} + 150 * SWC_{45cm} + 150 * SWC_{60cm} + 150 * SWC_{75cm} + 150 * SWC_{90cm} + 25 * SWC_{105cm} \quad (5)$$

3.6 Soil physical properties

3.6.1 Particle size distribution

Particle-size distribution was determined following the procedures outlined in Gee and Or (2002). After this process the silt and clay fractions were determined by the pipette method of Köhn. The percentages of the sand (>50 μm), silt (2-50 μm) and clay (<2 μm) were calculated on a dry weight basis. Textural classes were identified according to the USDA textural triangle, using USDA soil texture calculator (Saxton et al., 1986).

3.6.2 Soil water retention curve (SWRC)

Measurements of soil water content for the undisturbed samples were made at different matric potential as stipulated by Cornelis et al. (2005). For lower matric potential -1, -3,-5,-7 and -10 kPa, the sand box apparatus (Eijkelkamp Agrisearch Equipment, the Netherlands) was used. The rings were tied with a porous cloth and a rubber band at the lower side and its weight measured. The sandbox was then set on the different pressures per time and measurements were done until the weight of the sample become constant. After -10 kPa, the samples were subdivided into 3 sub samples for soil water content measurements at lower pressures of -33 kPa, -100 kPa and -1500 kPa using pressure chambers (Soilmoisture Equipment, Santa Barbara, CA, USA). The collected data enabled the construction of the soil water retention curve (SWRC) using the function of van Genuchten (1980) with $m = 1 - 1/n$. Total porosity (ψ = 0 kPa), matric porosity (MP, ψ = -10 kPa), field capacity (FC, ψ = -33 kPa), permanent wilting point (PWP, ψ = -1500 kPa), were then derived from the function, with ψ denoting matric potential. Soil dry BD was determined at -10 kPa matric potential. Finally, physical SQI were calculated as stipulated by Reynolds et al. (2007). To fit the van Genuchten equation, the RECT programme was used to obtain all the required parameters (θ_S, θ_r, α and n). To avoid obtaining negative fitted values, θ_r was set to zero (Dexter, 2004a) in equation 5 and 6.

$$\theta = \theta_r + (\theta_s - \theta_r)\ \left[\frac{1}{1+(\propto[h])^n}\right]^m \quad (6)$$

where θ is volumetric soil water content ($m^3\ m^{-3}$) at a given matric head, h (cm), θ_S is the volumetric soil water content at saturation ($m^3\ m^{-3}$), θ_r is the residual volumetric soil water content ($m^3\ m^{-3}$) and α (cm^{-1}) as well as the dimensionless *n* and *m* are curve fitting parameters.

3.6.3 *S* index

The *S* index (Dexter, 2004a) was calculated by fitting the soil water retention data to the mathematical model of van Genuchten (1980).

$$S = -n(w_s - w_r)x\ \left[\frac{2n-1}{n-1}\right]^{\left(\frac{1}{n}-2\right)} \quad (7)$$

where w_S is the gravimetric soil water content at saturation (kg kg−1); w_r is the residual gravimetric soil water content ($kg\ kg^{-1}$), and α (cm^{-1}) as well as the dimensionless *n* and *m* are parameters related to *h* and the curve's slope at its inflection point, respectively.

3.6.4 Aggregate stability

Aggregate stability was evaluated using two methods, i.e., laboratory measurements based on Yoder method modified by Kemper and Rosenau (1986) and a field method based on visual evaluation of the degree of fragmentation and dispersion of aggregates after immersion in water (Beste, 1999).

For the Yoder method modified by Kemper and Rosenau (1986), a wet sieving apparatus (Eijkelkamp Agrisearch Equipment, the Netherlands) was used. Both dry and wet sieving was done to determine the aggregate stability of the soil. This method is based on the fact that unstable aggregate disintegrate within the first 3 minutes when immersed in water. For wet sieving, the soil was air-dried and rewetted prior to sieving in deionized water using a single sieve (0.25 mm). Slow wetting of aggregates was performed on a tension table at a matric potential of –0.33 kPa for 30 minutes. For both dry and wet sieving, 1-2 mm air-dried aggregates were wet sieved in deionized water for 3 minutes at a constant, automatically controlled speed. After mechanical shaking, the soil sample that remained on the sieve (0.25 mm) was shaken again in a solution of sodium hydroxide until the aggregates were fully dispersed. This was in order to conduct the correction of sand fraction. Results were expressed as water stable aggregates (WSA):

$$\left(\frac{W_S}{W_S+W_U}\right) \text{X } 100 \quad (8)$$

where Ws is the stable soil aggregate fraction (g) and Wu is the unstable soil aggregate fraction (g).

Visual aggregate stability assessment was conducted by visually evaluating the degree of fragmentation and dispersion of aggregates after immersion in water (Beste, 1999). The ability of the aggregate to maintain its initial shape and size after immersion in water was assessed.

Three soil clods of 1–2 cm in diameter per plot were placed in a plastic plate which was then filled with water until the aggregates were completely immersed. Ten minutes after immersion of the aggregates the degree of fragmentation and dispersion was assessed. This evaluation was done with aggregates at sampling water content, near field capacity.

3.7 Chemical analysis

SOC was determined using wet oxidation method (Walkley and Black ,1934). One gram of air dried soil was weighed and put into a 500 ml erlenmeyer flask. 10 ml of $K_2Cr_2O_7$ was added in the flask and shaken. Then 20 ml of H_2SO_4 concetrated was added under an exhaust hood and left for 30 minutes. After 30 minutes, 150 ml of distilled H_2O was added. Then this was titrated with $FeSO_4$ untill the colour changes from green to reddish brown. Before the titration, 10 ml of H_3PO_4 and 6 drops of ferroine indicator were added. Calculation were then made for SOC from the used $FeSO_4$.

pH measurements were done by use of a pH meter Model 420. For pH water 10 grams of soil were weighed and put in a 100 ml beaker. 50 ml of distilled water were added. It was shaken and left to stand for 18 hours after which the pH was measured. For pH KCl, 10 grams of soil were put in a 50 ml flask. 25 ml of KCl was added, stirred and left for 10 minutes after which the pH was measured.

Total nitrogen and $\delta^{15}N$ was determined using ANCA-SL (Automated Nitrogen Carbon Analyser - Solids and Liquids) interfaced with a SerCon 20-20 IRMS while available phosphorus, potassium, calcium, magnesium and sodium were determined using Inductively Coupled Plasma (ICP) method (Thermo scientific, iCAP 6000 SERIES, ICP spectrometer).

3.8 Soil biological analysis

3.8.1 Soil microbial biomass

Soil microbial biomass was determined using the SOLVITA soil test method analysis kit (Woods End Laboratories, Inc. Mt. Vernon ME, USA). 100 g of soil was sampled and oven dried at 50 ^{o}C for 24 hours after which it was ground and sieved using 2 mm sieve size. 40 g of the dried soil was then put in perforated 50 ml plastic beaker which was placed in 250 ml glass jar. To bring the soils to full water capacity by capillary, 25 mm of de-ionised water was carefully put into glass jar and avoiding spilling it on the soil. Using plastic tweezers a CO_2-probe was carefully placed into the glass jar and the lid was screwed tightly. The jar was kept under stable room temperature conditions of 22-25^{o}C for 24 hrs. After 24 hours the color of the probe was read by inserting the Digital Color Reader in the glass jar which then gives the result in terms of ppm CO_2 C. The DRC number is converted to CO_2-C by using (Haney et al., 2008):

$$y = 20.6 * (Solvita\ number) - 16.5 \quad (9)$$

3.8.2 Biological index computation (V index)

Using the microbial data obtained from the different treatments, the biological index was computed by using the V index adapted from Wardle (1995) as:

$$V = \frac{2M_{AC}}{M_{AC}+M_{CC}} - 1 \quad (10)$$

with M_{AC} and M_{CC} = microbial biomass under alternative (conservation) and microbial biomass under conventional cropping system, respectively. The index V ranges from −1 (maximum inhibition: microbes occur only in conventional cropping system) to +1 (maximum stimulation:

microbes occur only in alternative cropping system). Zero represents equal values. This computation was also used by Henneron et al. (2014) using abundance of organisms' data.

3.9 Visual soil assessment (VSA)

Soil quality was evaluated in the field using visual soil assessment (VSA) by Shepherd (2000) in conjunction with the individual score of the soil structure using the VSA protocol, and the visual type of aggregates index (Moncada et al., 2014). According to this method, a soil block of 20 cm by 20 cm was extracted using a spade and a mattock since the soil was very clayey and obtaining an intact clod using the spade alone was difficult. The clod was then dropped in a plastic basin a maximum of three times from 1 m height.

This method enabled the assessment of key indicators soil texture, soil structure, soil porosity, number and colour of soil mottles, soil colour, earthworms, soil smell, potential rooting depth, surface ponding, surface cover, surface crusting, and soil erosion as described by Shepherd (2000). For soil structure, the dropped soil clod was arranged from big to small clods and compared with the reference photos as shown in Figure 3.2. For soil porosity, visible pores and any earthworm holes were considered.

With all the considered indicators, comparisons were made with the reference photos and scores assigned accordingly. Scores ranged from 0 to 2 indicating poor to good, respectively. Each indicator was given a VS of 0 (poor), 1 (moderate), 2 (good), or an in-between score (0.5 = moderately poor and 1.5 = moderately good) in respect to reference photos. The given scores were then weighted and final overall score for soil structural quality was obtained. Weighting was done according to the importance of the indicator in determing soil quality (Shepherd, 2000). Soil erosion received a wighting of one, surface crusting, soil smell, soil colour and number and colour of mottles received a weighting of two and the rest of the indicators received a weighting of three. To enable a good comparison, a virgin land and a degraded land within the study area were identified first and VSA was done for them to set the benchmark for score assigning in the other plots.

3.10 Crop yield

At harvest, yield in terms of grain mass and the above ground biomass of maize, beans and dolichos were measured from each plot. Two grids of 2 m^2 around the access tubes were harvested by cutting the above ground biomass when the plant had dried up. The total biomass and grain yield were weighed using a balance. The maize was harvested at physiological maturity when it had moisture content of about 13% measured using digital moisture meter (GMK-303**,** G-won Hitech Co., Ltd., Korea).

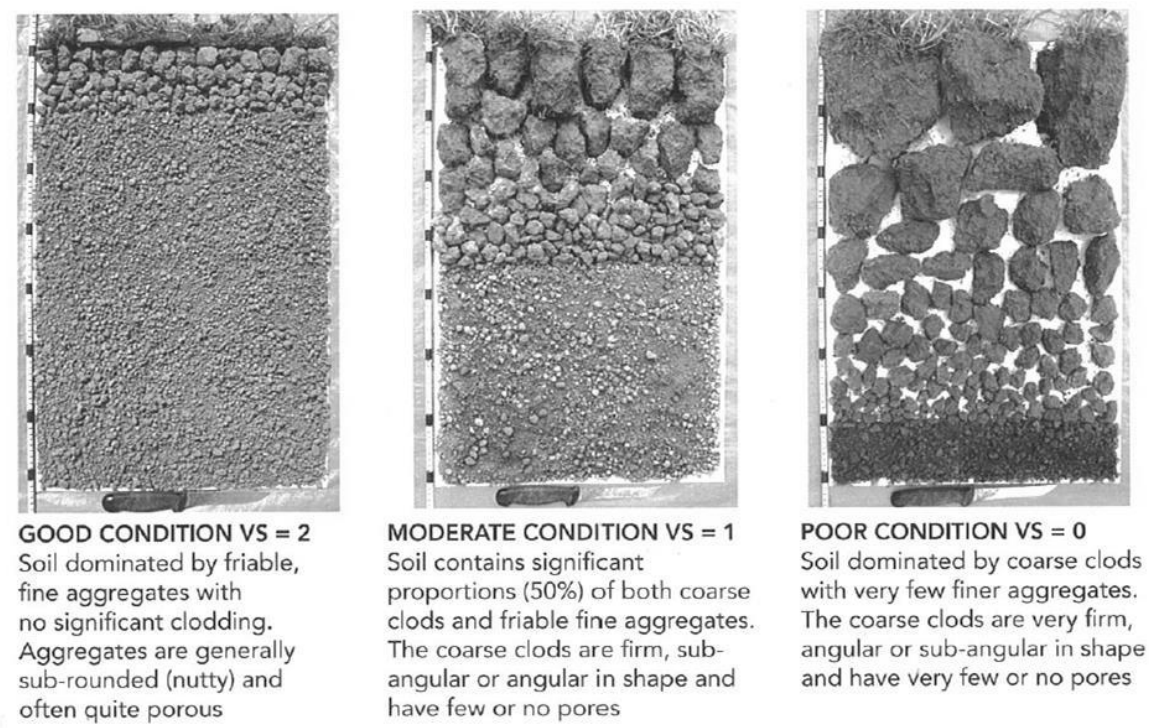

Figure 3.2: Visual scoring of the soil porosity using visual soil assessment method (Source: Shepherd, 2009).

3.11 Rain water use efficiency.

Rain water use efficiency (RWUE, kg ha^{-1} mm^{-1}) was calculated for the different plots of CA and CT. Total grain yield (TGY, in kg ha^{-1}) and total amount of rainfall (TR in mm) received during the entire growing season was used (Araya et al., 2012).

It was computed as:

$$RWUE = \frac{TGY}{TR} \tag{11}$$

3.12 Statistical analysis

Statistical analysis was performed using SPSS statistics Version 20 (IBM SPSS statistics). All the data were tested for normality and analyses of variances (ANOVA) conducted following the General Linear Model (GLM) procedure at a probability level of $P \leq 0.05$. Where significance was detected, means were compared using Tukey test. Lastly, the scores obtained in VSA method were correlated with the classical lab method to asses the validity of the VSA method. Correlation coefficients were calculated using Spearman's statistic for mean rank data. A criterion of $P<0.05$ was selected to represent statistical significance.

4. Results

4.1 Rainfall data

Monthly rainfall for 2014 and comparison with the 20-year mean (1994-2014) is shown in Figure 4.1.

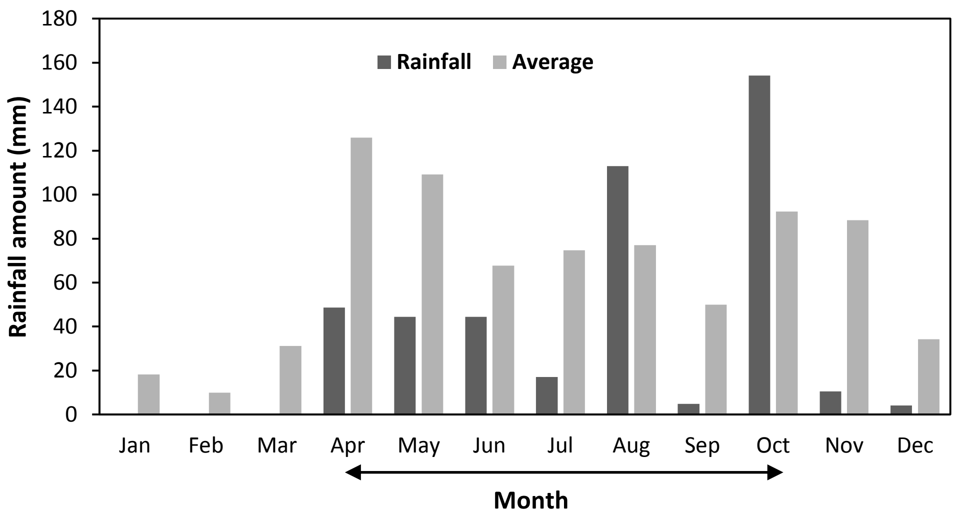

Figure 4.1: Comparison of monthly rainfall for 2014 with mean monthly rainfall (1994-2014) for Laikipia East sub county, Kenya. The arrow line shows the growing period.

Compared to the long-term annual mean (based on 20 years of data) of 751 mm, 2014 in which this study was conducted was a dry year with 417 mm. The return period and probability of exceedance for 2014's rain was 1.1 years and 92% respectively. A wet year is considered when the probability of exceedance is equal to or below 20%, i.e., above normal, whereas when it is equal to or exceeds 80% the year is considered as dry, i.e. below normal (Zinyengere et al., 2011).

4.2 Physical soil quality

4.2.1 Hydraulic conductivity (K_s)

There was a significant difference in K_s between the tillage practices. CT resulted in the highest K_s while NT resulted in the lowest (Figure 4.2). K_s was also significantly affected by intercropping and cover crops with BL resulting in the highest K_s and D showing the lowest. There was a significant interaction between tillage, intercropping and cover crops (p = 0.0001). CTBL showed the highest (29.9 cm day^{-1}) which was significantly different from the other treatments).

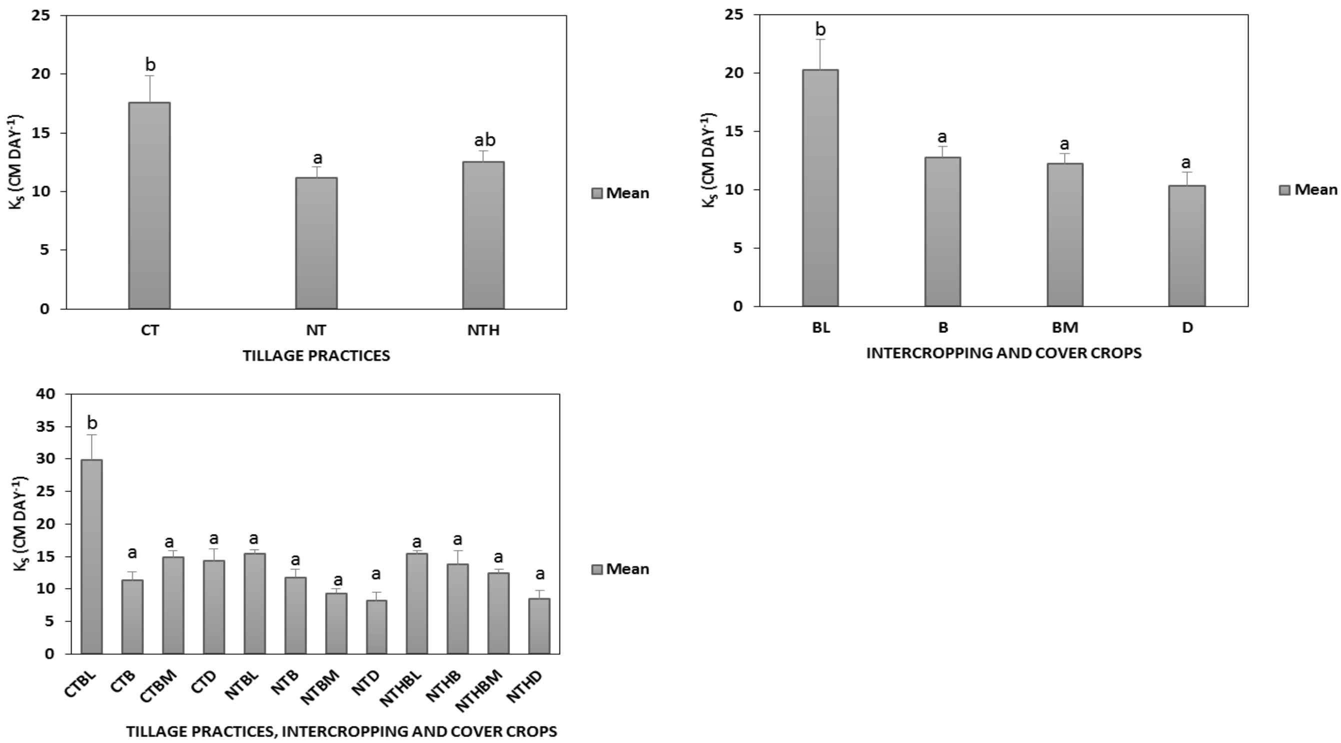

Figure 4.2: The effect of tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops (BL, bean and *leucaena*, B, bean, BM, bean and mulch, D, dolichos) on K_S. Means labeled with same letter are not significantly different. The error bars indicate standard errors about the mean.

4.2.2 Bulk density and parameters derived from water retention curve

There was no significant difference in bulk density (BD) of top (0-0.15m) and sub soil (0.15–0.30m) between the tillage practices (CT, NT, NTH), intercropping and cover crops (BL, B, BM, D) (Table 4.1 and 4.2). Though tillage practice, intercropping and cover crops had no significant effect on BD, CT and BL had slightly lower mean BD of 1.19 and 1.22 Mg m^{-3}, respectively, compared to the other treatments. There was no significant interaction observed between tillage, intercropping and cover crops (p = 0.351) in the top soil. In the sub soil, NT, B and BM resulted in slightly lower BD of 1.27, 1.28 and 1.28 Mg m^{-3}, respectively, as compared to other treatments.

No significant interaction was observed between the tillage, intercropping and cover crops ($p = 0.73$).

In the top soil there was no significant difference in field capacity (FC) between the tillage practices and between intercropping and cover crops (Table 4.1 and 4.2). There was no significant interaction observed between tillage, intercropping and cover crops ($p = 0.389$). In the sub soil, there was a significant difference in FC between the tillage practices with CT showing slightly lower water content (0.43 m^3 m^{-3}) as compared to NTH (0.47 m^3 m^{-3}). There was no significant difference in FC between intercropping and cover crops. There was no significant interaction between tillage, intercropping and cover crops ($p = 0.12$).

There was no significant difference in permanent wilting point (PWP) between the tillage practices and between intercropping and cover crops in the top soil (Table 4.1 and 4.2). Interaction between tillage, intercropping and cover crops was not significant as well in the top soil ($p = 0.223$). In the sub soil, however, a significant difference in PWP was observed between the tillage practices with CT resulting in a lower PWP (0.32 m^3 m^{-3}) as compared to NTH (0.36 m^3 m^{-3}). Cover crops in the sub soil did not show a significant effect on PWP. PWP was not significantly affected by the interaction between tillage, intercropping and cover crops ($p = 0.223$).

In both top and sub soil, plant available water capacity (PAWC) was not significantly affected by tillage and intercropping and cover crops (Table 4.1 and 4.2). Interaction between tillage, intercropping and cover crops in both top and sub soil was not significant ($p = 0.751$ and $p = 0.753$ respectively). The PAWC values for tillage, intercropping and cover crops and their interaction were not only non-significant, but were also below optimal values of 0.15 m^3 m^{-3}.

Both top and sub soil macroporosity MacPOR was not significantly affected by the tillage practices, intercropping and cover crops (Table 4.1 and 4.2). Tillage, intercropping and cover crops in the top and sub soil did not show any significant interaction ($p = 0.889$ and $p = 0.858$ respectively). However, CT and BL had slightly higher MacPOR. In the top soil, all tillage practices, intercropping and also cover crops resulted in values which fall within the optimal MacPOR range of 0.05–0.10 m^3 m^{-3}. The interaction between tillage, intercropping and cover crops had optimal MacPOR. Similarly, in the sub soil, tillage practices, intercropping and cover crops resulted in values which fall within the optimal range and all the interaction between tillage, intercropping and cover crops, except CTB, had optimal MacPOR values .

Table 4.1: Effect of tillage (conventional tillage CT, no tillage NT and no tillage with use of herbicides NTH) on top ($_T$) and sub ($_S$) soil bulk density (BD), field capacity (FP), permanent wilting point (PWP), plant available water content (PAWC), macro porosity (MacPOR), matric porosity (MatPOR), air capacity (AC) and relative water content (RWC). Means labeled with different letters are significantly different. P values indicated s and ns shows means that are significant or not, respectively.

Tillage	BD(Mg m^{-3})	FC (m^3 m^{-3})		PWP (m^3 m^{-3})		PAWC (m^3 m^{-3})	MacPOR (m^3 m^{-3})	MatPOR (m^3 m^{-3})	AC(m^3 m^{-3})	RWC(m^3 m^{-3})
CT_T	1.19±0.03	0.40±0.01		0.29±0.01		0.11±0.01	0.09±0.01	0.44±0.01	0.12±0.01	0.76±0.01
NT_T	1.28±0.03	0.43±0.02		0.32±0.01		0.11±0.01	0.07±0.01	0.48±0.01	0.11±0.01	0.80±0.02
NTH_T	1.26±0.01	0.43±0.01		0.32±0.01		0.11±0.01	0.07±0.01	0.49±0.01	0.12±0.01	0.78±0.02
P value	ns	ns		ns		ns	ns	ns	ns	ns
CT_S	1.32±0.02	0.43±0.02	a	0.32±0.01	a	0.11±0.01	0.07±0.01	0.47±0.01	0.11±0.01	0.79±0.01
NT_S	1.27±0.01	0.43±0.01	ab	0.34±0.01	ab	0.12±0.02	0.07±0.01	0.48±0.01	0.09±0.01	0.82±0.01
NTH_S	1.28±0.01	0.47±0.01	b	0.36±0.01	b	0.12±0.01	0.06±0.01	0.50±0.01	0.09±0.01	0.85±0.01
P value	ns	s		s		ns	ns	ns	ns	ns

Table 4.2: Effect of intercropping and cover crops (CC) (bean and *leucaena* BL, bean B, bean and mulch BM, dolichos D) on top ($_T$) and sub ($_S$) soil bulk density (BD), field capacity (FP), permanent wilting point (PWP), plant available water content (PAWC), macro porosity (MacPOR), matric porosity (MatPOR), air capacity (AC) and relative water content (RWC). P values indicated ns shows means that are not significantly different.

CC	BD(Mg m^{-3})	FC(m^3 m^{-3})	PWP(m^3 m^{-3})	PAWC(m^3 m^{-3})	MacPOR (m^3 m^{-3})	MatPOR (m^3 m^{-3})	AC(m^3 m^{-3})	RWC(m^3 m^{-3})
BL_T	1.22±0.03	0.41±0.01	0.30±0.02	0.11±0.01	0.09±0.01	0.45±0.02	0.13±0.01	0.75±0.02
B_T	1.23±0.04	0.44±0.01	0.31±0.01	0.12±0.01	0.07±0.01	0.47±0.01	0.10±0.01	0.81±0.02
BM_T	1.24±0.03	0.42±0.02	0.31±0.01	0.11±0.02	0.06±0.01	0.48±0.01	0.12±0.01	0.78±0.02
D_T	1.28±0.03	0.41±0.01	0.30±0.01	0.11±0.01	0.08±0.01	0.45±0.01	0.12±0.01	0.77±0.01
P value	ns	ns	ns	ns	ns	ns	ns	ns
BL_S	1.29±0.02	0.43±0.01	0.32±0.01	0.11±0.01	0.08±0.01	0.46±0.01	0.12±0.01	0.79±0.02
B_S	1.28±0.01	0.46±0.01	0.35±0.01	0.120±0.02	0.06±0.01	0.49±0.01	0.09±0.01	0.84±0.02
BM_S	1.28±0.02	0.46±0.01	0.35±0.01	0.11±0.02	0.06±0.01	0.49±0.02	0.08±0.01	0.84±0.01
D_S	1.31±0.02	0.45±0.02	0.34±0.01	0.11±0.01	0.06±0.01	0.49±0.01	0.09±0.01	0.82±0.02
P value	ns	ns	ns	ns	ns	ns	ns	ns

Different tillage practices and intercropping and cover crops did not show any significant difference in air capacity (AC) of both top and sub soil (Table 4.1 and 4.2). There was no significant interaction between tillage, intercropping and cover crops in both top and sub soil ($p = 0.603$ and $p = 0.614$ respectively). In the top soil, all tillage practices and intercropping and cover crops had optimal AC ≥ 0.10 $m^3 m^{-3}$. Table 4.1 shows that AC values due to interaction between tillage, intercropping and cover crops in the top soil achieved were optimal, except NTB and NTBM. Tillage, intercropping and cover crops in the sub soil resulted in below optimal values, except CT, BL and D, which had optimal AC values. AC due to interaction between tillage, intercropping and cover crops was below the optimal, except for CTBL, CTB, CTD, NTB and NTHBL, which had optimal values.

Table 4.1 and 4.2 shows that tillage, intercropping and cover crops and their interaction had no significant effect on relative water capacity (RWC) in both top and sub soils and all the RWC values in these treatments were above the optimal range (0.6-0.7 m^3m^{-3}) found in the literature.

4.2.3 Aggregate stability

In the top soil, there was a significant difference in percentage of dry water stable aggregates (from dry sieving, $\%WSA_D$) between the tillage practices. CT had the lowest $\%WSA_D$ (55.07) compared to NT (64.88). Intercropping and cover crops did not affect $\%WSA_D$ significantly (Table 4.3 and 4.4). Interaction between tillage, intercropping and cover crops was not significant ($p = 0.409$). In the sub soil, there was no significant difference in $\%WSA_D$ between tillage practices and also between intercropping and cover crops. There was no significant effect of interaction between tillage, intercropping and cover crops on $\%WSA_D$ ($p = 0.457$). All the tillage practices produced $\%WSA_D$ above the lower limit of 50% WSA suggested by Pulido et al. (2013) with CT in the top soil resulting in the lowest %WSA of 55.

There was no significant difference on percentage of wet water stable aggregates (from wet sieving, $\%WSA_W$) in the top soil between the tillage practices and cover crops (Table 4.3 and 4.4). However CT showed the lowest $\%WSA_W$ (90.69). There was no significant effect of interaction between tillage, intercropping and cover crops on $\%WSA_W$ ($p = 0.656$). In the sub soil, $\%WSA_W$ was not significantly affected by tillage practices. However, intercropping and cover crops had significant effect on $\%WSA_W$. Significant differences were observed between B and D, with D resulting in the lowest $\%WSA_W$ (90.85) as compared to B (94.00 $\%WSA_W$). There was no significant effect of interaction between tillage, intercropping and cover crops on $\%WSA_W$ ($p = 0.105$). All the tillage practices resulted in % WSA that was higher than the upper limit value of 70% WSA suggested by Pulido et al. (2013).

In top soil, there was a significant difference in %WSA between dry and wet sieving results from interaction between tillage, intercropping and cover crop with wet sieving resulting in a much higher %WSA (91.43) and dry sieving resulting in a much lower %WSA (59.43). A similar trend was observed in the sub soil where a significant difference in %WSA between wet (92.29) and dry (65.82) sieving results from interaction between tillage, intercropping and cover crops was also observed.

4.2.4 Structural stability index

Structural stability index (StI) in the top soil was significantly affected by tillage practice with CT resulting in the lowest StI (3.4) as compared to NT and NTH (3.9 and 4.2, respectively) (Table 4.3). Intercropping and cover crops had a significant effect on StI with BM showing significantly higher StI (4.5) as compared to D (3.4) (Table 4.4). There was a significant interaction observed between tillage, intercropping and cover crops ($p = 0.001$) with NTHBM having higher StI compared to other treatments. In the sub soil, tillage practice had a significant effect on StI with NTH resulting in the highest value (4.3) (Table 4.3). StI was also significantly affected by intercropping and cover crops with BM resulting in a high value (4.4) (Table 4.4). A significant interaction between tillage, intercropping and cover crops was observed ($p = 0.001$). All treatments in the top and sub soil fall below the critical values of 5 as suggested by Reynolds et al. (2007).

4.2.5 *S* index

Tillage, intercropping and cover crops did not significantly affect the *S* index in both top and sub soil. As the case with tillage, intercropping and cover crops, there was no significant effect on *S* index due to their interaction both in top and sub soil ($p = 0.762$ and $p = 0.721$, top and sub soil respectively). However, interaction between tillage, intercropping and cover crops of NTBL and NTBM in the top soil and NTHBM in the sub soil had slightly higher *S* index compared to the other treatments. All the treatments had *S* index above the optimal value of 0.035. Table 4.5 shows the *S* index and van Genuchten parameters used to calculate it.

Table 4.3: Effect of tillage (conventional tillage CT, no tillage NT and no tillage with use of herbicides NTH) on top ($_T$) and sub ($_S$) % dry water stable aggregates (% WSA_D), % wet water stable aggregates (%WSA_W) and structural stability index (StI). Means labeled with different letters are significantly different. P values indicated s and ns shows means that are significant or not, respectively.

Tillage	**%WSA_D**	**%WSA_W**	**StI [-]**
CT_T	55.07±2.76 a	90.69±0.87	3.4±0.18 a
NT_T	64.88±2.06 b	91.96±0.60	3.9±0.11 ab
NTH_T	58.79±3.36 ab	91.62±0.66	4.2±0.20 b
P value	s	ns	s
CT_S	60.73±2.53	92.47±0.61	3.5±0.19 a
NT_S	68.06±2.61	92.80±0.65	3.9±0.15 ab
NTH_S	68.81±2.68	91.58±0.75	4.3±0.24 b
P value	ns	ns	s

Table 4.4: Effect of intercropping and cover crops (CC) (bean and *leucaena* BL, bean B, bean and mulch BM, dolichos D) on top ($_T$) and sub ($_S$) soil % dry water stable aggregates (% WSA_D), % wet water stable aggregates (%WSA_W) and structural stability index (StI). P values indicated ns shows means that are not significantly different.

Cover crops	**%WSA_D**	**%WSA_W**	**StI [-]**
BL_T	62.25±2.63	91.62±0.70	3.9±0.20 ab
B_T	57.85±3.38	91.74±0.88	3.4±0.16 a
BM_T	57.13±4.04	90.47±0.86	4.5±0.25 b
D_T	61.08±3.69	91.87±0.93	3.4±0.21 a
P value	ns	ns	s
BL_S	63.9±3.50	92.33±0.64 ab	4.3±0.19 bc
B_S	66.80±3.68	94.00±0.61 b	3.5±0.22 ab
BM_S	65.88±2.51	92.01±0.71 ab	4.4±0.23 c
D_S	66.80±3.36	90.85±0.84 a	3.3±0.18 a
P value	ns	s	s

4.3 Soil chemical quality

The pH H_2O and KCl in both top and sub soil were not significantly influenced by different tillage and intercropping and cover crops (Table 4.6 and 4.7). No significant interaction between tillage, intercropping and cover crops was observed in top soil for pH H_2O and KCl (P = 0.680 and P = 0.314 respectively) and sub soil for pH H_2O and KCl (p = 0.643 and p = 0.827 respectively). Even though there was no significant difference in pH, generally the sub soil in all the treatments had a slightly higher pH as compared to top soil and pH H_2O was higher than pH KCl.

Table 4.5: The effect of interaction between tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops capacity (BL, bean and *leucaena*, B, bean, BM, bean and mulch, D, dolichos) on top ($_T$) and sub ($_S$) soil *S* index and van Genuchten (1980) parameters. The values of θs, α, and *n* were calculated using the constraint $m = 1 - 1/n$ and the residual water content (θr) was fitted to zero. Parameters were obtained from RECT programme.

Tillage practice	Cover crops	S_T index[-]	θ_{ST} (kg kg^{-1})	α_T(cm^{-1})	n_T [-]	S_S index [-]	θ_{SS} (kg kg^{-1})	α_S (cm^{-1})	n_S [-]
CT	BL	0.071	0.5570	0.0007	1.4015	0.058	0.4997	0.0250	1.3508
	B	0.080	0.5580	0.0127	1.3677	0.086	0.5084	0.0022	1.6972
	BM	0.068	0.5473	0.0086	1.2814	0.064	0.5077	0.0193	1.4717
	D	0.075	0.5513	0.0029	1.4609	0.055	0.4976	0.0168	1.3723
NT	BL	0.117	0.5519	0.0034	1.6993	0.058	0.5142	0.0074	1.2858
	B	0.057	0.5287	0.0107	1.2522	0.090	0.5256	0.0793	1.6611
	BM	0.107	0.5068	0.0038	1.6979	0.088	0.5357	0.0136	1.9516
	D	0.041	0.4854	0.0058	1.2406	0.038	0.5098	0.0252	1.1641
NTH	BL	0.047	0.5550	0.0188	1.2159	0.068	0.5308	0.0495	1.3718
	B	0.070	0.5216	0.0140	1.4360	0.115	0.5193	0.0023	1.6525
	BM	0.096	0.5363	0.0057	1.8077	0.164	0.5078	0.0090	2.4325
	D	0.078	0.5188	0.0199	1.4789	0.099	0.5100	0.0020	1.7585

Organic carbon (OC) content in the top soil was significantly affected by tillage practice. CT resulted in the lowest amount of OC (14.9 g kg^{-1}) as compared to NT and NTH (17.5 and 18.8 g kg^{-1}, respectively) (Table 4.6). Intercropping and cover crops had a significant effect on OC with BM having significantly higher OC (20.2 g kg^{-1}) than the other cover crops (Table 4.7). There was a significant interaction observed between tillage, intercropping and cover crops ($p = 0.0001$), with NTHBM and NTHBL having higher OC than the other treatments. Tillage practice had a significant effect on OC in the sub soil with NTH resulting in the highest OC (19.1 g kg^{-1}) (Table 4.6). OC was significantly affected by intercropping and cover crops with BM resulting to a high value (19.6 g kg^{-1}) (Table 4.7). A significant interaction between tillage, intercropping and cover crops was observed ($p = 0.001$). All treatments in the top and sub soil fall below the critical values of 2.30 g kg^{-1}, except NTBM and NTHBM which were slightly above this value.

Total N in the top soil was not significantly affected by tillage nor by intercropping and cover crops. However, NTH and D had slightly higher N contents, 0.16 and 0.16 ppm, respectively (Table 4.6 and 4.7). No significant interaction on N was found between tillage, intercropping and cover crops ($p = 0.883$).

Table 4.6: Effect of tillage (conventional tillage CT, no tillage NT and no tillage with use of herbicides NTH) on top ($_T$) and sub ($_S$) soil pH (H_2O and KCl), organic carbon OC, total nitrogen N, delta 15 values $\delta^{15}N$ and available phosphorus P. Means labeled with different letters are significantly different. P values indicated s and ns shows means that are significant or not, respectively.

Tillage practice	**pH H_2O**	**pH KCl**	**OC (g kg^{-1})**	**N (ppm)**	**$\delta^{15}N$ (‰)**	**P (ppm)**
CT_T	6.5±0.1	4.7±0.2	14.9±0.7 a	0.15±0.01	7.9±0.2	11.84±2.24
NT_T	6.6±0.1	5.0±0.1	17.5±0.5 ab	0.15±0.02	7.9±0.2	8.76±2.26
NTH_T	6.6±0.1	4.8±0.2	18.8±1.2 b	0.16±0.01	7.8±0.2	8.33±1.87
P value	ns	ns	s	ns	ns	ns
CT_S	6.6±0.1	4.8±0.2	14.8±0.7 a	0.15±0.01 b	8.1±0.2	6.25±1.48
NT_S	6.7±0.1	4.9±0.1	18.1±0.7 b	0.13±0.01 ab	7.7±0.2	9.56±3.40
NTH_S	6.7±0.1	5.0±0.1	19.1±1.1 b	0.12±0.01 a	7.6±0.2	8.35±2.84
P values	ns	ns	s	s	ns	ns

Table 4.7: Effect of intercropping and cover crops (bean and *leucaena* BL, bean B, bean and mulch BM, dolichos D) on top ($_T$) and sub ($_S$) soil pH (H_2O and KCl, organic carbon OC, total nitrogen N, delta 15 values $\delta^{15}N$ and available phosphorus P. Means labeled with different letters are significantly different. P values indicated s and ns shows means that are significant or not, respectively.

Cover crops	**pH H_2O**	**pH KCl**	**OC (g kg^{-1})**	**N (ppm)**	**$\delta^{15}N$(‰)**	**P (ppm)**
BL_T	6.6±0.1	4.9±0.1	17.8±0.9 ab	0.15±0.01	8.0±0.2	9.34±2.19
B_T	6.7±0.1	5.1±0.2	15.0±0.7 a	0.14±0.01	7.6±0.2	11.10±2.48
BM_T	6.5±0.1	4.5±0.2	20.2±1.2 b	0.15±0.01	8.0±0.3	8.86±2.45
D_T	6.0±0.1	4.7±0.1	15.2±0.8 a	0.16±0.01	7.9±0.1	8.86±2.98
P value	ns	ns	s	ns	ns	ns
BL_S	6.7±0.1	5.0±0.1	19.1±0.9 b	0.14±0.01	7.8±0.2	11.65±4.38
B_S	6.8±0.1	5.1±0.2	15.8±1.0 ab	0.14±0.01	7.8±0.3	7.83±1.63
BM_S	6.7±0.1	4.9±0.1	19.6±1.1 b	0.13±0.01	7.9±0.1	5.03±1.29
D_S	6.5±0.1	4.7±0.1	14.8±0.8 a	0.14±0.01	7.9±0.2	8.11±3.80
P value	ns	ns	s	ns	ns	ns

In the subsoil, N was significantly affected by tillage practices with CT resulting in the highest N content (0.15) (Table 4.6). Intercropping and cover crops did not significantly affect N content (table 4.7). N was not significantly affected by interaction between tillage, intercropping and cover crops (p = 0.618).

Values for $\delta^{15}N$ ranged from +7.1 to +8.4 per mil (‰). There was no significant difference in $\delta^{15}N$ values observed between tillage, intercropping and cover crops, both in top and sub soil (Table 4.6 and 4.7). However, $\delta^{15}N$ values under CT in the sub soil were slightly higher (8.1‰) than in NT and NTH. $\delta^{15}N$ values were not significantly affected by interaction between tillage, intercropping and cover crops in top and sub soil (p= 0.933 and p= 0.858, respectively).

Available P, both in the top and sub soil, was not significantly affected by tillage and intercropping and cover crops (Table 4.6 and 4.7). Interaction between tillage, intercropping and cover crops had no significant effect on P both in the top and sub soil (p = 0.883 and p = 0.811, respectively).

Exchangeable K^+, Ca^{2+}, Mg^{2+}, Na^+, both in the top and sub soil, were not significantly affected by tillage practice, intercropping and cover crops (Table 4.8 and 4.9). Interaction between tillage, intercropping and cover crops had no significant effect on these elements both in the top and sub soil.

4.4 Soil biological quality

In the top soil and sub soil, there was a significant difference in soil microbial biomass carbon (SMBC) between tillage practices (Table 4.8). CT showed significantly the lowest SMBC compared to NT which had the highest SMBC. There was no significant effect on SMBC due to intercropping and cover crops both in top and sub soil (Table 4.9) but BM resulted in slightly higher SMBC as compared to the other treatments in both top and sub soil.

In both top and sub soil, comparing CT versus NT, and CT versus NTH, intercropping and cover crops resulted in positive values of V index except D which showed negative values (Table 4.10).

Table 4.8: Effect of tillage (conventional tillage CT, no tillage NT and no tillage with use of herbicides NTH) on top ($_T$) and sub ($_S$) soil exchangeable potassium K^+, Calcium Ca^{2+}, Magnesium Mg^{2+}, sodium Na^+ and soil microbial biomass carbon SMBC. Means labeled with different letters are significantly different. P values indicated s and ns shows means that are significant or not, respectively.

Tillage practice	**K^+(cmol kg^{-1})**	**Ca^{2+}(cmol kg^{-1})**	**Mg^{2+}(cmol kg^{-1})**	**Na^+ (cmol kg^{-1})**	**SMBC (ppm)**
CT_T	1.0±0.1	19.3±1.5	4.9±0.2	0.4±0.1	966 a
NT_T	1.0±0.1	18.6±0.8	5.3±0.2	0.5±0.1	1581 b
NTH_T	1.1±0.1	18.3±1.2	5.3±0.3	0.5±0.1	1206 ab
P value	ns	Ns	ns	ns	s
CT_S	0.9±0.1	19.2±1.6	5.3±0.3	0.6±0.1	845 a
NT_S	1.0±0.1	19.5±1.0	5.5±0.2	0.6±0.1	1435 b
NTH_S	1.0±0.1	20.6±0.8	5.7±0.2	0.7±0.1	1095 ab
P value	ns	ns	ns	ns	s

Table 4.9: Effect of intercropping and cover crops (bean and *leucaena* BL, bean B, bean and mulch BM, dolichos D) on top ($_T$) and sub ($_S$) on soil exchangeable potassium K^+, Calcium Ca^{2+}, Magnesium Mg^{2+}, sodium Na^+ and soil microbial biomass carbon SMBC. P values indicated ns shows means that are not significant.

Tillage practice	**K^+(cmol kg^{-1})**	**Ca^{2+}(cmol kg^{-1})**	**Mg^{2+}(cmol kg^{-1})**	**Na^+ (cmol kg^{-1})**	**SMBC (ppm)**
BL_T	0.9±0.1	17.9±1.7	5.0±0.3	0.4±0.1	1197
B_T	1.0±0.1	19.9±1.7	5.1±0.2	0.4±0.1	1069
BM_T	1.2±0.1	19.2±1.1	5.5±0.3	0.6±0.1	1575
D_T	1.0±0.1	17.9±1.2	5.0±0.3	0.5±0.1	1137
P value	ns	ns	ns	ns	ns
BL_S	1.1±0.1	19.8±1.7	5.5±0.3	0.5±0.1	1080
B_S	1.1±0.1	20.9±1.7	5.5±0.2	0.5±0.1	986
BM_S	0.9±0.1	19.0±1.1	5.5±0.3	0.7±0.1	1406
D_S	1.0±0.1	19.01±0.7	5.6±0.2	0.7±0.1	1026
P value	ns	ns	ns	ns	ns

4.5 Soil water content

The soil water storage results presented belong to only two periods of the growing season. One during the first month of the growing season (between 5th and 28th May), representing 13 days of maize crop establishment stage and 11 days of vegetative stage, and a second during the fourth month of the growing period (between 1st and 29th August), representing 29 days of yield formation stage.

Table 4.10: Effect of tillage (conventional tillage CT, no tillage NT and no tillage with use of herbicides NTH), and intercropping and cover crops,(bean and *leucaena* BL, bean B, bean and mulch BM, dolichos D) on top ($_T$) and sub ($_S$) soil V index presented as CT versus NT and NTH. Positive values indicate more SMBC under NT or NTH while negative values indicate more SMBC under CT.

Cover crops	**Tillage practice**			
	CT_T versus:		CT_S versus:	
	NT_T	NTH_T	NT_S	NTH_S
BL	0.22	0.09	0.27	0.13
B	0.22	0.09	0.25	0.11
BM	0.31	0.25	0.31	0.28
D	0.20	-0.05	0.19	-0.07

During the first period, soil water storage was not significantly affected by tillage practice or by intercropping and cover crops. However, NT resulted in slightly higher water storage (340 mm) as compared to CT (336mm) and BM showed slightly higher water storage (342 mm) as compared to B (331 mm). Even though interaction between tillage, intercropping and cover crop did also not affect water storage, NTHBM resulted in the highest water storage (355 mm) as compared to the other treatments.

Water storage during the second period was also not significantly affected by tillage practice or by intercropping and cover crops. However, CT showed the lowest water storage (277 mm) as compared to NT and NTH both resulting in similar value (285 mm) and BM showed higher water storage (286 mm) compared to B (275 mm). Water storage was not affected significantly by interaction between tillage, intercropping and cover crops but NTBM showed higher water content (297 mm) compared to the other treatments.

Looking at the two periods, NTBM and NTHBM showed significantly higher water storage during intra dry spell as compared to other treatments (figure 4.3) and more prominent during maize yield formation stage. Table 4.11 and 4.12 shows the calculated water deficit during the two periods. In the first period, water deficit was not significantly affected by tillage nor by intercropping and cover crops but CT resulted in the highest water deficit (-99.1 mm) as compared to NTH which showed the lowest (-42.3 mm). During the second period, yield formation stage, water deficit was significantly affected by tillage practice with CT showing the highest (-143.8 mm) and NTH the lowest (-71.3 mm). Intercropping and cover crops did not affect water deficit significantly.

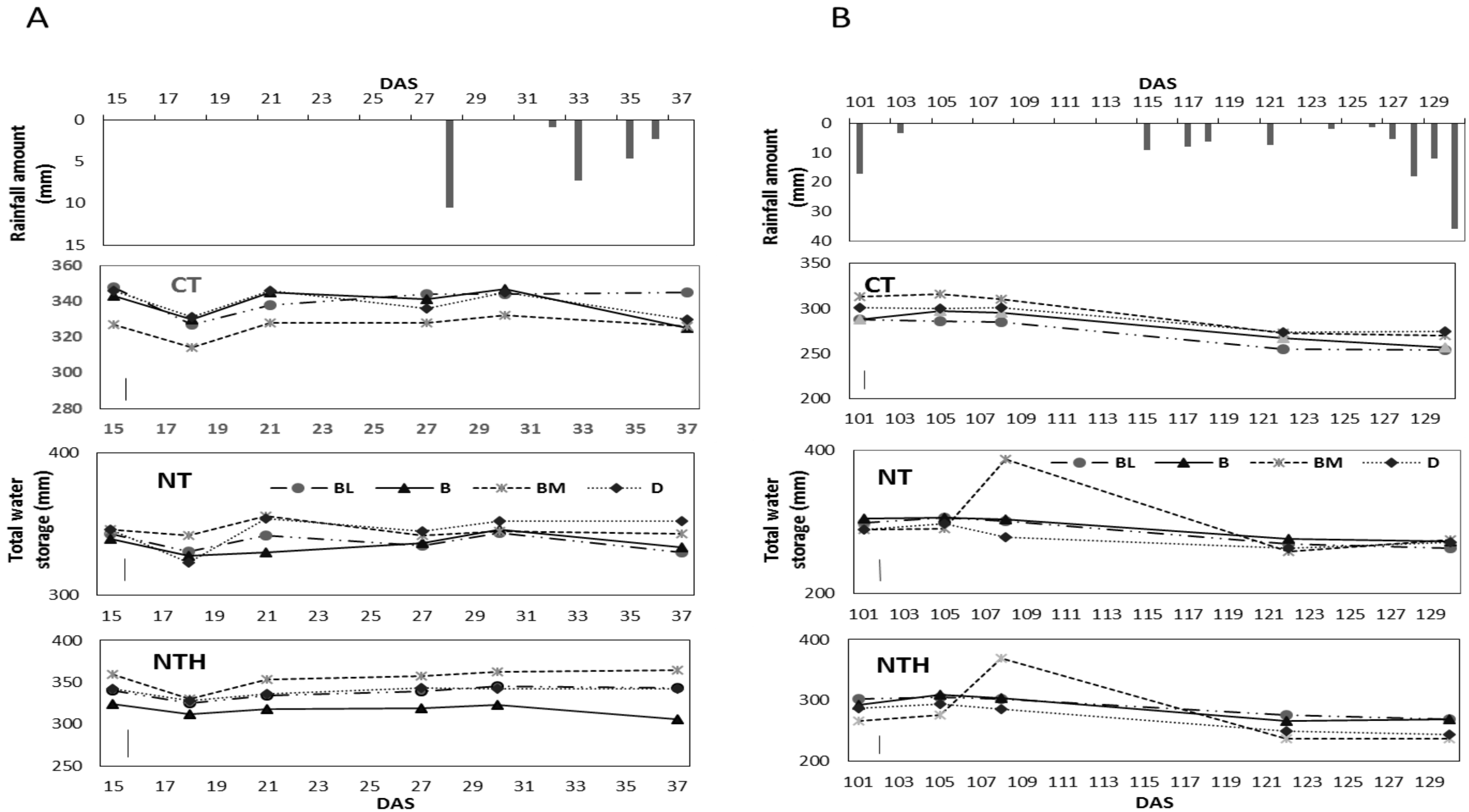

Figure 4.3: The effect of tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops (BL, bean and *leucaena*, B, bean, BM, bean and mulch, D, dolichos) on total soil water storage for period A, May (crop establishment stage) and period B, August (yield formation stage) shown as days after sowing (DAS). Rainfall amount for the two periods is also shown. Vertical bars represent LSD (5%) values.

Table 4.11: Effect of tillage (conventional tillage CT, no tillage NT and no tillage with use of herbicides NTH) on maize crop yield and soil water deficit for the month of May (crop establishment stage) and August (yield formation stage). Means labeled with different letters are significantly different. P values indicated s and ns shows means that are significant or not, respectively**.**

Tillage practice	**Water deficit (mm)**		**Yield (kg ha^{-1})**
	May	**August**	
CT	- 90.1	-143.8 a	1688 a
NT	- 63.2	- 91.7 ab	2260 b
NTH	- 42.3	- 71.3 b	2380 b
P value	ns	s	s

Table 4.12: The effect of intercropping and cover crops (bean and *leucaena* BL, bean B, bean and mulch BM, dolichos D) on maize crop yield and soil water deficit for the month of May (crop establishment stage) and August (yield formation stage). Means labeled with different letters are significantly different. P values indicated s and ns shows means that are significant or not, respectively**.**

Cover crops	**Water deficit (mm)**		**Yield (kg ha^{-1})**
	May	**August**	
BL	- 63.6	-98.6	2217
B	- 59.6	- 102.7	1860
BM	- 75.5	- 92.6	2327
D	- 68.5	- 115.2	2024
P value	ns	ns	ns

4.6 Visual soil assessment (VSA)

Scores for different soil indicators were given according to the score card photographs. Only scores for structure, porosity, soil color and overall score were different between treatments (Table 4.13). The others indicators had the same score for all treatments.

In the top soil, structure score from VSA method had a negative correlation with BD and measured total porosity (r = -0.38 and r=-0.39 respectively,) and a positive strong correlation with the overall score from VSA method (r=0.59) (Table 4.14). In the sub soil, structure score was only positively correlated with the overall score from VSA (r=0.58). Total porosity from VSA showed a weak positive correlation with the *S* index as well as with overall score from VSA (r=0.42 and r=0.42, respectively) while in the sub soil, total porosity score had a weak positive correlation with overall VSA score (r=0.42). Soil color in the top soil had a positive correlation with BD, total (lab) porosity and the overall score (r of 0.46, 0.47 and 0.35, respectively), while in the sub soil it was only correlated with overall score (r=0.36) (Table 4.12).

The overall score from VSA apart from its correlation with structure score, total porosity score and soil color as mentioned above also showed a strong negative correlation with BD and a strong positive correlation with measured total (lab) porosity (r of -0.60 and 0.60). In the sub soil, the overall VSA score had a positive correlation with porosity score and structure score (r of 0.42and 0.59, respectively).

4.7 Yield

Maize yield was significantly affected by the tillage practices with CT resulting in the lowest maize yield (1688 kg ha^{-1}) compared to NTH (2380 $kgha^{-1}$) which had the highest yield (Table 4.11). There was no significant difference in maize yield between intercropping and cover crops (Table 4.12). There was a significant effect of interaction between tillage, intercropping and cover crops on maize yield ($p= 0.008$). NTBM showed the highest yield (2633 kg ha^{-1}) and CTB the lowest yield (1523 kg ha^{-1}).

4.8 Rain water use efficiency (RWUE)

Tillage had significant effect on RWUE with CT resulting in a lower RWUE (6.26 kg ha^{-1} mm^{-1}) compared to NT and NTH (8.38 and 8.83 kg ha^{-1} mm^{-1}, respectively). RWUE was not significantly affected by intercropping and cover crops (Figure 4.4). There was a significant effect on RWUE by interaction between tillage, intercropping and cover crops ($p= 0.008$).

Table 4.13: Summary of the visual scores given to the indicators of the Visual Soil Assessment (VSA) method for each treatment showing interaction between tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops capacity (BL, bean and leucaena, B, bean, BM, bean and mulch, D, dolichos).

					Visual indicator of soil quality					
Tillage	Cover crop	Soil texture	Soil structure	Soil porosity	Color of soil mottles	Soil color	Earthworms numbers	Soil smell	Surface condition	Overall score
CT	BL	1.5	1.3±0.1	1.0±0.0	2	1.2±0.1	0	2	2	41.0±1.2
	B	1.5	1.3±0.3	1.3±0.1	2	1.2±0.2	0	2	2	38.3±1.3
	BM	1.5	1.5±0.2	1.5±0.2	2	1.0±0.0	0	2	2	39.0±2.1
	D	1.5	1.0±0.0	1.5±0.0	2	1.5±0.2	0	2	2	38.5±0.2
NT	BL	1.5	1.2±0.4	1.2±0.1	2	1.5±0.2	0	2	2	40.5±2.3
	B	1.5	1.2±0.0	0.8±0.1	2	1.0±0.0	0	2	2	34.5±1.3
	BM	1.5	0.8±0.1	1.3±0.1	2	1.2±0.3	0	2	2	37.8±0.8
	D	1.5	1.2±0.4	1.2±0.1	2	0.8±0.1	0	2	2	37.1±1.0
NTH	BL	1.5	0.8±0.3	0.8±0.1	2	1.0±0.2	0	2	2	36.5±1.2
	B	1.5	0.7±0.1	1.2±0.1	2	1.1±0.2	0	2	2	36.3±0.8
	BM	1.5	1.0±0.2	1.3±0.1	2	1.7±0.1	0	2	2	39.3±1.3
	D	1.5	1.0±0.0	1.2±0.1	2	1.2±0.1	0	2	2	36.3±1.4

Score description: average from ≥ 0 - ≤ 0.5 (condition from poor to moderately poor); 1 = average from > 0.5 - < 1.5 (condition from moderately poor to moderately good); 2 = average from ≥ 1.5 - 2 (condition from moderately good to good). Overall score: ≥ 0 - ≤ 20 (poor soil quality); > 20 - < 37 (moderate soil quality); > 37 (good soil quality).

Table 4.14: Correlation coefficient between scores of the field assessment methods and soil physical parameters of soil quality

VSA scores	OC	BD	WSA_D	WSA_W	PAWC	Lab porosity	Porosity VSA score	KS	Overall VSA score	*S* index
Soil structure $_T$	-0.17	-0.38*	0.02	0.01	0.02	0.39*	0.11	0.12	0.59**	-0.03
Soil porosity $_T$	-0.12	-0.31	-0.21	-0.03	-0.15	0.30	0.23	-0.19	0.42*	0.42*
Soil color $_T$	0.09	-0.46*	0.11	-0.06	0.18	0.47*	0.20	0.11	0.35*	0.09
Overall VSA score $_T$	0.09	-0.60**	-0.05	0.10	-0.03	0.61**	0.58**	0.22	1	0.27
Soil structure $_S$	-0.25	-0.09	-0.26	-0.11	0.08	0.08	0.11	0.12	0.58**	-0.22
Soil porosity $_S$	-0.30	-0.18	-0.30	-0.07	-0.11	-0.18	0.42	-0.19	0.42*	0.06
Soil color $_S$	0.03	0.11	-0.18	-0.18	0.19	-0.10	0.20	0.08	0.36*	0.20
Overall VSA score $_S$	-0.33	-0.04	-0.40*	0.03	0.12	0.05	-0.21	0.21	1	-0.21

$_T$ = top soil; $_S$ = sub soil, OC = organic carbon; BD = bulk density; WSA_D = dry water stable aggregates; WSA_W = wet water stable aggregates; PAWC = plant available water capacity; K_S= saturated hydraulic conductivity; **Correlation is significant at the 0.01 level (2- tailed). *Correlation is significant at the 0.05 level.

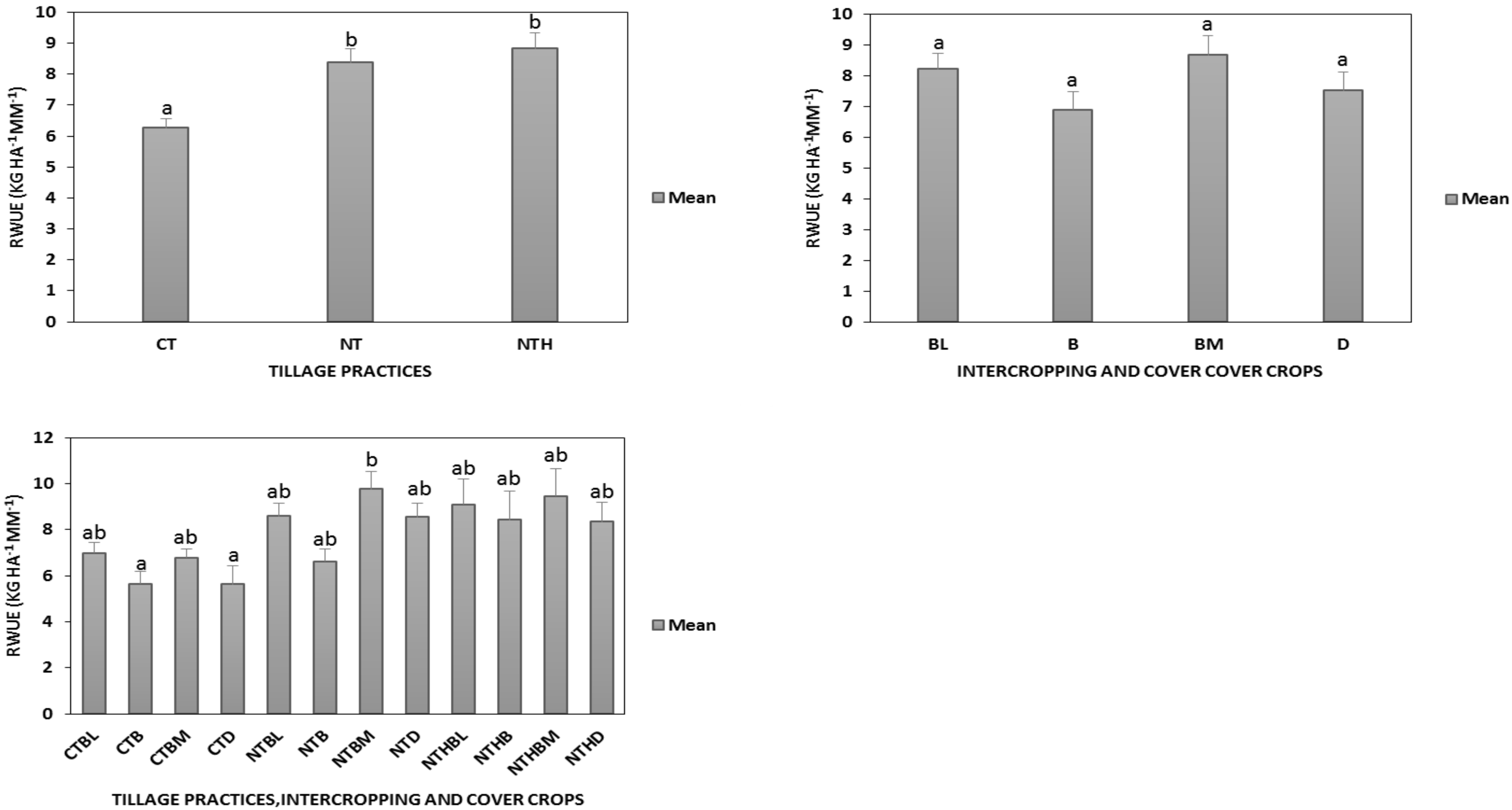

Figure 4.4: The effect of tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops (BL, bean and leucaena, B, bean, BM, bean and mulch, D, dolichos) and their interaction on RWUE. Means labeled with same letter are not significantly different. The vertical T- bars indicate standard errors about the mean.

5. Discussion

5.1 Soil physical properties

5.1.1 Hydraulic conductivity

Tillage systems change the arrangement of soil pores reducing their ability to transport water (Kahlon et al., 2013). It was expected that due to lack of soil inversion, NT and NTH maintain continuous pores which enhance water infiltration. In this study, however, CT resulted in the highest K_S compared to NT and NTH. This is in line with the slightly lower BD and higher MacPOR observed in CT, compared to NT and NTH. The low K_S in these practices can also be due to lack of continuous pores in the same practices. Even though NT and NTH practices showed the highest microbial activity, it is possible that the micro-organisms did not create a network of vertical interconnected pores. This effect was less pronounced in NTH which showed slightly higher K_S as compared to NT. These results are similar with those of Lal (2007) whose experiment in Ohio showed an increase in microbial activity in NT and surprisingly no influence on water infiltration. Ferreras et al. (2000) reported only a slight increase in infiltration rate in NT compared to CT. It should be noted that our soil had a clay texture and had already a low hydraulic conductivity. Tillage thus seems to have some positive effect on K_s of such soils.

Other studies that have contradicting results to our study are Choudhury et al. (2014) in sandy loam soils, Thierfelder et al. (2014) in loamy to sandy loam soils using time to pond method, Kahlon et al. (2013) in silt loam soils, Thierfelder and Wall (2009) in sandy soils and using simulated rainfall, and Gicheru et al. (2004) in sandy loam soils. The difference in soil types and also measurement methods could have being the cause of the differences obtained with this study.

With interaction between tillage, intercropping and cover crops, BL combined with CT had highest K_S as compared to the others. This could be maybe due to the biological action of leucaena roots creating biopores and hence increasing preferential water flow through the pores. This can also be due to greater number of voids and abundant soil macropores caused by the tillage practice. This observation can be supported by the slightly higher MacPOR and slightly lower BD observed in both CT and BL. As reported by Benegas et al. (2014), tree roots swell, shrink, die and decompose, all of which promote MacPOR formation leading to improved infiltration and soil hydraulic conductivity.

5.1.2 Bulk density and parameters derived from water retention curve

Even though there was no significant difference in BD between CT, NT and NTH in both top and sub soil, it was slightly lower in the top soil under CT. The low BD in top soil CT could be attributed to the use of the tillage hoe (up to 20 cm) for land preparation in CT which breaks the soil clods thus making it loose, while the lower one in NTH as compared to NT could be due to the effect of complete non inversion and less compaction in the top soil during weeding. In the subsoil, NT resulted in a slightly lower BD, which can be explained by the fact that with CT the use of tillage hoe created a hard pan in the sub soil resulting in soil compaction and increased BD which is not the case with NT and NTH. It could also be due to use of crop residues and increase in microbial activity. The slightly higher BD in NTH as compared to NT in the sub soil could be due to the less MacPOR observed in the same layer. Our results agree with those of Reynolds et al. (2003) who found no significant difference in BD between CT and CA. Malecka et al. (2012) reported no significant difference in BD at 10-20 cm, but CT resulted in slightly lower BD compared to NT. On the contrary, Alam et al. (2014) found that NT showed the highest reduction on BD as compared to other tillage practices after four years. It should also be noted that in the long run, some studies (e.g., Malecka et al., 2012) show that BD continues to reduce with CA as compared to CT due to presence of mulch in CA which creates a good environment for microorganisms which loosens the soil.

In the top soil FC and PWP did not result in any significant difference, despite the significantly higher OC in NT and NTH. However, in the sub soil, CT resulted in the lowest FC and also lowest PWP, although differences in OC between treatments were similar to those of the top soil. Also clay content and mineralogy, which besides OC also greatly affect both parameters (Or and Wraith, 2002), were similar in both top and sub soil. However, the lower FC and PWP values found in the sub soil of CT might be attributed to its lower OC.

Given the above, PAWC did not show differences between CT, NT and NTH in the top soil, but also not in the sub soil. Plant growth and development is highly affected by FC and PWP which determine the amount of soil water available to the plant. In our study all the tillage practices, intercropping and also cover crops fall below the critical value of 0.15 m^3 m^{-3} as suggested by Reynolds et al. (2009). This shows that the soils have limited water available for crop uptake. This could be due to the high clay content of this soil resulting in water being held in the soil matrix with high tensions and thus unavailable for crop use. This results are in agreement with Mloza-Banda et al, (2014) who found no significant difference in PAWC between CA based tillage and ridge tillage in sandy clay loams of central Malawi. Similar results were obtained by D'Haene et al. (2008) in silt loam soils of Belgium where differences in total PAWC were not significant between CT and reduced tillage. CT and CA also showed no significant difference in PAWC in clay loam soils of Flanders (Vermang et al., 2010).

The slightly higher MacPOR values in CT and BL are related with the slightly lower BD in those treatments. This could be due to loosening of the soil by tillage resulting in increase in large pores volume (Abrol and Sharma, 2012) and with the deep leucaena roots that can create continuous large pores as compared to those from maize, beans and dolichos. The slightly lower MacPOR in NTH as compared to NT in the sub soil could be due to the slightly high BD in NTH in the same layer. All the tillage practices, intercropping and cover crops resulted in MacPOR values in the optimal range of 0.05 to 0.10 m^3 m^{-3}. This means that, irrespective of the treatment, the soil was in good physical condition and their potential to quickly drain excess water and allow for root development was good (Reynolds et al., 2009). Even though some cover crops under different tillage practices show values lying on and one below the lower critical value, they are all above the suggested MacPOR of 0.04 m^3 m^{-3} which indicates poor physical quality. Vermang et al. (2010) found no significant difference in MacPOR between CT and CA. Similar results were also obtained in central Malawi in sandy clay loams where MacPOR was not significantly different between CA and ridge tillage after 2 and even 4 years of conversion to CA (Mloza-Banda et al., 2014).

Air capacity is an important physical property indication of the soil aeration capacity that affects root growth and microbial activity, thus an important parameter to evaluate soil management practices. The slightly lower AC in the interaction between NT with BM and B in the top soil may be attributed to low porosity in the absence of tillage that turns the soil eliminating hardpans in the top soil if they exist. The better AC in CT and cover crops D and BL in the sub soil may be attributed to the porosity caused by loosening the soil by tillage and enhanced pores by the roots of maize, beans and leucaena that are in this treatment. However, all the tillage, intercropping and cover crops resulted in values above the critical values of 0.10 m^3 m^{-3} indicating that in our study area top soils have good aeration for microbial activity (Reynolds et al, 2009). This results are in agreement with Mloza-Banda et al. (2014) who found no significant difference in AC between CA based tillage and ridge tillage in sandy clay loams of central Malawi after 4 years. In their study in Flanders, Vermang et al. (2010) reported no significant differences between in AC between CT and CA.

RWC was not affected by tillage, intercropping and cover crops. This is a parameter is related to AC hence to FC and saturation, all depending on BD and total porosity which were also not affected by the treatments. The below optimal values seen in all the treatments are an indicator that these soils cannot achieve maximum microbial activity due to air limitation even though the AC indicated that microbial activity was not restricted (Reynolds et al, 2009). Similar results were reported by Vermang et al. (2010) where CT and CA showed no significant differences in RWC. In their study in central Malawi, Mloza-Banda et al. (2014) found that RWC was not significantly different between CA based tillage and ridge tillage after 2 years with significant differences occurring after 4 years.

5.1.3 Aggregate stability

The lower WSA_D in CT may be attributed to the continuous tillage and low OC in CT resulting in weaker aggregates as compared to NT and NTH. In the top soil, the slightly higher WSA_D in NT as compared to NTH could be due to the higher SMBC in NT probably leading to increased aggregate stability in this treatment. Similar results were obtained by Govaerts et al. (2009) where NT with residue resulted in higher aggregate stability compared to NT without residue and CT in Phaezomes soils. Brunel et al. (2013) and Blanco and Lal (2009), on clay and silt loam soils, respectively, found similar results. Also on Vertisols, Araya (2012) found NT-practices to show higher stability as compared to CT. The reason for the higher WSA_W in B as compared to D in the sub soil is that D might have less roots in the sub soil leading to poor aggregation and slightly less stability. Wet sieving produced higher WSA in top and sub soil as compared to dry sieving, that concur with results of Govaerts et al. (2009). This could be explained by the process of slaking which is less in wet aggregates as compared to dry aggregates. With dry aggregates, as the entrapped air escapes, it creates pressure which leads to enormous breaking of soil aggregates (Vermang et al., 2009). All dry and wet aggregate stability values were above the critical limit meaning the soils had good aggregate stability (Moncada et al., 2013).

5.1.4 Structural stability index

StI is closely related to OC and clay content of the soil as demonstrated by Pieri's formula. Higher values of StI obtained in NTH, BM and NTHBM could be linked to OC content of this treatment which was also higher in the same. The obtained results of all treatments lying below the critical value of 5 as suggested by Reynolds et al. (2007) can be explained by the fact that our soil contains high clay content and this automatically lowers the StI value. It thus does not mean that our soil is structurally degraded. D'Haene et al. (2008) observed significant differences in StI between CT and reduced tillage in some fields after 5 years with other fields showing no significant difference in depth 10 -15 cm in silt loam belt of Belgium.

5.1.5 *S* index

The values of *S* index obtained in this study were above the critical value indicating that our top and sub soils have good physical soil quality. The reason for the slightly higher *S* index obtained in NTBL, NTBM and NTHBM is probably non-inversion and addition of residues which help keep the soil intact and increase microbial activity of the soil. This could also be linked with the deep rooting system of leucaena creating good structure in the soil. Nevertheless, our results agree with D'Haene et al. (2008) in silt loam belt of Belgium who found no significant difference in *S* index between CT and reduced tillage in 10 -15 cm depth in 5 years with differences occurring after 5 years. In the some study, at depth 25-30 cm, some fields showed significant difference after 2 years while others showed on significant difference even after 10 years. However the use of *S* index as a sole indicator for soil physical quality has been questioned by authors (Moncada et al., 2015, Reynolds et al., 2009). A study done by Moncada et al. (2015) concluded that there was no clear trend for high or low values of *S* to relate to a good or limiting soil conditions respectively, for crop production on Belgian and Venezuelan soils.

5.2 Soil chemical quality

Generally the soil pH was within the acceptable level for crop growth. The slightly lower total pH observed in top soil in CT and NTH could be due to leaching of basic cations from top to sub soil related to the observed higher K_S in this treatments. Similar results were obtained by Shemdoe et al. (2009) in sand soils of Tanzania and by Franzluebbers and Hons (1996) in silt clay loam soils. Soils with pH H_2O higher than pH KCl indicate negative charge sites on the clay complex and capacity to exchange cations, meaning that our top and sub soil are not weathered soils.

The lower OC in CT compared to NT and NTH may be explained by the fact that under NT and NTH there was no turning of the soil and organic matter is prevented from rapid oxidation which happens in CT. The higher one in NTH as compared to NT could be due to the complete non soil disturbance in this tillage. The slight scrubbing done in NT may have caused some oxidation of OC. The higher OC in BM is not surprising given that the maize residues covering the soil provides a continuous supply of soil organic matter resulting in higher OC. Similar results of higher OC under NT and residue cover have been obtained by Goel and Behl (2002), Sharma et al. (2013), Navarrete et al. (2012), Liu et al. (2009), Alam et al. (2014), Melacka et al. (2012) and Mupungwa et al. (2013). On the contrary, results obtained by Thierfelder et al. (2013) in loamy to sandy loam soils and Paul et al. (2013) in Ferrasol and 9 years of experiment showed no significant difference in OC between CT and CA.

All treatments except NTHB in top soil and NTHBM in sub soil showed OC values below the critical value of 23 g kg^{-1} found in crop lands as proposed by Greenland (1981) in Reynolds et al. (2007) indicating that loss of soil structure may be evident. The high OC in NTHB and NTHBM could be due to non-inversion, large soil cover provided by B and residue through mulch which prevent oxidation of OC.

N availability in the soil is believed to be driven by carbon dynamics. However, in our study, OC and N in the top and sub soil had weak positive correlation coefficients of r=0.26 and r=0.02, respectively, while N and δ^{15}N values in the top and sub soil showed correlation coefficients of r=0.68 and r=0.42, respectively. The positive results of δ_{sample} indicate enrichment in the heavy isotope with values of between 6 and 10 which demonstrates that the N source in our soil was atmospheric N, which was fixed by the leguminous cover crop.

The slightly higher N content in top soil under NTH can be due to complete non soil inversion leading to less oxidation of N, while the slightly higher N content in sub soil CT may be due to mixing of the top and sub soil. The latter can also be explained by the slightly higher $\delta^{15}N$ values under CT in the sub soil. The slightly higher N in top soil of D may indicate that D had higher nodulation than B. Irrespective of the source of N, the results obtained in this study are similar to Malecka et al. (2012) who found no significant difference in total N between CA and CT in 10-20cm depth even after 7 years. Similarly, Sainju et al. (2006) did not find tillage and cropping system to affect total N. Other authors who found an increase in total N in CA compared to CT are Alam et al. (2014) with 4 years experiment in clay loam soil, Muchabi et al. (2014) with 16 years experiment, and Liu et al. (2009) in silt loam soil and 6 years experiment. Muchabi et al. (2014) explained that differences in total N between CA and CT were only significant in the 4^{th} and 16^{th} year of their experiment.

There was no difference in available P and exchangeable K^+, Ca^{2+}, Mg^{2+}, Na^+ both in the top and also sub soil. This is in line with Shemdoe et al. (2009) and Derpsch (2007) whose research found that available P was not affected by tillage systems. On the country, Alam et al. (2014) reported higher available P in CA as compared to CT after 4 years of experiment. With available P, the reason for this could be probably the higher contents of P in this soil at the beginning of the experiment.

The exchangeable K^+, Ca^{2+}, Mg^{2+} and Na^+ were also not affected by tillage practices. This is in line with Shemdoe et al. (2009), Govaerts et al. (2007), Duiker and Beegle (2006) and Du Preez et al. (2001) who found out that these elements are not affected by tillage practices.

5.3 Soil biological quality

Both in the top and sub soil, microbial biomass was significantly lower in CT as compared to NT and NTH. The higher SMBC in NT and NTH may be associated with favourable conditions under NT such as reduced soil disturbance, increased aeration, cooler and wetter conditions, lower temperature and moisture fluctuations, and higher SOC. With NTH, the slightly lower SMBC as compared to NT could be the slightly lower total pH in this tillage. Our findings of higher SMBC in NT and NTH than CT concur with those in other studies (Spedding et al., 2004; Wang et al., 2012; Henneron et al., 2014; Muchabi et al., 2014). These results were also confirmed by the V index which indicated that microbial biomass was higher in the CA-based alternatives as compared to CT. The higher SMBC in BM can be due to the input of mulch resulting in high substrates and hence high SMBC.

5.4 Soil water content (SWC)

Soil structure was expected to be improved by NT and NTH resulting in an increase of the soil's capacity to store water. However, in this study this was not the case. The results obtained can be explained by behaviour of BD and hence of total porosity of this soils which also showed no significant difference. However, NT and NTH resulting on slightly higher water content could be attributed to good soil structure created by these practices. In addition, NTBM and NTHBM showing higher water content during dry spell can be explained by reduced evaporation in this treatment and lower water content in BL and D can be explained by water uptake by this crops. These results are in agreement with the results found by Logsdon and Karlen (2004) whose study of Phaeozems showed no significant difference in SWC CT and NT. These results contradict with what Ngigi et al. (2006) found in the same study area as our study, i.e., Laikipia. They found that CA increased soil water moisture by 18-50% as compared to CT. However, it should be noted that Ngigi et al. (2006) did not directly measure soil water content but used grain yields from farms under conservation tillage and traditional farming system as a proxy to soil moisture content.

5.5 Visual soil assessment (VSA)

From the VSA done on tropical Kenyan soil, a few associations with results from classical laboratory methods were found. Several parameters did not show any difference which is in accordance with the results from the classical soil analysis. This also explains why correlations between both approaches (visual vs classical) are so small. According to this study, our soils have good overall soil quality which agrees with results found for *S* index. VSA is proofing to be a very instrumental method which is easy to use by both researchers and farmers. However there are very few studies reporting the evaluation of soil quality as effected by soil management practices using the same method.

5.6 Maize yield and RWUE

Maize yield was significantly higher in NTH and NT as compared to CT. Maize yield in NT and NTH was 34% and 41%, respectively, higher than under CT. Given that most soil quality parameters were not significantly affected by the treatments as discussed above, this might be surprising even though it might be due to the overall effect of the slightly better values observed in NT and NTH as compared to CT in most of the physical and chemical parameters. On the other hand, CA has been reported to result in higher yields, especially in years that have rainfall below average (Jin et al., 2007; Mupangwa et al., 2012), which was the case in this study. The increase in yield can be attributed to the higher OC and microbial biomass, aggregate stability and the slightly high N content found in NT and NTH as compared to CT. Although the real mechanisms behind the substantial higher yields observed under NT and NTH are yet to be unfolded, it is believed to be probably linked to the lower water stress in these treatments which occurred during yield formation stage as well as the higher RWUE as compared to CT. Nevertheless, those higher yields are in agreement with Abrol and Sharma (2012) who reported that the efficiency of moisture use is slightly higher in CA based tillage than CT. This results are in accordance with Thierfelder et al. (2014), Ngwira et al. (2012; 2014), Mupangwa et al. (2012) and Liu et al. (2009) who also reported higher yields in CA as compared to CT.

On the contrary, several authors have also reported lower yields under CA as compared to CT (Mason et al., 2015 especially during the first years of the experiment; Lahmar et al., 2008 in wetter climates of Europe; Melecka et al., 2012 in loamy sands overlying loamy material and for 7 years). The different results could be explained by differences in period of the experiment, soil type and climate of the area.

6. Conclusion and recommendation

Drylands are faced with a problem of suboptimal yield production resulting from suboptimal soil and water management. The major challenge is coping with inter seasonal dry spells rather than low total rainfall amount. From the above findings, it can be concluded that CA based tillage systems give better yields as compared to CT in this areas. Even though many soil physical and chemical parameters were not significantly affected by tillage, they showed slightly better values under CA based tillage than CT and their combined overall effect played a role in producing better yields. With time it is expected that these parameters will be significantly different as the effect of CA on soil parameters is believed to improve over time. Soil water content, which is mainly the major yield limiting parameter in dry areas and especially during dry spells, emerged to be one of the key factors that influenced yield in this study together with OC and SMBC. Even though the effect of intercropping and cover crops was not significant, BM was performing better and especially under CA based practices due to less soil disturbance and adequate soil cover. We therefore recommend the use of CA based tillage combined with cover crops and mulch to farmers in this area for improved crop yield.

It is recommended that further investigation should be carried out and for at least more than three years in order to ascertain the effects of CA on soil quality after several years which is believed to accrue over time. For water content, a further analysis based on water balance evaluation is recommended.

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7. Appendices

Table 7.1: Textural class and % sand, silt and clay for different treatments tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops (BL, bean and leucaena, B, bean, BM, bean and mulch, D, dolichos).

Tillage	Cover crop	Sand (%)		Silt (%)		Clay (%)		Textural class
		Top	**Sub**	**Top**	**Sub**	**Top**	**Sub**	
CT	BL	25.3	26.0	17.3	15.3	57.4	58.7	Clay
	B	24.0	21.3	18.6	17.3	57.4	61.4	Clay
	BM	21.3	24.6	18.7	14.7	60.0	60.7	Clay
	D	22.0	23.3	20.0	18.7	58.0	58.0	Clay
NT	BL	21.3	22.0	18.0	16.7	60.7	61.3	Clay
	B	24.7	22.0	18.0	16.0	57.3	62.0	Clay
	BM	24.0	22.0	16.0	14.7	60.0	63.3	Clay
NTH	D	23.3	22.6	19.3	16.7	57.4	60.7	Clay
	BL	20.0	21.3	16.6	15.4	63.4	63.3	Clay
	B	23.4	22.0	17.3	16.7	59.3	61.3	Clay
	BM	22.1	21.3	18.6	18.0	59.3	60.7	Clay
	D	24.0	20.0	18.7	20.0	57.3	60.0	Clay
P value	ns	ns	ns	ns	ns	ns	ns	

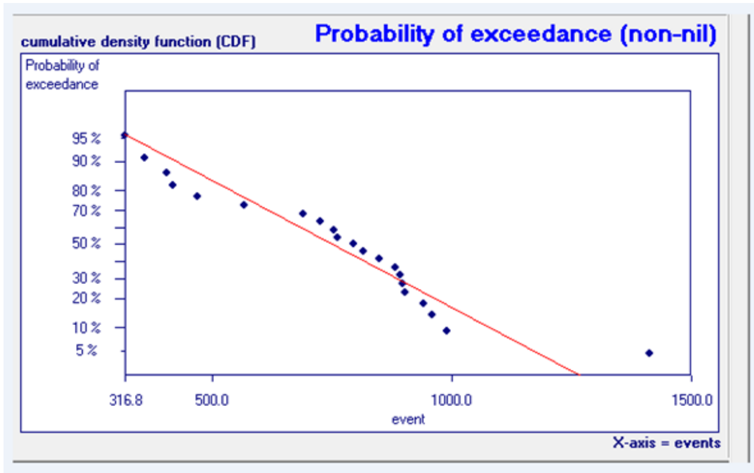

Figure 7.1: Probability of exceedance graph from Rainbow programme based on rainfall data for 20 years (1994 - 2014). X axis shows the rainfall amount while y axis shows the probability of exceedance.

Table 7.2: The effect of interaction between tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops (CC) (BL, bean and leucaena, B, bean, BM, bean and mulch, D, dolichos) on) on top and sub soil bulk density (BD), field capacity (FP), permanent wilting point (PWP), and Plant available water content (PAWC). P values indicated ns shows means that are not significantly different.

Tillage	**CC**	**B.D (Mg m^{-3})**		**FC (m^3 m^{-3})**		**PWP (m^3 m^{-3})**		**PAWC (m^3 m^{-3})**	
		Top	**Sub**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**
CT	BL	1.18±0.08	1.32±0.07	0.40±0.03	0.37±0.02	0.30±0.03	0.28±0.01	0.09±0.01	0.08±0.02
	B	1.17±0.09	1.30±0.01	0.39±0.01	0.42±0.03	0.27±0.01	0.32±0.01	0.12±0.01	0.10±0.01
	BM	1.20±0.04	1.31±0.02	0.41±0.01	0.45±0.02	0.30±0.02	0.33±0.01	0.10±0.01	0.11±0.01
	D	1.18±0.04	1.33±0.03	0.40±0.02	0.46±0.03	0.27±0.02	0.34±0.03	0.13±0.01	0.11±0.01
NT	BL	1.18±0.07	1.28±0.02	0.38±0.01	0.45±0.01	0.27±0.01	0.32±0.01	0.11±0.01	0.13±0.01
	B	1.26±0.07	1.25±0.03	0.47±0.02	0.48±0.02	0.33±0.01	0.35±0.01	0.13±0.01	0.13±0.01
	BM	1.30±0.03	1.22±0.02	0.45±0.04	0.46±0.02	0.33±0.02	0.35±0.01	0.12±0.03	0.11±0.01
	D	1.36±0.04	1.29±0.06	0.42±0.01	0.42±0.03	0.32±0.01	0.31±0.02	0.09±0.01	0.11±0.01
NTH	BL	1.28±0.02	1.24±0.01	0.46±0.02	0.46±0.03	0.32±0.02	0.34±0.02	0.14±0.01	0.12±0.01
	B	1.27±0.03	1.27±0.03	0.45±0.01	0.48±0.03	0.32±0.01	0.36±0.01	0.12±0.01	0.11±0.01
	BM	1.22±0.04	1.30±0.01	0.42±0.03	0.48±0.01	0.31±0.02	0.35±0.01	0.11±0.01	0.12±0.01
	D	1.27±0.02	1.30±0.01	0.41±0.02	0.47±0.02	0.30±0.01	0.36±0.00	0.10±0.01	0.11±0.01
P value		ns	ns	ns	ns	ns	ns	ns	ns

Table 7.3: The effect of interaction between tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops (CC) (BL, bean and leucaena, B, bean, BM, bean and mulch, D, dolichos on top and sub soil macro porosity (MacPOR), matric porosity (MatPOR), air capacity (AC) and relative water content (RWC). P values indicated ns shows means that are not significantly different.

Tillage	**CC**	**MacPOR (m^3 m^{-3})**		**MatPOR (m^3 m^{-3})**		**AC (m^3 m^{-3})**		**RWC (m^3 m^{-3})**	
		Top	**Sub**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**
CT	BL	0.10±0.03	0.08±0.04	0.44±0.05	0.40±0.02	0.15±0.01	0.12±0.04	0.73±0.04	0.77±0.06
	B	0.08±0.02	0.06±0.01	0.42±0.01	0.46±0.02	0.11±0.02	0.09±0.02	0.79±0.04	0.82±0.04
	BM	0.07±0.02	0.06±0.01	0.45±0.02	0.49±0.02	0.11±0.02	0.10±0.01	0.79±0.03	0.81±0.03
	D	0.09±0.03	0.08±0.02	0.44±0.04	0.50±0.03	0.13±0.01	0.12±0.02	0.75±0.03	0.79±0.05
NT	BL	0.10±0.01	0.07±0.01	0.42±0.01	0.49±0.01	0.14±0.02	0.10±0.02	0.73±0.04	0.81±0.03
	B	0.06±0.01	0.08±0.01	0.50±0.01	0.51±0.01	0.09±0.02	0.11±0.01	0.84±0.04	0.81±0.03
	BM	0.05±0.01	0.05±0.02	0.49±0.02	0.49±0.02	0.09±0.01	0.08±0.01	0.84±0.02	0.85±0.02
	D	0.08±0.02	0.07±0.02	0.46±0.02	0.45±0.02	0.11±0.02	0.09±0.02	0.79±0.03	0.81±0.04
NTH	BL	0.08±0.02	0.09±0.02	0.51±0.02	0.50±0.04	0.12±0.01	0.13±0.01	0.79±0.03	0.78±0.02
	B	0.05±0.02	0.04±0.01	0.50±0.01	0.50±0.02	0.11±0.02	0.06±0.01	0.81±0.04	0.88±0.02
	BM	0.06±0.01	0.07±0.01	0.49±0.04	0.49±0.02	0.14±0.03	0.08±0.02	0.75±0.04	0.86±0.03
	D	0.07±0.01	0.05±0.01	0.45±0.02	0.50±0.01	0.11±0.01	0.07±0.01	0.78±0.01	0.87±0.02
P value		ns	ns	ns	ns	ns	ns	ns	ns

Table 7.4: The effect of interaction between tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops (CC) (BL, bean and leucaena, B, bean, BM, bean and mulch, D, dolichos on % dry water stable aggregates (% WSA_D), % wet water stable aggregates (%WSA_W) and structural stability index (StI). Means labeled with different letters are significantly different. P values indicated s and ns shows means that are significant or not, respectively.

Tillage	**CC**	**%WSA_D**		**%WSA_W**		**StI [-]**	
		Top	**Sub**	**Top**	**Sub**	**Top**	**Sub**
CT	BL	53.5±2.8	56.5±3.8	90.5±1.6	93.4±1.5	3.5±0.4 a	3.7±0.3 abcd
	B	55.7±7.6	54.7±5.6	92.6±2.1	92.8±1.0	3.0±0.3 a	2.9±0.2 a
	BM	56.1±7.8	63.1±5.5	88.7±1.4	91.3±1.7	3.8±0.2 a	3.9±0.2 abcd
	D	54.9±6.1	67.9±3.8	91.0±1.8	92.2±0.7	3.2±0.4 a	3.3±0.3 ab
NT	BL	67.6±3.6	64.6±8.1	92.3±0.5	92.3±0.8	4.0±0.2 ab	4.3±0.2 bcd
	B	59.1±3.4	72.1±3.2	90.3±0.5	94.3±1.4	3.7±0.1 a	4.1±0.1 abcd
	BM	66.6±4.3	66.6±606	91.5±1.7	93.4±0.9	4.3±0.1 ab	4.1±0.1 abcd
	D	66.2±5.1	69.2±4.5	93.7±0.9	91.3±1.7	3.7±0.2 a	3.5±0.3 abc
NTH	BL	63.6±1.3	70.6±4.5	93.3±0.9	91.2±0.6	3.5±0.2 a	3.6±0.1 abc
	B	58.7±7.9	73.7±3.9	92.3±1.5	94.8±0.5	5.5±0.2 b	5.1±0.2 d
	BM	53.8±6.6	67.8±2.2	90.8±0.8	91.2±0.9	4.3±0.3 ab	4.8±0.1 cd
	D	62.1±8.1	64.1±9.6	90.8±1.8	88.9±1.3	3.4±0.4 a	3.3±0.3 ab
P value		ns	ns	ns	ns	s	s

Table 7.5: The effect of interaction between tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops (CC) (BL, bean and leucaena, B, bean, BM, bean and mulch, D, dolichos) on) on top and sub soil pH (H_2O and KCl), Soil organic carbon OC, total nitrogen N, delta 15 values $\delta^{15}N$ and available phosphorus P. Means labeled with different letters are significantly different. P values indicated s and ns shows means that are significant or not, respectively.

		pH H_2O		pH KCl		OC (g kg^{-1})		N (ppm)		$\delta^{15}N$ (‰)		P (ppm)	
Tillage	**CC**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**
CT	BL	6.6±0.2	6.8±0.2	5.0±0.3	5.1±0.3	14.9±1.5 ab	15.9±0.7 abc	0.16±0.02	0.16±0.01	8.4±0.4	8.2±0.7	13.58±5.17	6.63±2.64
	B	6.6±0.2	6.7±0.2	5.1±0.2	5.1±0.2	13.3±1.3 a	12.9±0.8 a	0.14±0.02	0.15±0.01	7.3±0.5	8.1±0.6	14.15±0.06	9.63±4.50
	BM	6.2±0.1	6.4±0.1	4.6±0.2	4.6±0.1	17.2±1.3 abc	17.2±1.3 abcd	0.15±0.01	0.13±0.01	8.3±0.2	8.1±0.1	13.25±7.12	4.62±2.20
	D	6.4±0.1	6.4±0.1	4.7±0.1	4.6±0.0	14.3±1.8 ab	13.3±1.3 ab	0.16±0.02	0.14±0.01	7.9±0.2	8.2±0.5	6.35±3.57	4.09±2.51
NT	BL	6.4±0.1	6.5±0.1	5.1±0.2	4.8±0.1	18.4±1.1 abc	19.6±0.8 bcd	0.15±0.01	0.13±0.01	7.7±0.2	7.7±0.1	8.08±4.03	11.97±9.29
	B	6.8±0.2	6.9±0.2	5.2±0.1	5.1±0.1	16.1±0.8 ab	18.5±1.5 abcd	0.14±0.01	0.13±0.01	8.1±0.3	7.1±0.6	6.73±3.43	8.17±2.72
	BM	6.8±0.1	6.9±0.1	4.8±0.2	5.2±0.1	19.0±0.3 abc	18.5±0.9 abcd	0.16±0.01	0.12±0.01	8.1±0.9	7.6±0.4	7.53±0.74	3.60±1.02
	D	6.5±0.1	6.4±0.1	5.1±0.1	4.7±0.2	16.4±0.9 ab	15.8±1.2 abc	0.17±0.01	0.15±0.01	7.7±0.2	7.9±0.6	12.69±8.59	15.68±10.94
NTH	BL	6.8±0.2	6.8±0.2	4.1±0.2	5.1±0.1	20.2±1.2 bc	21.9±0.8 cd	0.17±0.01	0.13±0.01	8.1±1.1	7.4±0.3	6.11±1.13	16.33±10.65
	B	6.8±0.2	6.8±0.1	5.2±0.2	5.0±0.1	23.4±1.0 c	16.1±0.9 abc	0.15±0.01	0.13±0.01	7.4±0.3	8.2±0.5	12.42±6.83	5.67±5.73
	BM	6.6±0.1	6.8±0.1	4.1±0.1	5.0±0.2	15.6±1.4 ab	23.0±1.2 d	0.14±0.01	0.12±0.01	7.7±0.6	7.8±0.2	6.11±1.76	6.85±3.30
	D	6.4±0.2	6.6±0.1	4.7±0.2	4.8±0.2	15.0±1.5 ab	15.4±0.9 ab	0.15±0.01	0.12±0.01	8.2±0.3	7.5±0.3	8.67±3.22	4.55±3.04
P value		ns	ns	ns	ns	s	s	ns	ns	ns	ns	ns	ns

Table 7.6: The effect of interaction between tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops (CC) (BL, bean and leucaena, B, bean, BM, bean and mulch, D, dolichos) on top and sub soil exchangeable potassium K^+, Calcium Ca^{2+}, Magnesium Mg^{2+}, sodium Na^+ and microbial biomass SMBC. P values indicated ns shows means that are not significant.

		K^+(cmol kg^{-1})		**Ca^{2+}(cmol kg^{-1})**		**Mg^{2+}(cmol kg^{-1})**		**Na^+ (cmol kg^{-1})**	
Tillage practice	**Cover crops**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**	**Top**	**Sub**
CT	BL	1.0±0.1	0.9±0.2	19.4±4.5	18.2±4.7	4.6±0.7	4.7±0.7	0.2±0.1	0.4±0.1
	B	1.1±0.1	1.0±0.0	20.4±5.0	20.5±5.2	4.6±0.5	5.1±0.6	0.2±0.1	0.5±0.3
	BM	0.9±0.2	0.8±0.1	19.8±1.7	20.0±1.5	5.1±0.4	5.7±0.5	0.5±0.1	0.7±0.2
	D	1.0±0.1	1.0±0.0	17.5±1.2	18.0±1.5	5.1±0.3	5.4±0.4	0.6±0.1	0.7±0.1
NT	BL	0.9±0.1	1.0±0.0	16.5±2.8	19.8±2.5	4.9±0.6	5.6±0.5	0.4±0.1	0.5±0.1
	B	0.9±0.1	1.1±0.1	17.7±1.2	21.8±1.9	5.3±0.3	6.0±0.1	0.7±0.1	0.5±0.1
	BM	1. 0±0.1	0.9±0.1	19.5±1.5	17.4±2.5	5.5±0.6	4.9±0.4	0.5±0.1	0.6±0.1
	D	1.0±0.2	1.0±0.1	20.3±0.2	18.7±1.1	5.1±0.3	5.2±0.1	0.4±0.1	0.4±0.1
NTH	BL	1.0±0.1	1.3±0.1	16.3±1.5	21.4±1.6	4.9±0.0	5.8±0.2	0.6±0.1	0.5±0.0
	B	1.1±0.1	1.1±0.1	21.5±2.4	19.6±1.9	5.4±0.2	5.3±0.2	0.2±0.1	0.4±0.0
	BM	1.3±0.1	0.9±0.1	18.7±2.2	20.8±2.5	5.8±0.5	5.6±0.6	0.6±0.1	0.8±0.2
	D	0.8±0.2	0.9±0.1	15.7±3.1	20.4±1.2	4.8±0.9	6.1±0.3	0.4±0.1	0.8±0.1
P value		ns	ns	ns	ns	ns	ns	ns	ns

Table 7.7: The effect of interaction between tillage (CT, conventional tillage, NT, no tillage and NTH, no tillage with use of herbicide) and intercropping and cover crops (CC) (BL, bean and leucaena, B, bean, BM, bean and mulch, D, dolichos) on total water storage for May and August, K_S, yield and RWUE, rain water use efficiency. Means labeled with different letters are significantly different. P values indicated s and ns shows means that are significant or not, respectively.

Tillage	Cover crop	Total Water storage for May (mm)	Total Water storage for August (mm)	K_S (cm day^{-1})	YIELD Yield (kg ha^{-1})	RWUE kg ha^{-1} mm^{-1})
CT	BL	341±11	288±12	29.9±4.5 b	1882 ab	6.98±0.45 ab
	B	339±13	293±9	11.3±1.2 a	1523 a	5.65±0.52 a
	BM	326±19	280±14	14.8±0.9 a	1829 ab	6.78±0.38 ab
	D	339±6	281±8	14.3±1.8 a	1517 a	5.63±0.81 a
NT	BL	338±7	273±5	15.4±0.5 a	2316 ab	8.59±0.55 ab
	B	336±4	281±6	11.7±1.2 a	1787 ab	6.63±0.55 ab
	BM	343±10	297±5	9.3±0.7 a	2633 b	9.77±0.74 b
	D	345±14	290±11	8.2±1.2 a	2305 ab	5.88±0.61 ab
NTH	BL	338±11	291±6	15.4±0.5 a	2453 ab	9.10±1.09 ab
	B	317±11	258±8	13.7±2.4 a	2270 ab	8.42±1.24 ab
	BM	355±4	289±9	13.4±0.6 a	2550 ab	9.46 ±1.18 ab
	D	389±2	273±8	8.46±1.2 a	2249 ab	8.34±0.84 ab
P value		ns	ns	s	s	s