Cropping system effects on soil water, soil temperature and dryland maize productivity

by

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DECLARATION

I, Reedah Makgwadi Mampana, hereby declare that this dissertation submitted for the degree MSc (Agric) Soil Science at the University of Pretoria, is my own work and has never been submitted for a degree at this or any other University.

Signed: ________________

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ABSTRACT

Improved soil water conservation has become an important subject in semi-arid areas due to low and erratic rainfall which is often combined with higher temperatures to provide unsuitable conditions for successful crop productivity. Dryland agriculture remains vulnerable to yield losses in these areas. This calls for implementation of conservation agricultural practices that would improve dryland maize productivity. An on-station field trial was started in 2007 at Zeekoegat experimental farm (24 kilometers north of Pretoria), to establish the effect of different conservation agriculture practices on soil and plant properties. The experimental lay-out was a split-plot randomized complete block design, replicated three times, with each replicate split into two tillage systems (whole plots) and then each whole plot (reduced tillage (RT) and conventional tillage (CT)) was subdivided into 12 treatments (two fertilizer levels x 6 cropping patterns). The present study explored the impacts of different tillage practices, cropping patterns and fertilization levels on soil water content, soil temperature and dryland maize productivity during the 2010/11 and 2011/12 growing seasons. To improve the quality of soil water content (SWC) data, the effect of correction for concretions on soil bulk density and the relationship between volumetric soil water content (SWC) vs neutron water meter (NWM) count ratios was also investigated. Corrections for concretions on soil bulk density did not improve NWM calibrations in this study. In all seasons, significantly higher mean SWC was found under RT treatment than in CT at all depths except at 0-300 mm. For example, during the 2010/11 growing season, SWC under RT was 1.32 % and 1.10 % higher than CT for the 300 – 1350 mm and 0 – 1350 mm soil profiles, respectively. The mean weekly SWC was consistently higher for RT throughout both the growing seasons. Significantly higher SWC was also found under monoculture at all soil depths (except at 0-300 mm during 2011/12) compared to treatments under intercropping. For example, during 2010/11, at 0-300mm, SWC under maize monoculture was 1.72 % higher than under intercropping. The maximum and minimum soil temperatures were significantly higher at 100 and 400 mm soil depths under CT than under RT during 2010/11. During 2011/12, significantly higher minimum soil temperatures at 100 mm depth and lower temperature differences (maximum – minimum soil temperatures) at 400 mm depth were observed under intercropping. Despite the higher SWC and reduced soil temperature under RT, the maize seeds emergence rate was lower and plant stand was reduced. This is attributed to other factors associated with RT systems such as increased soil penetration resistance which often leads to poor root development. The lower soil temperatures under RT were generally within the range that would not be expected to inhibit growth and uptake of nutrients. Slower growth under RT resulted in lower biomass and grain yield. Plants that received high fertilizer rates grew more vigorously than plants under lower fertilizer levels when water was not a limiting factor, but produced lower grain yield due to water shortage in March, especially in 2011/12. The harvest index was therefore lower for treatments that received high fertilizer levels. Maize biomass under monoculture x low fertilizer level was significantly lower compared to other fertilizer x cropping pattern treatments. Maize plant growth under intercropping was improved throughout the seasons, which led to significantly higher grain yield than under maize monoculture. It is therefore recommended that farmers in dryland areas take the advantage of intercropping maize with legumes to obtain higher maize productivity. Further research should focus on investigating the possibility of roots restrictions occurring under RT conditions and under various environmental and soil conditions.

Key words: soil water content, soil temperature, intercropping, neutron probe calibration, dryland maize growth and yield, reduced tillage.

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LIST OF SYMBOLS AND ABBREVIATIONS

CA – Conservation agriculture

CT – conventional tillage

F1 – low fertilizer level

F2 – High fertilizer level

ha - hectare

ha^{-1} – per hectare

K - Potassium

MI - Maize-cowpea intercropping

MM - Maize monoculture

N – Nitrogen

P – Phosphorus

p.a – per annum

RT – Reduced tillage

SWC – soil water content

SOM – Soil organic matter

CHAPTER 1: GENERAL INTRODUCTION

Dryland agriculture in many parts of Africa and South Africa is faced with a formidable challenge of crop failure, low yields and food insecurity. This is not only due to low erratic rainfall that is poorly distributed in the area, but also a consequence of poor rainfall utilization (Rockstrom & Steiner, 2003). After rainfall events, a considerable percentage of rainwater in dryland areas is lost as surface run-off and much of the rest evaporates or drains deep into the ground (Van Duivenbooden *et al*., 2000). Bennie & Hensley (2001) reported that in South Africa, evaporation from the soil surface can amount to 50 - 70% of the annual rainfall. Thus urgent measures are required to improve the capture of rainfall and water storage in the crop root zone of dryland agricultural lands.

Conservation agriculture (CA) is suggested to be an appropriate system that holds great assurance for achieving sustainable and profitable agriculture. Conservation agriculture is a set of management practices that is increasingly being promoted due to its potential to enhance crop productivity through improved natural resource management and substantially minimized external inputs (FAO, 2004; FAO, 2010). This is achieved through simultaneous application of three key principles; (i) minimal soil disturbance, i.e. reduced tillage (RT) or no-tillage (NT) (ii) crop residue retention (iii) multiple cropping, i.e. crop rotation and intercropping (Bot & Benites, 2005). There are several socio-economic (Mazvimavi, 2011) and environmental benefits to CA relative to traditional conventional agriculture for farmers, especially small holder, resource-constrained farmers.

CA has been developed in the South American countries of Brazil and Argentina as a need to curb soil erosion (Lahmar, 2008) and is now receiving preference in many parts of Southern Africa for sustainable agricultural productivity (Mati & de Lange, 2003; Mazvimavi, 2011). In South Africa, the subject of CA was mainly driven by land degradation, increasing water scarcity, low water use efficiency and economic considerations (Du Toit, 2007). Over the past 20 years, the CA system has been promoted to smallholder farmers by governmental departments and nongovernmental organizations in South Africa. The ARC-Institute for Soil, Climate and Water (ARC-ISCW) is one of the main institutions involved in encouraging the practice of CA.

The ARC-ISCW aims to research and promote sustainable agricultural systems, which emphasize the use of practices, such as CA, that integrate natural processes into food production and land rehabilitation, but simultaneously improve the livelihoods of farmers and contribute to the long-term sustainability of the resource base. In an effort to do that, a larger multi-disciplinary project was started in 2007 to quantify the effects of CA practices on soil and plant properties. The project is conducted as a field trial on the Zeekoegat Experimental Farm outside Pretoria. The experimental lay-out is a split-plot randomized complete block design, replicated 3 times, with each replicate split into two tillage systems (main plots) and then each main plot (reduced and conventional tillage) is subdivided into 12 treatments (2 Fertilizer levels x 6 Crops). The present study focused on tillage, two cropping systems and fertilizer regimes as well as their interactions.

Objective of the study

The overall objective of the study was to evaluate the effect of different cropping systems on soil water conservation and temperature moderation that could improve the sustainability of dryland maize production.

Hypotheses

(i) The inclusion of soil physical and chemical properties in the calibration will improve the accuracy of Neutron Water Meter readings.

(ii) Reduced tillage and intercropping practices have the potential to enhance soil water holding capacity and moderate soil temperature.

(iii) Reduced tillage and intercropping practices have the potential to improve maize growth and therefore, biomass and grain yield.

(iv) Reduced tillage and intercropping treatments will increase soil water content and moderate soil temperature, which will result in improved maize growth and grain yield.

Specific objectives

(i) To calibrate the neutron scattering method against gravimetric measurements for determining soil water content; and to investigate the effect of soil elements other than H on the field calibration of the neutron scattering method.

(ii) To determine the effect of tillage and cropping patterns on soil temperature and soil water.

(iii) To establish how tillage practices and cropping patterns will affect maize growth and grain yield.

(iv) To investigate the effect of soil water and soil temperature on maize yield.

CHAPTER 2: LITERATURE REVIEW

Water scarcity is an acknowledged problem responsible for significant crop failure and yield losses for dryland farmers. In dryland areas of Sub-saharan Africa, rainfall is often low, irregular and poorly distributed both during the growing seasons and between years (Van Duivenbooden *et al*., 2000; Peterson *et al*., 2006). The insufficient and unreliable rainfall is often combined with high temperatures and infertile soils to create extremely high crop production risks (World Bank, 2010). FAO (2005) reported that crop production in dryland areas worldwide can be reduced by about three-quarters of the total farm land due to changing rainfall patterns.

The necessity to improve or stabilize dryland crop production in a sustainable way therefore remains a priority in many parts of Africa and South Africa. Dryland agriculture is a key to food security for many people, as it is a source of staple food production in most rural households. This is particularly important in Sub-Saharan Africa where rainfed agriculture constitute about 96% of the cultivated area (World Bank, 2010). In Africa, IPCC (2007) projected that yield output in dryland agriculture could be reduced by approximately 50% by 2020 due to climate change, thus threatening livelihoods of many people. An increasing demand for food also continues to outstrip supply as human population increases, thus also placing more pressure on staple food production worldwide (FAO, 2010).

South Africa is a semi-arid, dry country and experiences generally low, erratic and unevenly distributed mean rainfall of about 497 mm p.a. This is well below the world average rainfall of 860 mm p.a. and is compounded by higher evaporation rates (Thompson, 2006). South Africa is in fact poorly endowed with agricultural resources and much of the land is considered marginal and susceptible to degradation (Laker, 1993). Soil organic matter (SOM) content is very low, with more than half (58%) of the soils containing less than 0.5% SOM, and only 4% contain more than 2% organic matter (Du Preez *et al*., 2011). Low SOM, combined with marginal soils, poor soil cover, low infiltration rates, among others, lead to reduced soil water content and excessively high soil temperatures, and provide extremely unfavourable conditions for crop growth and yield.

The constraints under dryland conditions call for implementation of appropriate cropping systems in order to improve and make more efficient use of already limited natural resources to enhance crop productivity. Conservation Agriculture (CA) is suggested as a potential agricultural system to attain sustainable agriculture, which is essential for sustainable food production (Du Toit, 2007; Thierfelder *et al*., 2013).

2.1 Conservation Agriculture

Conservation agriculture is a set of soil management practices aiming to conserve and improve natural resources and maximize rainwater use efficiency, while also lessening production inputs and negative environmental impacts of agriculture (Dumanski *et al*., 2006). CA is being promoted in Sub-saharan Africa as a means to achieve stable yields, minimize land degradation and increase food security (Du Toit, 2007). The CA system is centred on the principles of minimizing mechanical soil disturbance, retention of crop residues from the previous season and multiple cropping in the form of intercropping or crop rotations (Du Toit, 2007; Reicosky & Saxton, 2007). CA is based on old, well known practices, but the principles are combined to form a complete system of conservation-related agricultural practices (Friedrich & Kienzle, 2008; Farooq *et al*., 2011).

The basis underlying the principles of CA is their role in building up SOM, which stabilizes soil and improves water holding capacity. SOM is considered the principal basis of long-term sustainable agriculture and that is the reason why CA is so vital, particularly for dryland conditions (Reicosky & Saxton, 2007; Friedrich & Kienzle, 2008; Thierfielder & Wall 2009). CA is especially important for small holder-resource constrained farmers in sub-Saharan Africa (Hobbs *et al*., 2008). According to Du Toit (2007), crop yield improvement in CA is mainly credited to enhanced soil conditions, which leads to increased soil water content and fertility.

2.2 Soil water under dryland conditions

Water shortage is likely to occur anytime during a crop growing season due to variable and insufficient rainfall which leads to water stress for crops. However, crops may also experience water stress due to either low water storage in the soil or limited ability of crop roots to extract soil water (Van Duivenbooden *et al*., 2000). Farmers, small-holder poor farmers in particular, are essentially risk-averse in rainfed crop production and in an attempt to improve production, they tend to use cropping systems that in fact leads to low yield even in near normal rainfall years (World Bank, 2010).

Soil water content in the root zone is the main determinant of the success of dryland crop production (FAO, 2005; World Bank, 2010). It is therefore important that rainwater is stored and used efficiently to reduce crop vulnerability to water stress during the growing season (Peterson *et al*., 2006). The infiltration of rainwater should be kept at highest level, while water losses are reduced (Bennie & Hensley, 2001). The water gains and losses from the soil are governed by the soil physical conditions, which are affected by, amongst other factors, tillage and surface cover (Hillel, 2003).

2.2.1 Effect of tillage practices on soil water

Tillage practices that leave the soil exposed and intensively cultivated are associated with loss of water due to the destruction of soil structure and soil organic matter (Pieri *et al*, 2002). Conventional tillage (CT), which generally involves turning of the soil with mouldboard or disc plough, is an ancient practice among many farmers basically used for weed control and seed-bed preparation (Pieri *et al*., 2002; Hillel, 2008). Although CT can provide a weed-free and fine seed-bed, in the long term, the practice could lead to increased soil bulk density (Power *et al*., 1986), crusting, surface sealing, and soil erosion, and therefore poor water storage in the root zone (Hobbs *et al*., 2008; Van Donk & Klocke, 2012).

From the previous research, there is a growing interest amongst researchers and farmers to adopt non-inversion tillage practices with which soil and water can be conserved. Great attention has been directed to conservation tillage practices. The term conservation tillage covers a range of tillage practices where soil is disturbed as little as possible, and residues of the previous crop are left on the soil surface (Power *et al*., 1986). This includes reduced tillage (RT), minimum tillage and no-tillage practices (Memon *et al*., 2012). These practices differs in ploughing intensity but have the common aim of minimizing mechanical soil disturbance and therefore seems to offer the best opportunity for improving and saving soil water (Van den Putte *et al*., 2010).

Improved soil water status in semi-arid areas was realised under RT compared to conventionally ploughed treatments as per the following studies: Berry *et al*. (1987); Dumanski *et al*. (2006); Mupangwa *et al*. (2007); Thierfelder & Wall (2009); Ngwira *et al*. (2012). With RT, mechanical soil disturbance is kept at minimum level as possible and this is especially beneficial when combined with crop residue retention. The crop residues enhance infiltration by trapping rainwater on the soil surface and simultaneously reducing water runoff across the land (Peterson *et al*., 2006; Govaerts *et al*., 2007; Mupangwa *et al*., 2007; Verhulst *et al*., 2011a). Thierfielder *et al*. (2013) reported increased rainwater infiltration in RT plots of about 24–40% greater than in CT plots. Berry *et al*. (1987) have shown how water storage increase with increasing amount of crop residues on the soil surface. Under dryland conditions, increased soil water storage under RT can potentially provide better assurance against intra-seasonal dry spells (Dumanski *et al*., 2006; Zhang *et al.*, 2011).

With CT, poor water storage is ascribed to increased evaporation due to the drying effect of wind and surface exposure to sun rays. Water losses in the form of run-off are also reported because of a sealed surface caused by the negative impact of splashing raindrops on soil aggregates (Hobbs *et al*., 2008; Verhulst *et al*., 2011a). Kosgei *et al*. (2007) reported that about double as much water runoff was produced from CT treatments than from RT.

In the long term, a RT system could lead to improved soil organic matter and associated advantages such as increased aggregate stability and water holding capacity (Shaxson & Barber, 2003; Reicosky & Saxton, 2007). These improvements in soil physical properties will result in enhanced soil water capture and storage (Beukes, 1992; Peterson *et al*., 2006). Soil pores resulting from undisturbed root channels of the previous crops and greater microbial activity, supported by crop residue, may help maintain large, continuous pores at the soil surface which are necessary for infiltration (Shaxson & Barber, 2003). Doube & Schmidt (1997) also showed how soil biological activity is improved in RT with residue retention.

2.2.2 Effect of cropping patterns on soil water

Intercropping, the practice of growing two or more crops on the same piece of land at the same time is a very widespread practice in developing countries (Willey, 1990). In most cases, maize is intercropped with legumes such as cowpeas for the purpose of efficient utilization of resources and to reduce the risk of total crop failure (Ghanbari *et al*., 2010). Higher soil profile water content is anticipated under intercropping practice in a variety of environments. Intercropping can improve SWC through shading effect of canopy cover and protection of the soil surface from raindrop impact, thereby increasing water infiltration into the soil (Walker & Ogindo, 2003; Ghanbari *et al*., 2010). Evaporative losses from bare inter-rows of crops planted in monoculture may lead to lower water content (Passioura & Angus, 2010). Intercropping can therefore be a sustainable option for smallholders under dryland cropping conditions (Walker & Ogindo, 2003).

However, in a more extreme environment the benefits of intercropping are not always realised. If water supply by rainfall is less than the potential water losses from the surface and plants, intercrops grown with grain crops may compete for water and nutrient resources (Van Duivenbooden *et al*., 2000). This has been shown in semi-arid areas of Kenya, where Miriti *et al*. (2012) found reduced water content under maize/cowpea compared to a sole maize crop. Under intercropping, as the intercrops develop and canopy cover increases, more water is likely to transpire (Willey, 1990), leading to increased water demand by both crops and decreased water content in the soil. Carlson (2008) stated that having different root systems in the soil may increase uptake of water and increase transpiration.

From an economic viewpoint, an additional benefit under intercropping is increase in overall land productivity of the crops, leading to lower financial input (Friedrich & Kienzle, 2008; Nel & Purchase, 2003). Intercropping has been proven to reduce the risk of total crop failure by reducing the weed population due to shading effects (Admasu *et al*, 1996). Reduced use of pesticides and herbicides has also been reported, which in turn enhance the soil biodiversity (Dumanski *et al*., 2006).

2.3 Soil temperature as affected by tillage and cropping patterns

Soil temperature influences water and nutrient up-take by plant roots, seed germination, seedling emergence and growth, root development as well as soil microbial activity (Mazvimavi, 2011). For most crops, the ranges of ideal soil temperature for successful seed germination and plant growth is very narrow (Pregitzer & King, 2005). Soil temperatures below minimum or above maximum can be detrimental to crops, and therefore cropping systems should be aimed at optimising soil temperature (da Veiga *et al*., 2010).

The soil temperature below and above the surface depends on the energy changes between incoming and surface emitted solar radiation (Verhulst *et al*., 2010). The heat available to warm the soil depends on the weather conditions, the soil coverage and the physical properties of the soil profile such as soil composition, bulk density, and water content (Baver *et al*., 1972; Dalmago *et al*., 2004; Licht & Al-Kaisi, 2005). Most of these factors are in turn affected by the intensity and type of tillage systems.

Dalmago *et al*. (2004) stated that surface covering is the most important factor affecting soil temperature when comparing RT to CT practices. Vegetative cover, in the form of crop residues, insulates the soil and captures a large amount of sunlight, causing less heat to flow into the soil and protecting the soil beneath from getting as warm as the bare soil during hot days (Berry *et al*., 1987; Zhang *et al*., 2009). As a consequence of these depressive effects of crop residues, the final result is reduction in soil temperature extremes in RT systems on a diurnal basis, in comparison to CT practices (Wall & Stobbe, 1984). A decrease of about 0.8 to 2.8^{0}C due to the presence of crop residues on the surface on RT was recorded by Alletto *et al. (*2011).

According to Campbell & Norman (1998), soil temperature extremes are mostly evident in the topsoil because that is where radiant energy changes take place and therefore soil temperature variations decrease with depth during the day. Moraru & Rusu (2012) reported reduced thermal amplitudes at 0 – 15 cm depth in treatments with reduced tillage intensity compared to CT. During the night or colder periods, the incoming sun rays are lower and soil warmth is lost to the atmosphere, resulting in low temperatures in the soil profile, depending on the soil conditions (Liu *et al*., 2011). In RT systems, the residues trap the heat in the soil and therefore causing less heat to be lost to the atmosphere, thus moderating soil temperature extremes (Baver *et al*., 1972).

Intensively tilled soil is associated with low water content, increased soil porosity and consequently higher soil temperature under CT (Sarkar & Singh, 2007). According to Arya (2001), the water in the soil surface and subsurface also has potential to reduce soil temperature during the day. This is caused by evaporative losses of water from the soil and that can result in higher temperatures in dry soil.

The insulation effect of crop residues on the surface is the same as for a cover crop or in intercropping system. As the intercrops grow and increase its foliage, the soil surface gets covered. Ghanbari *et al.* (2010) observed reduction in soil temperature in plots with maize-cowpea intercropping compared to those with sole maize stand. The investigator explained this as due to the shading effect of two crops in the intercropping system, which also reduced water evaporation from the soil surface.

2.4 Maize production under dryland conditions

Maize (*Zea mays* L.) belonging to the grass family Gramineae, is ranked the third most important cereal crop after wheat and rice in the world. It is an important staple food in many regions, is also used as animal feed and in industrial manufacturing

(Huang *et al*., 2006). In South Africa, maize is the main grain crop and is the most broadly grown field crop, followed by sugarcane and then wheat (Fowler, 1996).

About 60% of SA's arable land is covered by maize, constituting about 70% of grain crop production in the area (Akpalu *et al*., 2008). South Africa continues to face the need to increase maize production to meet demand of its own growing population and for exports to other countries. About 50% of the maize in the Southern African Development Community (SADC) region is produced in South Africa, and it is therefore the major source of food for the Southern African region (Akpalu *et al*., 2008).

Although maize is a summer crop, longer and frequent water stress (Durand, 2006) and soil temperature extremes during the growing season could have detrimental effects on its development, which leads to grain yield reduction (Akpalu *et al*., 2008).

2.4.1 Water requirements

According to Du Plessis (2003), maize needs about 450 to 600 mm of water for the whole growing season. Water plays an important role in crop seed germination, during the process of photosynthesis by which crops manufacture their own assimilates and for extraction of nutrients from soil by plant roots (Shaxson & Barber, 2003). Therefore, any occurrence of water shortage during the growing season may limit crop development, crop growth and final yield.

Maize water use pattern and requirements are mostly dependent on their development stage (Moeletsi, 2004). Maize tends to require more water as it develops, because of increase in crop height and the leaf area, resulting in increase in evapotranspiration rate (Allen *et al.,* 1998). The effects of water shortage at specific maize development stages during growing the season are well documented in literature. Occurrence of water stress during crop establishment, at flowering and during grain filling has the potential to greatly reduce grain production (Guelloubi *et al*, 2005). According to Asare *et al.* (2011), maize grows exceptionally well when supplied with sufficient water, but it can also stand dry periods, particularly during the early weeks (three to four weeks) of growth. Huang *et al.* (2006) reported that prolonged water stress at seedling stage may harm the development of secondary roots.

The reproductive stage of tasseling, silking, and pollination is reported to be more sensitive to water stress than all development stages (Cairns *et al*., 2012). According to Cairns *et al*. (2012) and (FAO, 2012), water stress, combined with high temperatures during the reproductive stage could account for significant reduction in grain yield, due mainly to a reduction in grain number per cob. Hall (2001) reported that even a short dry spell at tasseling may result in poor kernel development. Zaidi *et al.* (2004) observed maize cobs that have very few kernels due to decreased anthesis and silking caused by lengthy soil water shortage during the reproductive stage.

Low water content in the soil may reduce water uptake by plant roots, leading to dehydration of leaves, which subsequently result in stomatal closure. The closed stomata further lead to reduced photosynthesis, and therefore reduced growth and biomass accumulation (Shaxson & Barber, 2003). Water shortage may negatively affect stem elongation and leaf enlargement, causing the crop to intercepts less sunlight. These effects may result in low above ground biomass production (Udomprasert *et al*., 2005) and cobs with poor kernel development (Zaidi *et al*., 2004).

2.4.2 Soil temperature requirements

It has been shown that germination and emergence becomes more rapid as the soil temperature increases, but up to certain level (Baig & Gamache, 2005). At 20 ^{o}C, maize seeds should begin to germinate and emerge within six days after planting (IITA, 2009), provided soil water is also available. At temperatures of below 10 ^{o}C, maize seeds will not germinate. The ideal minimum soil temperature requirement for germination and early seedling growth is 12°C or greater, and for maize growth and development the optimum is between 18 to 32°C (Belfield & Brown, 2008). However, Moeletsi (2004) stated that crop seedlings are not likely stressed by cooler soil temperatures alone, but this condition may slow down the emergence.

Maize biomass and grain yield are reported to be greatly improved when average daily temperature is around 27°C at 100 mm soil depth (Moeletsi, 2004). Stone *et al*. (1999) observed that at higher temperatures maize is able to quickly reach maximum leaf area index through fast-tracked rate of "full leaf expansion". According to Belfield and Brown (2008), the temperature at tasseling stage should be 21 to 30°C, with temperatures exceeding 35°C regarded as inhibitory. Maize temperature requirements for best flowering is 19 to 25 ^{0}C. Increases in soil temperature also speed-up bio-physical processes such as soil microbial activity (Dalmago *et al*., 2004) and water and nutrients up-take by plant roots (Mazvimavi, 2011).

2.4.3 Fertilizer requirements

Fertilization is one of the key factors for increased crop growth and yield. Shortages of essential major elements such as Nitrogen (N), Phosphorus (P) and Potassium (K) can extremely retard growth and development. Law-Ogbomo & Law-Ogbomo (2009) recommended the optimum fertilizer application level of 60 kg ha^{-1} N, 27 kg ha^{-1} P and 50 kg ha^{-1} K as effective for the optimum growth and yield of dryland maize. Phosphorus is mainly needed by plants for good root development, whereas nitrogen is needed for improved foliage production. The improved rooting system and improved foliage may enable better soil water uptake and this is especially important in dryland areas (Shaxson & Barber, 2003).

In dryland areas, soil water shortage may negatively affect nutrient uptake (Suriyagoda *et al*., 2014). Nutrients are extracted from soil by plants through the process of diffusion, which may be limited in dry soil (Suriyagoda *et al*., 2014). This suggests that even supra-optimal fertilizer levels may not result in improved yields when water is a limiting factor. Bennet *et al*. (1989) found that combined water and nitrogen stress extended the period from emergence to reproductive stage.

2.4.4 Maize performance as affected by tillage and intercropping under dryland conditions

Greater improvements in maize yields are expected from RT due to increased soil water, as was found in a wide range of environments (e.g Thierfielder & Wall (2009) and Baker & Saxton (2007)). Similarly, Wang *et al*. (2011) reported about 5–20% increase in maize grain yield under RT compared to CT. On the same breath, Thiagalingam *et al*. (1991) also reported 42% maize yield benefit under no-tillage, relative to CT. The authors pointed out that maize performance under no-tillage was much better during dry growing seasons due to higher soil water content. This confirms the potential beneficial effects of RT in providing favourable soil conditions such as increased soil water and adequate temperatures. Soil water content in the crop root zone permits growth of good root systems that are effective in soil water and nutrient uptake (Thiagalingam *et al*., 1991; Nyakudya & Stroosnijder, 2011).

The increased soil water content under RT can result in lower soil temperature, and that is often linked to reduced germination rate and low grain yield. Verhulst *et al*. (2011a) observed slower maize seedling growth but the growth rate was fast-tracked at later stages, which resulted in high grain yield. Similarly, Berry *et al*. (1987) found that seeds planted under surface cover took longer time to germinate and seedling growth was slow. Hayhoe *et al*. (1996) also found reduced stand in RT compared conventionally tilled plots.

Fengyun *et al.* (2011) is of the view that low temperatures under RT could be good for summer crops, as the harmful effect of high temperatures will be reduced, and therefore evaporation will be reduced, resulting in improved soil water content. According to Govaerts *et al*. (2007), higher soil water in RT is beneficial only if such water is available for crop uptake during critical growing periods such as reproduction stage. The authors found increased wheat yield in no-tillage with crop residues due to greater water content during the flowering stage.

In some studies, maize yield improvements under RT were only realized after several years of CA practice. Farooq *et al*. (2011) analysed about 25 experiments under rainfed agriculture and concluded that the increase in crop yields under CA was slim as compared to conventional tillage. This was also supported by Govaerts *et al*. (2009) who found improved crop yields in RT with residue retention after a period of up to 10 years of continuous practice. Further evidence came from a five year study conducted by Ghuman & Sur (2001). The latter authors reported that CT out-performed RT during the first two years in terms of maize grain yield production.

The use of legumes as intercrops can serve as a cheaper source of organic fertilizers. Legumes may contribute N though biological N fixation and therefore not compete with maize for inorganic N fertilizers (Adu-Gyamfi *et al.,* 2007). That is especially beneficial on soils with poor N content (Vesterager *et al*., 2008). Because of this benefit, poor farmers continue to depend on intercropping as a valuable system to avoid risks (Kutu & Asiwe, 2010; Mousavi & Eskandari, 2011).

Intercropped legumes may also benefit subsequent maize yield through water conservation and weed, insect and pest control (Ghanbari *et al.,* 2010). In sole cropping, root systems tend to take up soil water and nutrients from the same root zone, leading to a decrease in nutrient availability, which may reduce maize yields. Ngwira (2012) found increased maize yield with no tillage, crop residue retention and intercropping with legumes. As with soil water, efficient nutrient extraction is often assumed to be higher because of higher root concentrations in the root zone (Willey, 1990).

In some cases, intercropping maize with legumes may reduce the maize grain yield due to competition of resources because of increased plant population. Miriti *et al*. (2012) found lower maize grain yield under intercropping because of water shortage during the growing season, which resulted in increased water competition between the crops.

2.5 Soil water content measurement methods

Accurate measurements of soil water content (SWC) are critical for a variety of plant-soil-water and hydrological studies. Soil water content can be measured directly by the gravimetric method, or indirectly using the neutron scattering method such as neutron water meter (NWM) Indirect methods, as the name implies, do not measure soil water content directly, but measure a property that can be related to soil-water content by using calibration equations (Bittelli, 2008). However, that property measured by the sensors is expected to be affected by the soil physical characteristics and chemical composition, thus affecting the quality of soil water data.

The NWM has been widely used for more than 50 years due to its speediness, ability of measuring a large soil volume and the possibility of scanning at several soil depths (Zazueta & Xin, 1994). During measurements, a radioactive probe is lowered to different depths into an access tube pre-installed vertically into the soil (Evett *et al*., 2003). High energy neutrons emitted into the soil from a radioactive source rapidly slow down and become thermalized when they collide with low atomic mass substances such as hydrogen (Schmugge *et al*., 1980; Zazueta & Xin, 1994). The assumption is that, in soil, hydrogen is the principal neutron thermalizer and that it occurs primarily in soil water (Chanasyk & McKenzie, 1986). The number of thermalized neutrons re-emitted towards the probe per unit time are counted and then used to estimate SWC (Grimaldi *et al.,* 1994; Chanasyk & Naeth, 1996).

It is well documented that elements such as boron, chlorine, iron, potassium and carbon are also neutron thermalizers, and may interfere with the scattering and absorption properties of the soil (Chanasyk & McKenzie, 1986; Hignett & Evett, 2002). The neutron absorbing elements existing in the soil can reduce NWM count rates and this reduction is related to SWC. This could result in a drop in the gradient of the calibration curve (Yuen *et al.,* 1997). Their abundance in the soil can introduce errors in soil water determination (Yuen *et al.,* 1997). Similarly, hydrogen content in soils with a high percentage of clay minerals and organic matter will contribute to the total count rate of NWM (Goldberg *et al*., 1955), resulting in overestimation of SWC.

High soil salinity (especially in arid and semi-arid environments) can also influence the concentration of thermalized neutrons (Fares & Polyakov, 2006).

To account for the influence of within profile and horizontal soil variations on sensors' response, several authors pointed out the field calibration of the sensors as a critical step on which the accuracy of water content monitoring greatly depends (Grimaldi *et al.,* 1994; Chandler *et al*., 2004). Although general calibration equations are usually provided by the manufacturers, evidence exist that these equations are generally not appropriate to establish exact SWC estimates of specific soils. A specific field calibration of each individual sensor for the specific soils and conditions in which they will operate is therefore recommended (Seyfried & Murdock, 2004; Hignett & Evett, 2002; Chanasyk & McKenzie, 1986).

The sensors are calibrated using the gravimetric method, which determines SWC by using the difference in mass before and after oven-drying the soil sample for approximately 24 hours at 105^{o}C (Walker *et al.,* 2004). Water content is expressed as the mass of water over the mass of dry soil (g/g) (Muñoz-Carpena, 2009). If a specific volume of soil is used, the volumetric water content is achieved by multiplying the gravimetric value by the soil bulk density (Schmugge *et al*., 1980). Although this method is destructive and time consuming (Zazueta & Xin, 1994), it is accurate and inexpensive.

CHAPTER 3: GENERAL MATERIALS AND METHODS

3.1 Study site

This study formed a component of a larger multi-disciplinary project being conducted by ARC-Institute for Soil, Climate and Water. The project started in 2007, but the current study only focused on selected plots within the broader study and also only for the growing seasons 2010/11 and 2011/12. The larger project is being conducted as an on-station field trial at the ARC-Animal Production Institute (ARC-API), Roodeplaat Experimental Farm at Zeekoegat (25º36’55”S and 28º18’56”E, altitude of 1249 m above sea level) under dry land conditions. The soil at Zeekoegat consists mostly of deep red soils with moderately fine to medium blocky structure and clay texture. The soil form is a Shortlands, with underlying Gabbro (Soil Classification Working Group, 1991). Concretions occur from 60 cm downwards, and are more abundant on the southern side of the trial (Swanepoel *et al*., 2010).

3.2 Climate

The temperature data during the respective growing seasons were obtained from an ARC-ISCW Roodeplaat automatic weather station at a bearing of 72^{o} from true north (north east) and at a distance of 4.1 km from the trial site (Table 5.3). Daily rainfall during the growing seasons was recorded with an automatic rainfall gauge that was installed at the trial site (Fig 5.1).

3.3 Experimental design and treatments

The experimental layout of the bigger trial was a split-plot randomized complete block design, replicated three times, with each replicate split into two tillage systems (whole plots) and then each whole plot (tillage system) was subdivided into 12 treatments (two fertilizer levels x six cropping systems) (Appendix 1). For the purpose of this study, two cropping patterns (maize monoculture and maize-cowpea intercropping), two fertilizer levels (low and high) as well as tillage systems, conventional tillage (CT) and reduced tillage (RT), were considered. These eight treatment combinations were replicated three times. Plot dimensions were 7.2 m wide and 8 m long, giving a total plot area of 57.6 m^2 (0.00576 ha) each. Measurements were taken towards the centre of plots to limit the effect of nutrients movement between plots.

3.4 Trial preparation

Trial preparations started in October each year, when crop residues remaining from the previous growing season were slashed into smaller pieces to avoid large pieces of residues being dragged across the field during soil preparation. The CT treatments were ploughed with a mouldboard plough and then disked with a disc harrow at the end of November, while the RT plots were only slashed. At planting, eight plant row furrows per plot were drawn 0.9 m apart with a four tine cultivator on both CT and RT plots.

The first herbicide application was on 26 October during the 2010/11 growing season, when glyphosate (3 L/ha) and S-metolachlor (1.7 L/ha) were mixed and applied in 200 litres of water, while Sodium cacodylate (7 L/ha) and 400 L/ha of water was applied on 24 November during 2011/12. A tractor and calibrated sprayer were used to apply the herbicides. In December and February, insecticide (40% Cypermethrin WP at 250 ml/ha) was applied to combat stalk borers. Manual weeding was done at the end of January and February.

3.5 Crop husbandry

Planting of the main crop (maize) was on the 29 and 30th of November during both seasons, while the cowpea intercrop was planted about three weeks later. Planting was done by hand at a spacing of 0.3 m to yield a plant density of 37 000 maize plants ha^{-1} and cowpea at 120 000 plants ha^{-1}. Standard row spacing (0.9 m) was used for the maize (yellow maize cultivar 6P/110 from United Seed) monoculture plots, while tramline rows (1.8 m spacing between maize) were used for the intercropping plots. Three rows of cowpea were planted in the 1.8 m strips between maize rows.

Fertilizer (N, P and K) was applied at two levels, *viz.* a high fertilizer input (F2) which is based on optimum target maize yield of 4 ton ha^{-1} (dryland production) and a low fertilizer input (F1) which was 50% of F2 (MVSA, 1997). A similar level of fertilizer application rate was selected for inoculated cowpea, but with different fertilizers to account for the N fixing ability of legumes.

For maize (treatment F2), N fertilizer in the form of Limestone ammonium nitrate (LAN) was applied at 42 $kgha^{-1}$ N at planting, with a follow-up fertilizer application of 28 $kgha^{-1}$ N. A total of 70 $kgha^{-1}$ N was therefore applied, in accordance with the fertilizer guidelines (MVSA, 1997). Application for F2 per plant row (8 m) was 108 g LAN and F1 treatments received half, i.e. 54 g per 8 m row. The P fertilizer was applied as Supergrow (20.3% P) at 39.4 $kgha^{-1}$ P, which is 28.4 g per row for F2 and 14.2 g per row for F1. Cowpea rows in the F1 treatment received 28 g per row of Supergrow, and F2 received 56 g per row. A combination of Supergrow and LAN was used for maize crops, while only Supergrow was used for the legume intercrops. According to the soil analysis (Appendices 2 and 3), the average K in the soil (0-60 cm) was very high at 462 mg/kg (soil K level of >200 mg/kg is considered high) (Mandiringana *et al*., 2005). According to those fertilizer guidelines, no additional K was needed for the target yield.

CHAPTER 4: CALIBRATION OF NEUTRON WATER METER (NWM)

4.1 Introduction

To account for the effect of soil physical and chemical properties in the soil on the response of sensors for measuring soil water content (SWC), field calibration for specific soils is necessary (Grimaldi *et al.,* 1994). Universal calibration equations are usually provided by the manufactures, but they are generally not applicable to all soil types and therefore may result in over estimation or under estimation of SWC (Chanasyk & McKenzie, 1986; Hignette & Evett, 2002).

Research has shown that water content for stony or concretion-rich soils can be wrongly estimated. This is because concretions can occupy a significant volume in the soil and contribute noticeably to the mass (and consequently the soil bulk density) without making an equal contribution to the water capacity of the soil (Black *et al.*, 1965; Gardner, 1986). It is therefore imperative to correct bulk density and SWC values for the presence of concretions in the soil (Klute, 1996).

According to Bell (1987), each element has its own capacity to scatter or capture fast neutrons, thus affecting the NWM counts to a certain extent. The magnitude of capturing or scattering depends on the nuclear cross section of an element measured in “barns”. The elements Cadium (Cd), Boron (B), and Chlorine (Cl) are reported to have large capture cross sections, making them more capable of absorbing thermalized neutrons, which may reduce the number of slow neutrons returning to the detector (Bell, 1987). The capture cross sections for Cl, Iron (Fe) and Potassium (K), for example, are 34, 2.53 and 2.07 barns, respectively (Gardner, 1986) while manganese (Mn) has a barn value of 13.2 (De Juren & Chin, 1955). The higher the barn value, the more thermalized neutrons are captured. Burn (1966), as quoted by Visvalingam & Tandy (1972), reported that in a field calibration of a NWM, 9% of the neutron activity was reduced by a Fe content of 7% by weight. Holmes & Jenkinson (1959) found that increasing soil B concentration decreased the slope of the calibration curve. Grismer *et al*. (1995) found no significant correlation between count ratio and saturation extract Cl concentrations ranging from 355 - 3550 mg Cl L^{-1} and concluded that no adjustments to the NWM calibration equations were necessary to reflect Cl interference.

A review by Visvalingam and Tandy (1972) mentions that: (1) A Cl concentration of about 7400 mg Cl kg^{-1} soil can produce an underestimation of 10% in SWC values; (2) Soil K and magnesium can absorb neutrons to cause an underestimation of SWC; and (3) a soil Fe content of about 7% can reduce neutron activity by 9% at every SWC value. Al-Ain *et al.* (2009) found a lower correlation coefficient for the NWM calibration equation when soil Electrical conductivity (EC_e) values increased. Consequently, by including the latter parameter a slight improvement in the calibration equation was achieved under both wet and dry conditions. Phillips (2010) found that EC_e could only account for 3% in the variation of count ratio and, consequently, disregarded the effect of this soil property in the NWM calibration equation. Weber (2001) supplies a simple procedure to account for potential neutron absorption when calibrating a NWM. The author concludes that the calibration line requires a steeper slope to account for the missing neutrons that can be absorbed *inter alia* by B, Cd, Cl and Fe.

Variations in soil bulk density also have an effect on probe count vs. SWC and should be compensated for during the calibration process (Marais & De V Smit 1962; Lal 1974). In order to calculate volumetric SWC, as well as the depth of water in a soil profile, it is imperative that soil bulk density must be known (Gardner, 1986). The present study was conducted on a clay soil that contained varying amounts of >2 mm concretions (probably Fe and manganese hydroxy-oxides) with depth (Swanepoel *et al*., 2010). Taking into account the latter phenomenon, the following objectives were formulated for this chapter:

(1) To calibrate the neutron water meter against gravimetric measurements for determining soil water content;

(2) To determine which soil and concretion properties and elements (other than H) have a neutron capture/absorbing effect during the field calibration of the NWM; and

(3) To establish the statistical relationships between these parameters and NWM count ratios.

The following hypotheses were tested:

$H_0$1: Corrections for concretions on soil bulk density in the calibration will improve accuracy of NWM readings.

$H_0$2: The soil and concretion properties and elements (other than H) have neutron capture/absorbing effect on NWM field calibration.

$H_0$3: Statistical relationships exist between NWM count ratios and soil and concretion properties and elements.

4.2 Materials and methods

Field calibrations were performed whereby the NWM (Waterman neutron moisture probe, Model 2000) was calibrated against the gravimetric method (Gardner, 1986). Gravimetric soil water content (θg) measurements were done on seven occasions; 2 September 2010, 24 February 2011, 20 April 2011, 21 June 2011, 1 September 2011, 16 February 2012 and 30 May 2012. Soil samples were collected with an auger on selected plots at depth intervals shown in Table 4.1 and then put in a water tight bottle to prevent water loss from the soil. Gravimetric water content (Θg) was determined using Equation 4.1.

$$\Theta g = (\text{mass of wet soil} - \text{mass of dry soil}) / \text{mass of dry soil} \qquad (4.1)$$

Table 4.1: Soil depths for gravimetric and NWM soil water content (SWC) measurements

Method	Soil depth (mm)					
Gravimetric SWC	0-225	225-375	375-525	525-750	750-1050	1050-1350
NWM	150	300	450	600	900	1200

Soil bulk density was determined by Swanepoel *et al*. (2011) at each of the depth intervals in one profile pit per replicate/block as follows: Core samples (volume 295.4 cm^3) were taken in duplicate in the centre of each depth interval by excavating in a step-like way a side wall of the profile pit. These samples were transferred to paper bags and oven-dried at 105 ^oC for 24 hours. Concretion masses and volumes per individual soil core were also determined (samples were sieved to separate masses of the fractions >2 mm (concretions) from masses of <2 mm (soil)) in order to adjust bulk densities to a <2 mm soil fraction as recommended by Gardner (1986) and Klute (1996). Mean soil bulk density values for the duplicate samples were calculated and then multiplied by θg values to obtain volumetric soil water content (θv) expressed as percentage as shown in Equation 4.2 (Gardner, 1986).

$$\Theta v = \Theta g \times (\rho b / \rho w) \times 100 \quad (4.2)$$

Where ρw refers to density of water,

ρb refers to soil bulk density

Simultaneous NWM readings (counts) were recorded weekly, but for the purpose of calibration, data measured on the dates (dates above) and plots where gravimetric measurements were performed was considered. Table 4.1 shows the depths of measurements for the NWM method. Before each soil water measurement session, standard counts were taken with the probe in its shield and positioned on top of its carrying case. These counts were recorded for the purpose of calculating a count ratio (CR), which was done using equation 4.3

$$CR = Rd / Rsh \quad (4.3)$$

Where Rd is the counts taken for the soil and Rsh is the average of standard counts.

The volumetric SWC was then plotted against CR to obtain calibration equations.

Determination of the relationship between selected soil variables and NWM counts

Volumetric soil water content, soil and concretion properties and elements were determined on the soil samples from the calibration plots used for gravimetric soil water determination. The assumption was made that the calibration was based primarily on H from soil water because: (1) gravimetric SWC was determined at 105^{o}C (thereby excluding structural H in the clay minerals), and (2) mean soil organic matter (SOM) was only 2.5% and 1.9% in the A and B horizons, respectively (Swanepoel *et al*., 2010). According to Visvalingam and Tandy (1972), the contribution of H by SOM contents of up to 5-10% is negligible. These samples were composited per replicate and depth increment (depth increments were combined into 0-375, 375-525 and 525-1050 mm; the 1050-1350 mm interval was excluded and composite sub-samples taken. The samples were sieved and the masses of the fractions >2 mm (concretions) and <2 mm (soil) determined. Sub-samples of the concretions were ground and powdered to <0.5 mm diameter. Table 4.2 indicates the properties and elements that were included in the study, as well as their methods of determination.

Table 4.2 Extraction and measurement methods for soil chemical and physical properties

Sample type	Property/element analysed	Analysis method
NWM	Thermalized neutrons	Count ratio (Gardner, 1986)
Whole soil	SWC	Gravimetric (Gardner, 1986)
Soil (<2 mm) and Concretions (>2 mm)	Clay and silt	Pipette (Gee & Bauder, 1986)
	Chloride (Cl)	Extraction: Saturation extract (The Non-Affiliated Soil Analysis Work Committee (1990). Measurement: Liquid chromatography (Tabatabai & Frankenberger, 1996)
	Electrical conductivity (EC_e)	Extraction: Saturation extract (The Non-Affiliated Soil Analysis Work Committee (1990). Measurement: Conductivity-Cell (Rhoades, 1996)
	Potassium (K)	Extraction: Acid digestion (EPA 3050B, 1996) Measurement: ICP-MS (Parviz *et al*., 1996).
Concretions (>2 mm)	Iron (Fe)	Extraction: Dithionite-citrate-bicarbonate (The Non-Affiliated Soil Analysis Work Committee (1990). Measurement: ICP-MS (Parviz *et al*., 1996).

4.3 Statistical analysis

Calibration

Statistical analysis entailed a simple linear regression analysis of the data in order to determine the relationships between θ_v and NWM count ratio (equation 4.4). The regression coefficient “b” was tested with the Student’s t distribution, while the linear correlation coefficient, r, was tested against tabular r values.

$$\Theta v = a\,CR + b \qquad \text{(equation 4.4)}$$

CR is the count ratio, *b* and *a* are intercept and slope parameters, respectively.

Determination of the relationship between selected soil variables and NWM counts ratios

Soil and concretion analysis values were adjusted prior to statistical analysis according to the mass of concretions present per depth increment. The dataset comprised 21 sets of values on which simple linear regression analyses (Gomez & Gomez, 1984) were performed in order to determine the relationships between NWM count ratio, soil and concretion properties and elements. The regression coefficient "b" was tested with the Student's t distribution, while the linear correlation coefficient, r, was tested against tabular r values (Snedecor & Cochran, 1967). The "r" value is indicative of the closeness of fit between the estimated regression line and the observed points. Stepwise multiple regression analyses (SAS Institute Inc. 1999) were also performed on the data set, with the dependent variable (Y) taken as the NWM count ratio vs. the independent variables (X) being the properties and elements.

4.4 Results and discussion

Calibration

According to Pennock & Appleby (2003), corrections are of high importance for the soil with higher concretion content. In the present study, concretion distribution in the soil profiles has shown great variation, both vertically and horizontally among the replicate blocks (Fig 4.1). Maximum values ranging between 40-54 % occurred at different soil depths. From Fig 4.1, it is clear that the correction/adjustment of soil bulk densities to compensate for concretion fractions had a profound effect on final bulk density values - the larger the amount of concretions, the higher the bulk density. These results conform with the view of Pennock & Appleby (2003). For example, for the 525-750 mm layer of Profile Pit No 1, the original bulk density of 1.57 g cm^{-3} was adjusted to 1.11 g cm^{-3} due to the presence of 54 % gravel. The corrected (Soil-concretions) bulk densities that are depicted in Fig 4.1 show large variation among the replicate blocks and would have a significant effect on volumetric SWC (Klute, 1996). The decision was then made (Swanepoel *et al*., 2011) to calibrate the NWM for each replicate in order to more accurately calculate SWC from NWM readings.

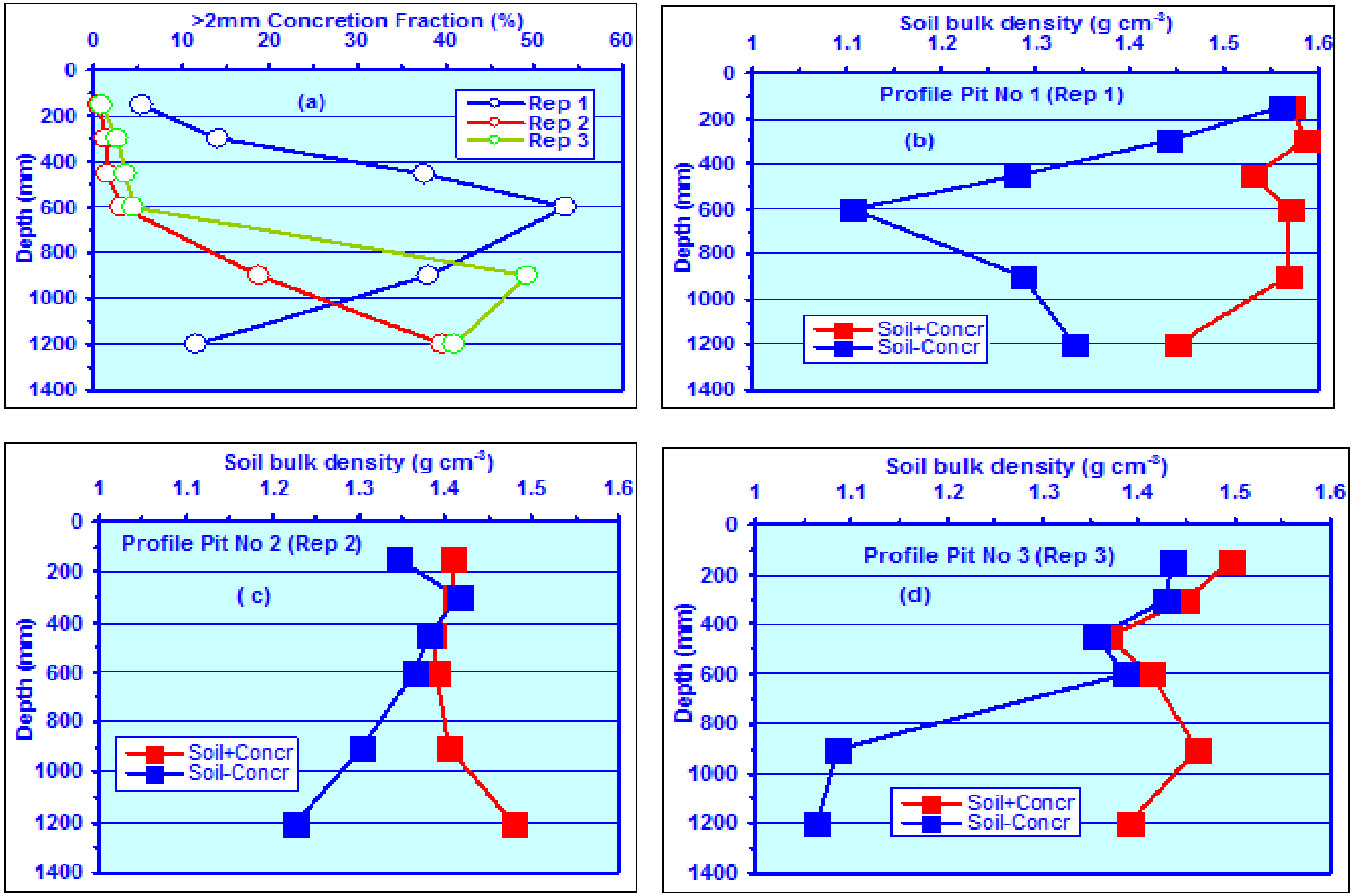


Fig 4.1: Concretion fraction and soil bulk density data for the experimental site before and after correction for concretion content.

Statistical data for the linear relationships between CR and θv (including calibration equations) are given in Appendix 3 and 4, while Table 4.3 shows coefficient of variations and variances for the relationships before and after correction of variances. The R^2 values indicate that 37 – 80 % of the variation in θv is accounted for by the linear functions. Highly significant correlation coefficients (r) were calculated for all linear relationships.

The explained variance (R^2) decreased with depth for block 1 from 77 to 37 % at 525-750 mm. When comparing these results with the concretion distribution of block 1 in Fig 4.2 it can be seen that the lowest R^2 value (37%) appears at the maximum concretion content of 54 % at 600mm depth. In the present study, the R^2 and coefficient of variations were generally the same before and after corrections of concretions. This is contrary to the view of Marais and De V Smit (1962) and Lal (1974) that abundance of concretions has a significant effect on the relationship between NWM count ratios and θv. It was observed that the three blocks yielded different calibration equations for the various depth increments, hence the decision to process routine NWM readings per individual calibration equation.

Table 4.3 A: Correlation coefficients and variances for NWM for different replicates and soil horizons (0 – 750 mm) before and after corrections for concretions

Depth Increment (mm)	Block	Df	Corrected for concretions		Before correction of concretions	
			Variance explained (R^2, %)	Correlation coefficient (r)	Variance explained (R^2, %)	Correlation coefficient (r)
0-225	1	24	77	0.8780***	79	0.888819***
	2	24	77	0.8758***	78	0.883176***
	3	23	80	0.8923***	81	0.9***
225-375	1	24	67	0.8201***	67	0.818535***
	2	24	78	0.8823***	78	0.883176***
	3	24	79	0.8862***	77	0.877496***
375-525	1	24	46	0.6772***	46	0.678233***
	2	24	53	0.7269***	53	0.728011***
	3	24	75	0.8640***	75	0.866025***
525-750	1	22	37	0.6090***	42	0.648074***
	2	24	56	0.7477***	55	0.74162***
	3	22	80	0.8935***	80	0.894427***

Table 4.3 B: Correlation coefficients and variances for NWM for different replicates and soil horizons (750 – 1350 mm) before and after corrections for concretions

750-1050	1	23	40	0.6275***	24	0.489898*
	2	24	64	0.8012***	64	0.8***
	3	24	74	0.8597***	79	0.888819***
1050-1350	1	21	39	0.6261***	39	0.6245***
	2	24	61	0.7803***	61	0.781025***
	3	24	71	0.8446***	76	0.87178***

The relationship between selected soil variables and NWM counts

From Table 4.4, it was found that *linear regression coefficients* have shown that the linear response of NWM count ratios to individual variables in their respective ranges was not significant at the 5% level of significance (t-test). The *Correlation coefficients* (r) have shown statistically significant positive relationships of NWM count ratio vs. volumetric SWC. This is in accordance with the theory of neutron scattering by H atoms (Gardner 1986). The finding of a statistically significant negative relationship of NWM count ratio vs. adjusted soil Cl is in agreement with those of Visvalingam and Tandy (1972) and Gardner (1986) that Cl can capture thermalized neutrons, leading to an underestimation of SWC. A negative relationship for NWM count ratio vs. soil K was measured. Although this trend was not statistically significant, the finding is in agreement with the findings of Visvalingam and Tandy (1972) and Gardner (1986).

Statistically negative relationships for NWM count ratio vs. soil and concretion EC_e were observed, which mean that as EC_e increases, the count ratio decreases, thereby enhancing the underestimation of SWC. Both Al-Ain *et al*. (2009) and Phillips (2010) reported effects of EC_e on the NWM calibration equation. The presence of concretion Fe did not exhibit the expected negative relationship for NWM count ratio vs. Fe (*i.e.* the capturing of thermalized neutrons) as reported in the literature (Gardner 1986). According to Visvalingam and Tandy (1972), the reduction in neutron activity was caused by a Fe content of 7%. In the present study the maximum Fe content was 4.9 % (Swanepoel *et al*., 2010). The presence of concretion Mn did not exhibit the expected negative relationship for NWM count ratio vs. Mn. With its relatively large barn value of 13.2, neutron capturing was anticipated.

Table 4.4 Statistical relationships of count ratio vs. soil and concretion properties

Description (Y vs X)	Calibration Equation (Y = a + bX)	Degrees of freedom (n-2)	t-test for regression coefficient (b)	Variance explained (R^2, %)	Correlation coefficient (r)
CR[1] vs Volumetric SWC	Y = 0.14787+ 0.06667X	19	-0.96NS[2]	55	0.7397**
CR vs Clay content	Y = 1.72301 + 0.00637X	19	0.21NS	2	0.1549NS
CR vs Clay+silt	Y = 1.67095 + 0.00550X	19	0.19NS	2	0.1416NS
CR vs Soil Cl	Y = 2.31188 - 0.07966X	19	-0.70NS	29	-0.5359*
CR vs Soil K	Y = 2.78742 - 0.00033X	19	-0.34NS	7	-0.2587NS
CR vs Soil ECe	Y = 3.42765 - 0.02019X	19	-0.92NS	46	-0.6767**
CR vs Concretion Cl	Y = 1.90350 + 0.21202X	19	0.25NS	3	0.1752NS
CR vs Concretion K	Y = 1.72999 + 0.00076X	19	0.54NS	17	0.4110NS
CR vs Concretion Fe	Y = 1.84122 + 0.00001X	19	0.39NS	9	0.2972NS
CR vs Concretion Mn	Y = 1.88207+ 0.00010X	19	0.32NS	6	0.2408NS
CR vs Concretion ECe	Y = 3.28579- 0.03418X	19	-0.71NS	30	-0.5447*

[1] count ratio;

[2] statistically not significant

* statistically significant at the 5% level of significance

** statistically significant at the 1% level of significance

The sequence of variables in Table 4.5 reflects the stepwise entering of variables into the multiple regression equation. Although the four variables in the equation had a highly significant ($p<0.0001$) effect and explain 86.9% of the variation in NWM count ratio, volumetric SWC and soil ECe account for most of the explained variation. All four variables positively or negatively affect the NWM count ratio (Visvalingam and Tandy 1972; Gardner 1986; Al-Ain *et al*., 2009; Phillips 2010).

Table 4.5 Statistical data for multiple regression analysis

Variables in equation	Total variance explained (R^2, %)	Regression coefficient	F-value	Probability (p)
Volumetric SWC	54.7	0.06264	22.9	0.0001
Soil ECe	82.4	-0.01412	42.1	<0.0001
Concretion Fe	84.4	0.00001	30.6	<0.0001
Soil K	86.9	0.00030	26.5	<0.0001

4.5 Conclusions

The abundance of concretions in the soil of the study area showed no effect on the calibration of the NWM when excluded or included from the bulk density. This suggests that the correction for concretions on the soil bulk density did not lead to improved correlation between CR and Volumetric SWC. The results of this study confirm that soil and concretion properties and elements other than H could have a neutron capture/absorbing effect during the field calibration of a NWM, and that statistical relationship between these parameters and NWM count ratios could be established. Apart from SWC, the inclusion of ECe in the calibration equation is recommended to improve the quality of soil water content measurements.

CHAPTER 5: RESPONSE OF SOIL WATER AND SOIL TEMPERATURE TO TILLAGE AND CROPPING PATTERNS

5.1 Introduction

Once the soil surface is supplied with water, it can enter into the soil, run off across the land, or pond over the surface from where it is lost as evaporation. These processes are affected by soil surface condition which is in turn affected by type of tillage and any form of soil cover (Shaxson & Barber, 2003). Tillage can therefore either damage or improve the soil environment, depending on the appropriateness or otherwise the type of cultivation practiced (Lal, 1991; Baker & Saxton, 2007).

It is well-known that reduced tillage (RT), coupled with crop residue retention, can lead to improved soil organic matter (SOM) and all the subsequent advantages such as increased water retention, fertility and, hence, soil productivity (Beukes, 1992; Bot & Benites, 2005). Crop residues left on the soil surface serve a manifold purposes by protecting the soil physically from the sun‘s radiation, raindrop impact and wind and, at the same time, increase water infiltration (Shaxson & Barber, 2003; Ngwira *et al*., 2012). This could result in reduced soil erosion and increased soil water content (SWC) (Dumanski *et al.*, 2006).

While RT seems to provide a win-win situation compared to conventional tillage (CT) in soil water conservation in a wide range of studies (Ngwira *et al*., 2012), those benefits, however, remain controversial for several reasons. Lal (1991) stated that suitable tillage practices vary among different soils and crops, as well as climatic conditions. This suggests that general benefits of RT are often not realized in some situations because the choice of tillage type depends on numerous factors. It was therefore important to evaluate the effects of tillage practices on soil profile water dynamics under local conditions.

Greater water savings are expected from intercropping practices in a variety of environments due to the shading effect of intercrops on the soil surface. In monoculture, water may evaporate from uncovered inter-rows, leading to lower SWC compared to intercropping systems (Willey, 1990). The cropping systems that lead to improved soil water storage in the root zone are especially important under dryland conditions, which is characterised by inter-seasonal dry spells. The preserved soil water can enable crops to establish successfully and survive dry spell occurrences during seasons which are normally a constraint in dryland cropping systems (Thierfelder & Wall, 2009). In contrast, Willey (1990) stated that as the intercrops develop and leaf area and therefore canopy cover increases, higher transpiration rates are expected. That could lead to increased water demand by two crops and therefore decreased SWC. Miriti *et al.* (2012) has observed lower SWC in plots under a maize/cowpea intercropping system than in maize monoculture. The authors postulated that this was due to full soil exploration and a greater water use by two crops, which increased planting density.

Tillage practices, through their effect on soil surface manipulation, are important factors affecting soil temperature (Power *et al*., 1986). Conventional tillage loosens the soil and increases soil pore spaces from which evaporation takes place. These changes on the surface speeds up soil heating and drying (Licht & Al-Kaisi, 2005). Vegetative cover, be it crop residues or cover-crops, insulates the soil and captures a large amount of sunlight, causing less heat to flow into the soil and protecting the soil beneath from getting as warm as the bare soil during hot days (Hanks & Ashcroft, 1980; Baver *et al*., 1972; Wall & Stobbe, 1984). During the night or colder periods, the incoming solar energy under protected soil is low and soil heat is lost to the atmosphere, causing lower soil temperature in the profile (Liu *et al*., 2011). Ghanbari *et al.* (2010) has clearly showed how intercropping could lead to reduced soil temperatures in intercropping systems.

Most crops are sensitive to soil temperatures that are below minimum or exceeding maximum limits for the particular crop, and therefore cropping systems that optimise soil temperature should be practiced (da Veiga *et al*., 2010). The purpose of this chapter was to determine the effect of tillage and cropping patterns on soil temperature and soil water, with the hypothesis that: Reduced tillage and intercropping practices have the potential to enhance soil water conditions and to moderate soil temperature.

5.2 Materials and methods

Soil water content was measured with the neutron scattering method (Neutron Water Meter (NWM) Waterman Model 2000)). Aluminium access tubes were installed in the intra-row area of the maize crop after planting. A hand auger (42 mm diameter) was used to drill holes to a depth of at least 1.3 m, followed by the insertion of the access tubes. After installation, all tubes were cut to protrude 100 mm above the soil surface, and then covered with an empty cool drink can to prevent rainwater from entering the access tubes. Weekly readings (counts) were taken at depths of 15, 30, 45, 60, 90 and 120 cm. The readings (counts) were calibrated against the gravimetric method (Chapter 4), to obtain volumetric SWC (%).

Soil temperature was measured with Aquacheck Basic capacitance probes. These capacitance probes had thermistors at depths of 100, 200, 300, 400, 600, and 800 mm. The probes were installed in the plant rows of 12 selected plots after the maize crop was planted (Table 5.1, extracted from Appendix 1) to a depth of 800 mm, using a special auger. Water was used during the augering process to ease extraction of the soil. Using the extracted soil, a slurry was prepared and poured into the holes before the probes were inserted to ensure good contact between the soil and the probes. Due to the nature of the project layout, the plots available for temperature measurements were fixed. The data was captured from the probes every two weeks with a hand held data logger. From the latter, the data was transferred to a computer for processing.

Table 5.1: Plots and probe numbers for soil temperature measurements

Plot number	5	7	17	19	29	34	41	46	49	60	61	72
Probe number	2417	2303	4504	2301	5470	5465	2370	2220	4513	4475	4478	5302

Prior to field installation, temperature calibrations of the thermistors were performed by Swanepoel *et al*. (2010) for all probes during October and November 2009. The obtained calibration equations were used to adjust thermistor readings of the 2010/11 and 2011/12 growing seasons.

5.3 Statistical analysis

The volumetric soil water and soil temperature readings were subjected to analysis of variance (ANOVA) and means were separated using Fisher's Protected LSD at 5% (volumetric soil water content) and 10% (soil temperature) significance level using Genstat Statistical package (Gomez & Gomez, 1984).

5.4 Results and discussion

5.4.1 Soil water content

Weekly rainfall distribution during the experiment is presented in Fig 5.1. In the 2011/12 growing season, the rainfall was low with the total of 424 mm being 267 mm less than the total rainfall received during the 2010/11 season. The best rainfall months were January for the 2010/11 and December for the 2011/12 seasons. Fig 5.1 also shows the very poor weekly rainfall distribution throughout the 2011/12 season, with a typical 'mid-summer drought' during January 2012. The observed differences in SWC among the seasons were influenced by the amount and timing of rainfall during the study.

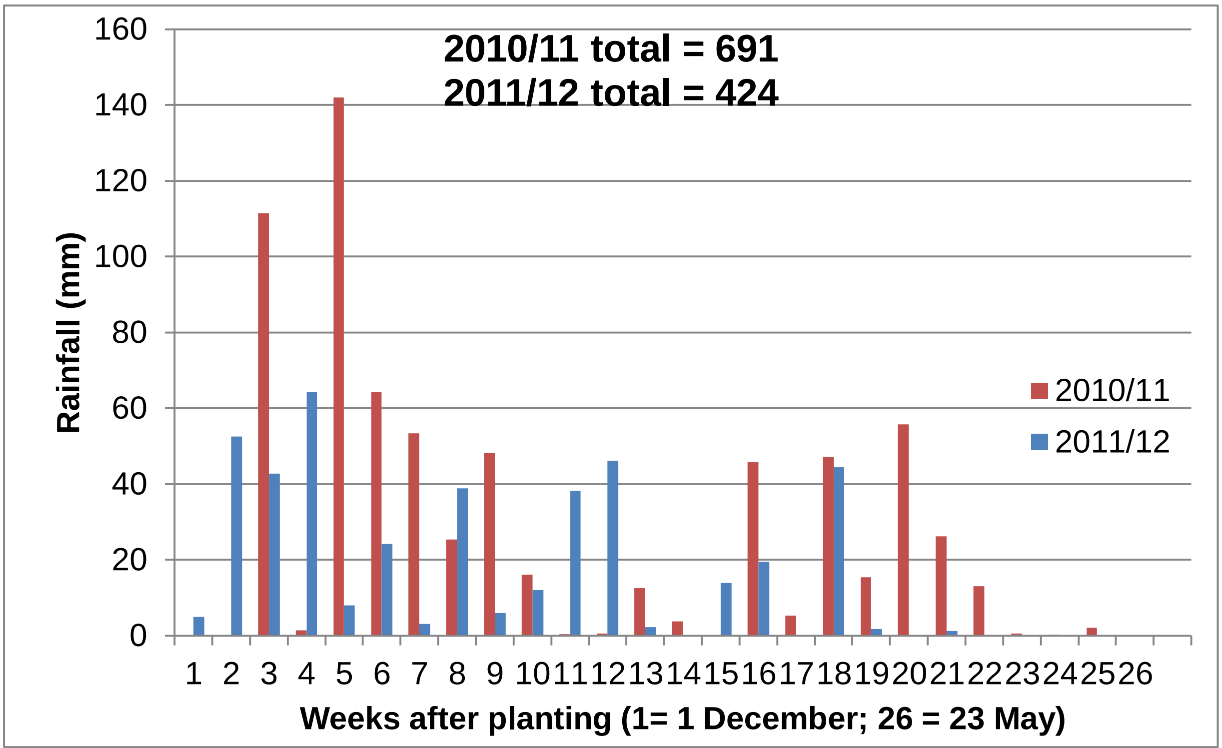
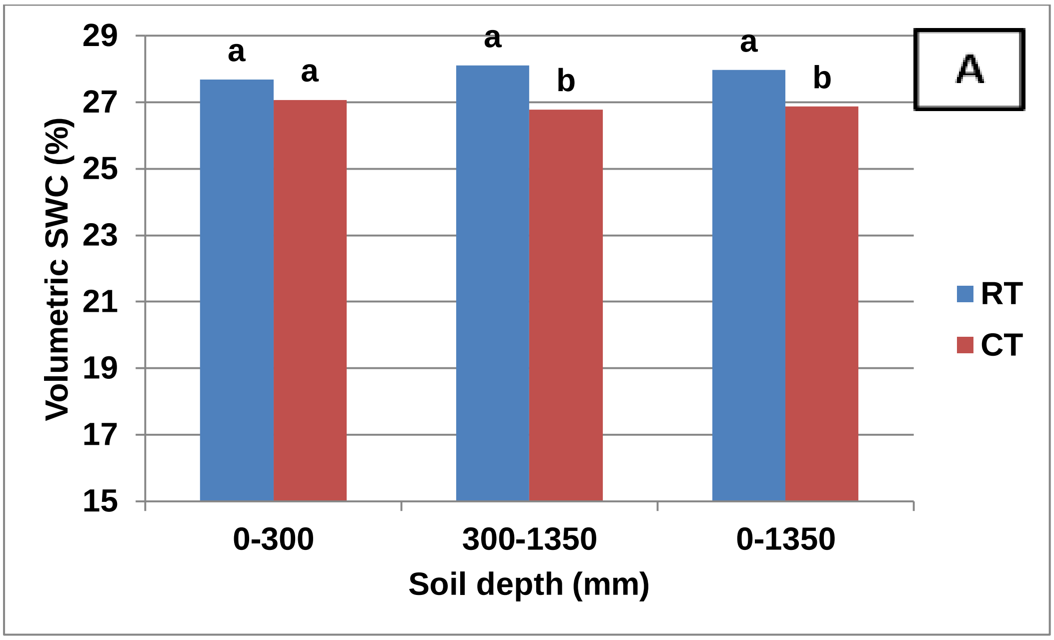


Figure 5.1: Weekly rainfall distribution for the 2010/11 and 2011/12 seasons.

The statistical significance of tillage and cropping patterns on SWC for both growing seasons are shown in Table 5.2 while LSD values are shown in Appendix 6. During both seasons, the effect of tillage on SWC was significant for the 300 – 1350 mm soil profile (subsoil) and for the total profile water content (0 – 1350 mm), but not statistically significant for the 0 – 300 mm soil profile (topsoil). As shown in Fig 5.2, the mean weekly SWC percentage of RT plots always exceeded that of CT plots at all soil depths and for both growing seasons (although differences were not always significant). For example, during the 2010/11 growing season, SWC under RT was 1.32% and 1.10% higher than CT for the 300 – 1350 mm and 0 – 1350 mm soil profile, respectively. When plotted over time (weekly intervals), for both growing seasons, SWC of the 300 – 1350 mm depth increment under RT continuously showed higher values than CT (Fig 5.3).

Table 5.2: PR> F probability values from the analysis of variance for treatment effects on SWC.

	2010/11 growing season			2011/12 growing season		
Treatments	0-300 mm	300 -1350 mm	0-1350 mm	0-300 mm	300-1350 mm	0-1350 mm
Tillage	0.260	0.008*	0.030*	0.064	0.041*	0.037*
Cropping pattern	0.05*	<.001*	0.002*	0.235	0.019*	0.043*
Fertilizer	0.973	0.049*	0.338	0.805	0.866	0.802
Tillage x cropping pattern	0.820	0.977	0.869	0.320	0.145	0.156
Tillage x fertilizer	0.711	0.957	0.754	0.462	0.892	0.574
Cropping pattern x fertilizer	0.129	0.070	0.777	0.191	0.046*	0.798
Tillage x cropping pattern x fertilizer	0.627	0.333	0.900	0.512	0.386	0.974
Week	<.001*	<.001*	<.001*	<.001 *	<.001*	<.001*
Tillage x week	0.607	0.003*	0.034*	0.355	0.980	0.752
Cropping pattern x week	0.002*	0.831	0.342	0.116	0.182	0.069
Tillage x cropping pattern x week	0.597	0.942	0.749	0.981	0.895	0.986
Tillage x week x fertilizer	0.735	0.998	0.949	0.766	0.910	0.618
Cropping pattern x week x fertilizer	0.002*	0.931	0.989	0.419	0.931	0.901



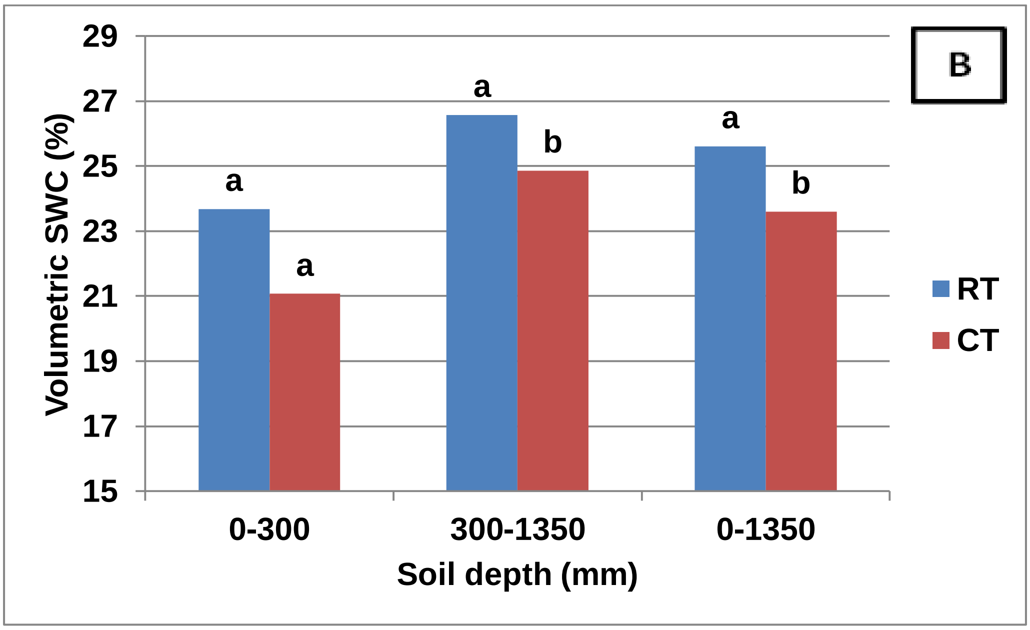


Fig 5.2: The effect of tillage practices on mean seasonal SWC during the (A) 2010/11 and (B) 2011/12 growing seasons. *RT refers to reduced tillage while CT refers to conventional tillage. (LSD values in Appendix 6)*

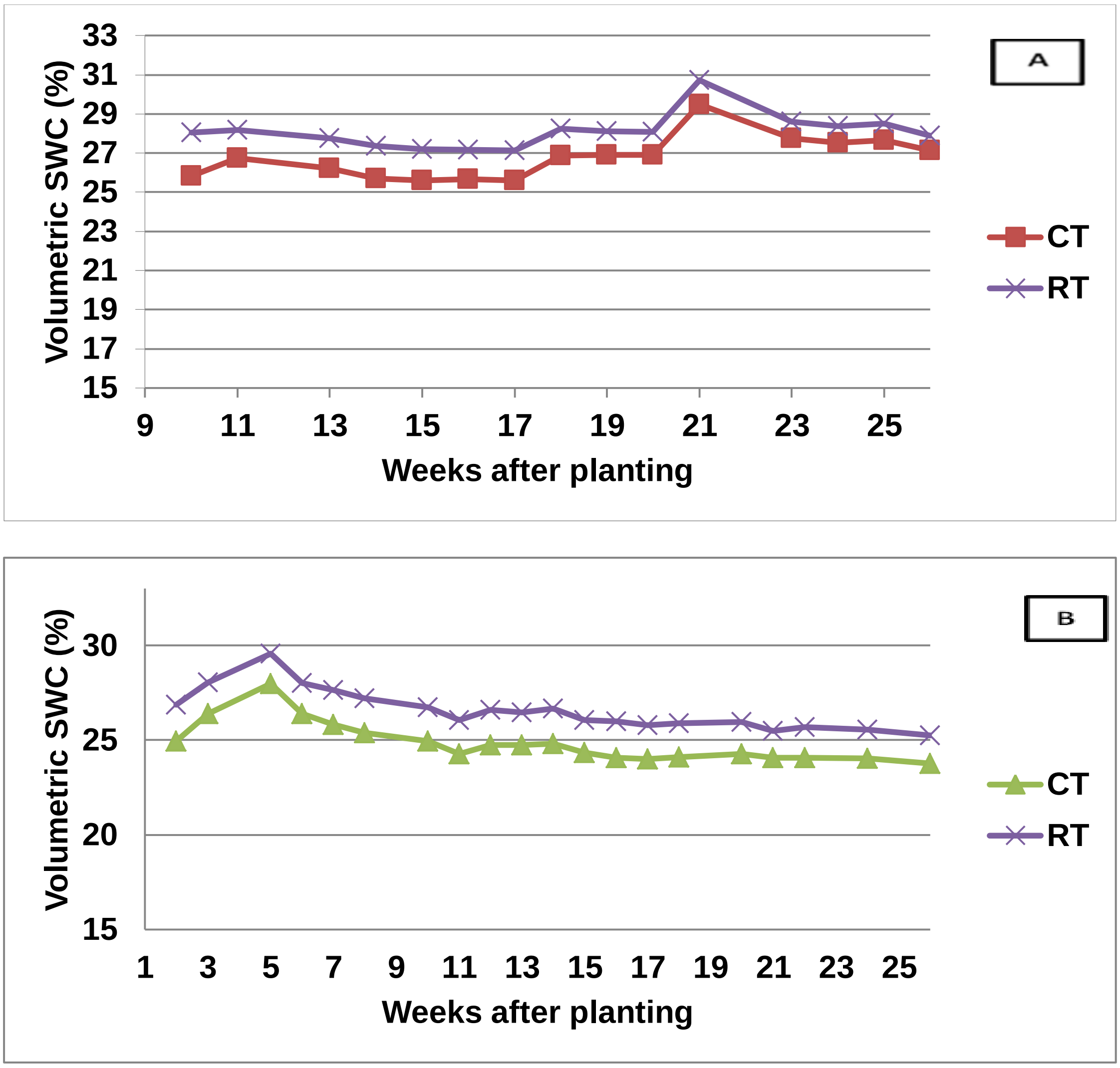


Fig 5.3: The effect of tillage practices on SWC (%) in the 300–1350 mm soil profile in the (A) 2010/11 and (B) 2011/12 growing seasons.

The higher SWC in RT plots confirms the beneficial effect of crop residue retention, in combination with RT in increasing water infiltration and reducing soil water loss compared to CT practice (Thierfelder & Wall 2009; Nyamadzawo *et al*., 2012). It was observed that SWC was constantly higher under RT compared to CT, and water uptake by roots did not result in complete soil drying. This shows that RT does not only increase water entry into the soil (infiltration), but also conserves soil water (Shaxson & Barber, 2003). Higher SWC under RT practice compared to the CT practice had also been reported by Verhulst *et al*. (2011b) and Thierfelder & Wall (2009). Tables of means, LSD values of SWC during both seasons are shown in Appendix 5 and 6, while coefficients of variation values are shown in Appendix 8.

With exception of the topsoil in the 2011/12 growing season, the cropping pattern effect on SWC was significant at all soil depth increments for both seasons (Table 5.2). Soil water content was higher in monoculture compared to intercropping treatments during both seasons (Fig 5.4). For example, during 2010/11, the topsoil (0 - 300mm) SWC under maize monoculture was 1.72% higher than under intercropping. When plotted over time (weekly interval) SWC of the 0 – 300 mm and 300 – 1350 mm soil profiles under intercropping generally exhibited lower values (drier soils) compared to monoculture (Fig 5.5).

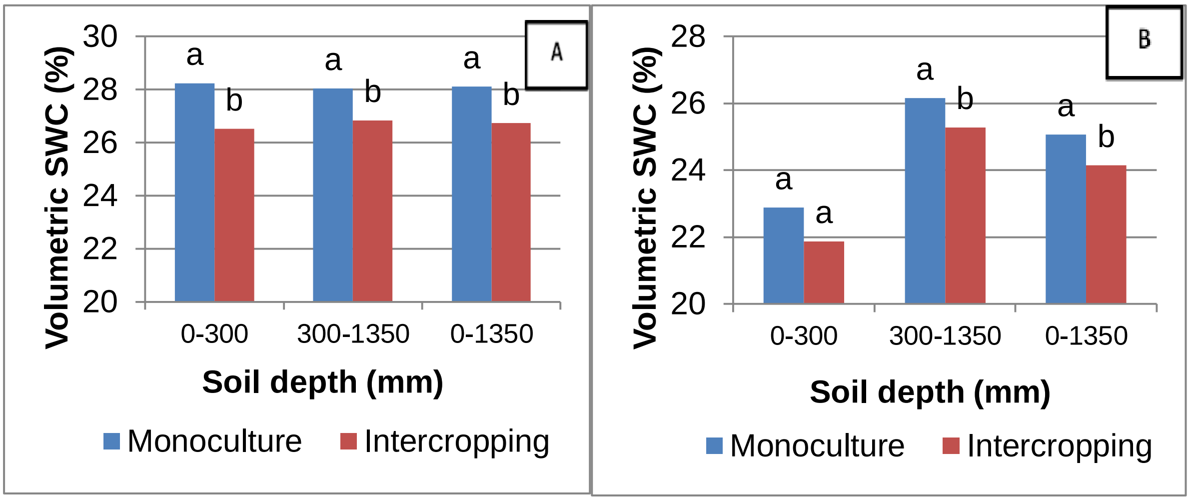


Fig 5.4: The effect of cropping patterns on mean seasonal SWC during (A) 2010/11 and (B) 2011/12 growing seasons (LSD values in Appendix 6).

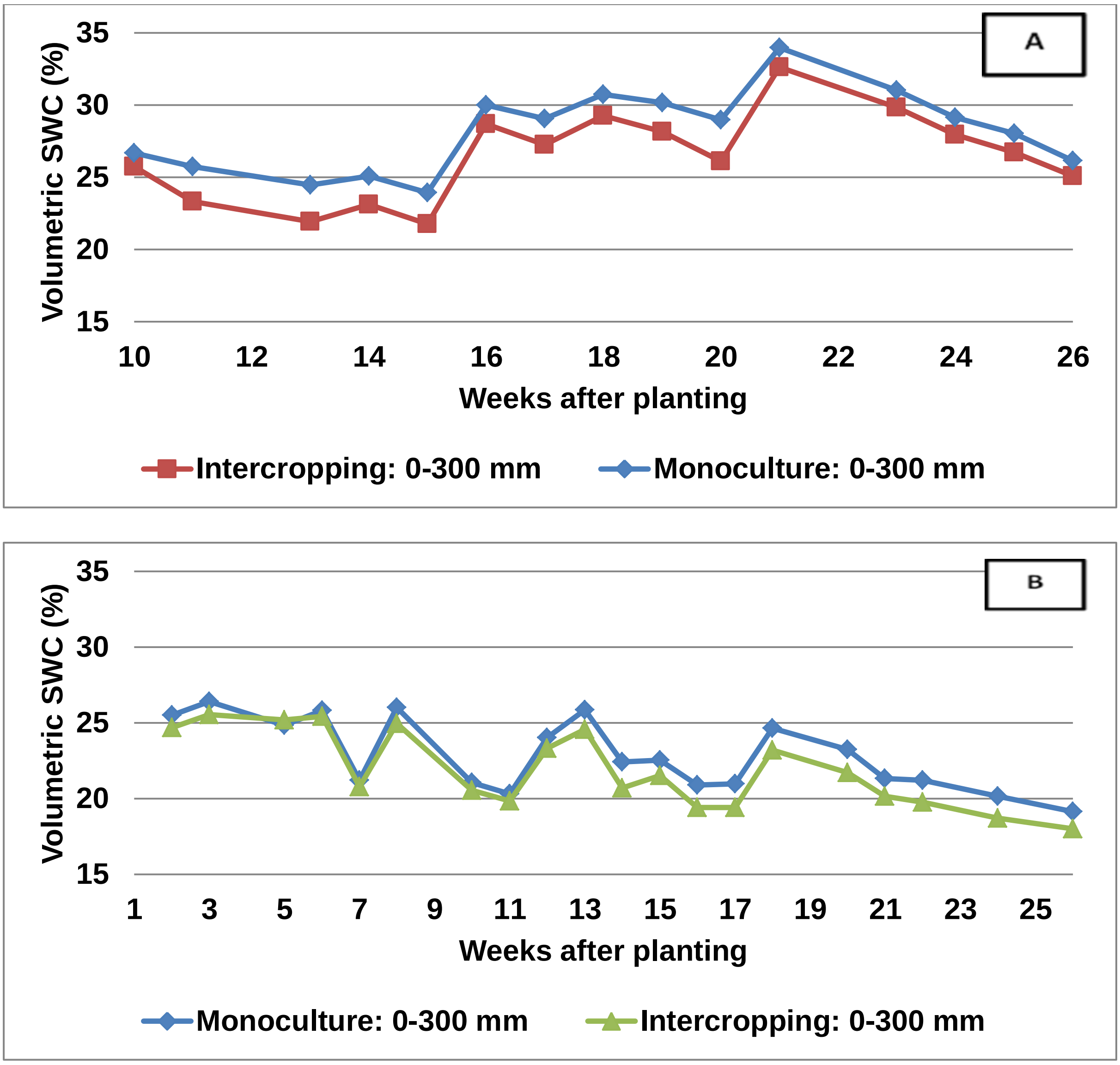


Fig 5.5: The effect of cropping patterns on weekly SWC during (A) 2010/11 and (B) 2011/12 growing seasons.

Increased SWC was expected from plots under intercropping systems due to the shielding effect of crop canopy and reduced surface evaporation losses (Ghanbari *et al*., 2010, Willey 1990). However, the intercropping system failed to show a water conservation benefit in this study. This could be attributed to lower water uptake by sole maize crop compared to water uptake by two crops in intercropping systems. According to Willey (1990) and Passioura & Angus (2010), as the intercrops grow and canopy cover increases, more of the water is transpired. Similar results have also been reported by Karuma *et al*. (2014). Furthermore, the spacing between maize plant rows was narrower and therefore little soil was exposed anyway. The additional intercrop therefore did not result in a huge reduction in evaporation losses. Consequently, water savings from less soil evaporation was far less than additional water used by the two crops.

A statistically significant interaction between fertilizer levels and cropping system on SWC was noted for the 300 – 1350 mm profile during the 2011/12 season, but the effect was weak (Fpr = 0.07) during 2010/11(Table 5.2). Low fertilizer (F1) x monoculture had significantly higher water content compared to other fertilizer x cropping pattern treatments. In this treatment, plant height and biomass accumulation were also significantly lower (discussed in detail in Chapter 6) and that could have been a result of lower water uptake by poorly growing plants, which resulted in higher SWC. According to O'Keeffe (2009), well fertilized soils are associated with denser crop stands than soils that are less fertile, because optimum amount of nutrients such as phosphorus are needed for effective roots growth, which are in turn necessary for greater water uptake. In other words, poorly developed roots under the said treatment may have led to poor water uptake.

5.4.2 Soil temperature

Air temperatures recorded during both growing seasons are presented in Table 5.3. Mean maximum and minimum air temperatures for the 2010/11 growing season were 26.77 and 11.30 ^{o}C, respectively and for 2011/12 they were 27.78 and 10.99 ^{o}C.

Table 5.3: Monthly maximum (Max) and minimum (Min) air temperatures during the 2010/11 and 2011/12 growing seasons.

	2010/11 season		2011/12 season	
Month	Max (^oC)	Min (^oC)	Max (^oC)	Min (^oC)
October	31.59	13.58	29.49	11.92
November	29.79	15.73	30.44	14.43
December	29.11	16.25	28.91	16.51
January	28.19	17.27	30.68	16.81
February	29.40	15.84	31.20	16.79
March	30.08	14.97	29.94	14.12
April	24.52	11.77	26.26	8.88
May	23.72	6.09	26.24	6.06
June	21.03	0.67	21.72	1.72
July	20.21	0.84	22.93	2.73

Reduced tillage decreased both maximum and minimum soil temperatures of all soil depths investigated during both growing seasons (Appendices 8 and 9A). Tillage (RT, CT) significantly affected both maximum and minimum soil temperatures at 100 and 400 mm depths during the 2010/11 growing season (Table 5.4). At the 100 mm and 400 mm depths, maximum soil temperatures under CT were 2.3^{0}C and 1.5^{0}C warmer than under RT, respectively (Fig 5.6). The lower maximum temperatures under RT were due to protective effect of crop residues accumulated on the soil surface (Power *et al*., 1986). Crop residues covering the soil surface insulates the soil and captures a large quantity of solar energy. Only a small amount of heat will penetrate into the soil and therefore, the soil covered with residues will not be as warm as the exposed soil during warm conditions (Hanks & Ashcroft, 1980). Consequently, the soil temperature is reduced in the soil under RT. Moreover, CT loosens the soil and increases its porosity and thermal conductivity, resulting in increased air exchange between the soil and the atmosphere. These result in increased maximum soil temperatures under CT practices. This is consistent with results from Wall & Stobbe (1984) and Malhi & O'Sullivan (1990).

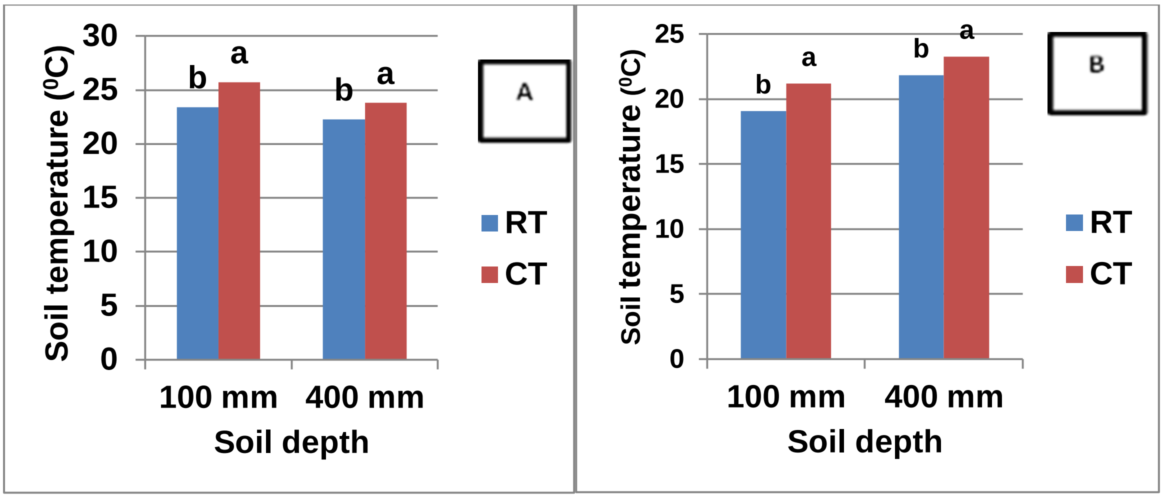


Fig 5.6: Tillage effect on mean (A) maximum and (B) minimum soil temperatures at different soil depths during 2010/11 (LSD values in Appendix 6).

Table 5.4: PR> F probability values for treatment effects on SWC during 2010/11 and 2011/12 growing seasons.

		100 mm		400 mm		800 mm	
Source	df	2010/11 season	2011/12 season	2010/11 season	2011/12 season	2010/11 season	2011/12 season
Maximum temperature (^{0}C)							
Block	2	0.54	0.09	0.32	0.11	0.47	0.34
Tillage	1	0.02*	0.13	0.07*	0.22	0.17	0.42
Cropping pattern	1	0.33	0.91	0.13	0.19	0.19	0.23
Tillage*Cropping pattern	1	0.04*	0.45	0.14	0.31	0.11	0.19
Till(Block*Crop)	4	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Week	22	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
Week*Cropping pattern	22	0.85	0.63	0.15	0.75	0.67	0.38
Week*Tillage	22	0.55	0.43	0.00*	0.28	<.0001	0.78
Week*Till*Crop	19	0.85	0.99	0.11	1.00	0.09*	0.98
Minimum temperature (^{0}C)							
Block	2	0.57	0.41	0.33	0.15	0.48	0.35
Tillage	1	0.03*	0.19	0.09*	0.21	0.19	0.47
Cropping pattern	1	0.16	0.10*	0.15	0.18	0.21	0.22
Tillage*Cropping pattern	1	0.06*	0.15	0.19	0.26	0.10*	0.18
Till(Block*Crop)	4	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Week	22	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
Week*Cropping pattern	22	0.84	0.96	0.00*	0.68	0.41	0.69
Week*Tillage	22	0.75	0.24	0.25	0.14	0.00*	0.31
Week*Till*Crop	19	0.10	0.62	0.15	0.97	0.06*	0.99
Temperature difference (Maximum - Minimum) (^{0}C)							
Block	2	0.29	0.7497	0.78	0.3688	0.92	0.3179
Tillage	1	0.67	0.6173	0.23	0.4367	0.68	0.2889
Cropping pattern	1	0.19	0.1164	0.48	0.0928*	0.47	0.3507
Tillage*Cropping pattern	1	0.50	0.4351	0.17	0.3395	0.57	0.7852
Till(Block*Crop)	4	0.00	<.0001	0.14	0.0107	0.39	0.0308*
Week	22	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
Week*Cropping pattern	22	0.95	0.5811	0.02*	0.8389	0.16	0.1889

** Significantly different at 10%, Till(Block*Crop) = Tillage x Block *Cropping pattern* Week*Till*Crop = Week x tillage x cropping pattern.*

In the case of minimum soil temperature, for example, at 100mm depth, minimum soil temperature was 2 ^{o}C warmer under CT than under RT (Fig 5.6). These results suggest that less heat penetrated into the soil under RT and therefore resulted in lower minimum temperature as less heat was probably lost during the nights when there was no incoming solar radiation. In some instances, RT is expected to have lower minimum soil temperature than CT because the crop residues may trap the heat in the soil during the nights. However, this is mainly observed during colder periods, probably in winter (Zhang *et al*. 2009).

Time of measurement (week) had a highly significant (Table 5.4) effect on both maximum and minimum soil temperature at all depths during both growing seasons. Although the differences were not significant in 2011/12 and at 800mm depth, RT decreased both maximum and minimum soil temperatures of all soil depths investigated (Appendices 8 and 9A). In 2010/11 growing season at 100mm depth, for example, weekly air temperature related well with soil temperature, although maximum air temperatures were mostly higher, while minimum air temperatures were lower than soil temperatures at 100 mm soil depth (Fig 5.7). Air and soil temperatures at 100mm depth followed the same trend due to the fact that both are determined by the energy balance at the soil surface (Hillel, 2003).

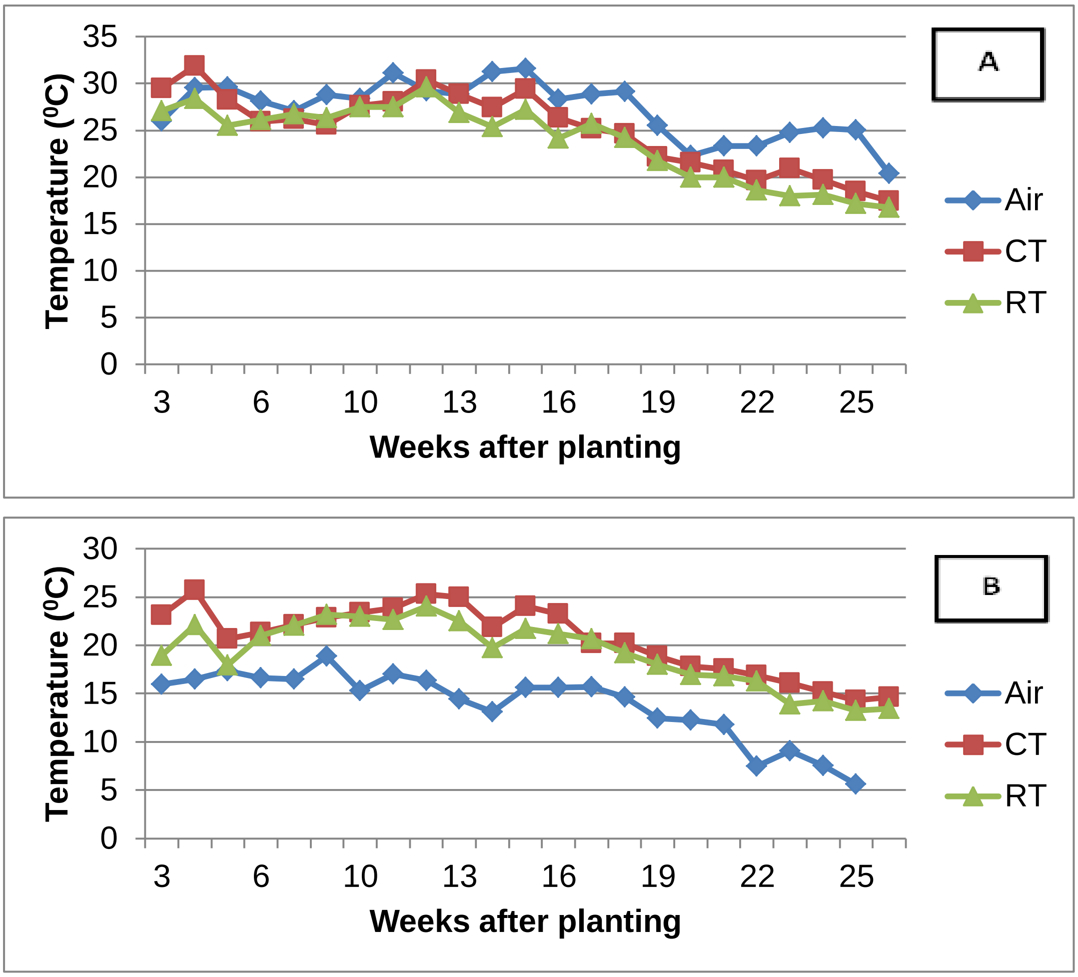


Fig 5.7: Mean weekly maximum (A) and minimum (B) soil temperature in response to tillage at the 100 mm soil depth during the 2010/11 growing season.

Monoculture and intercropping systems had similar maximum soil temperatures at all depths during both growing seasons (Table 5.4). The minimum temperature in response to cropping patterns was only significant at 100 mm depth during 2011/12, with intercropping treatments having higher (0.4^{0}C) minimum soil temperature than monoculture treatments (Appendix 9A). The higher minimum temperatures may be attributed to the insulating effect of soil surface cover. Intercrops, through their canopy cover, are able to prevent heat loss during the night or in the mornings when radiation supply is zero or low (Liu *et al*., 2011). The higher temperature (25^{o}C) at 100 mm depth under intercropping may improve water uptake by roots and therefore be advantageous to crops (Belfield & Brown, 2008).

In two consecutive occurrences, the mean weekly maximum temperatures at 400 mm depth under monoculture exceeded that of the intercropping by about 1.5 ^{o}C (Fig 5.8). In general, however, intercropping exhibited greater mean weekly maximum soil temperatures, a trend which persisted throughout both growing seasons. This is contrary to results found by Ghanbari *et al.* (2010), who found significantly higher soil temperature at maize monoculture in comparison with maize intercropping.

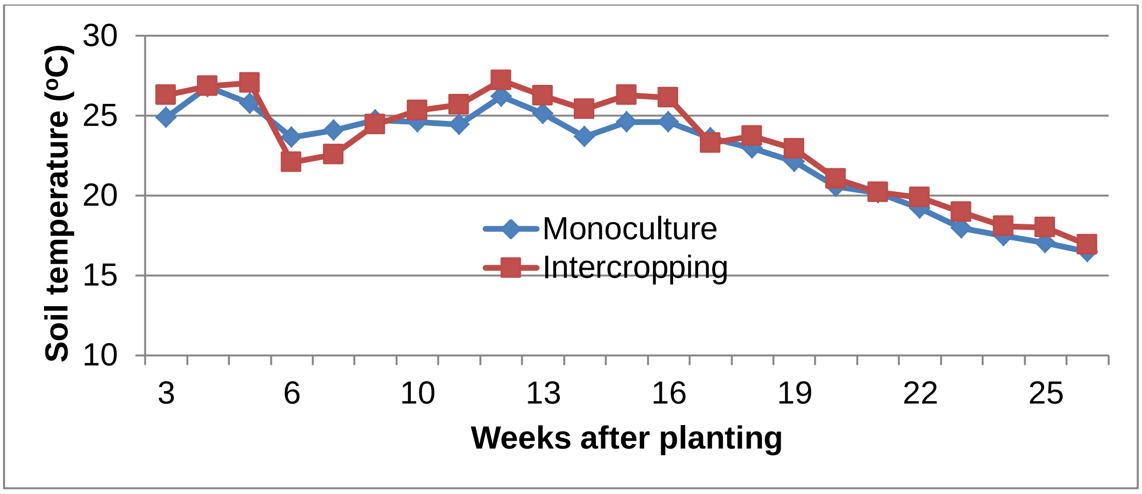


Fig 5.8: Effect of cropping pattern on maximum soil temperature at 400 mm depth.

Significant interaction effects of tillage and cropping pattern were only found during 2010/11 (Table 5.2). Tillage and cropping system interaction effect on maximum soil temperature was significant at 100 mm (Fig 5.9), while minimum temperature was significantly affected at both 100 mm and 800 mm depths. The CT x intercropping system had higher maximum and minimum soil temperatures than other treatment combinations. These findings suggest that the increase in soil temperature (maximum) was mainly due to tillage impact, other than the shading effect of intercropping, whereas intercropping played a major role in reducing heat loss from the soil during cool periods.

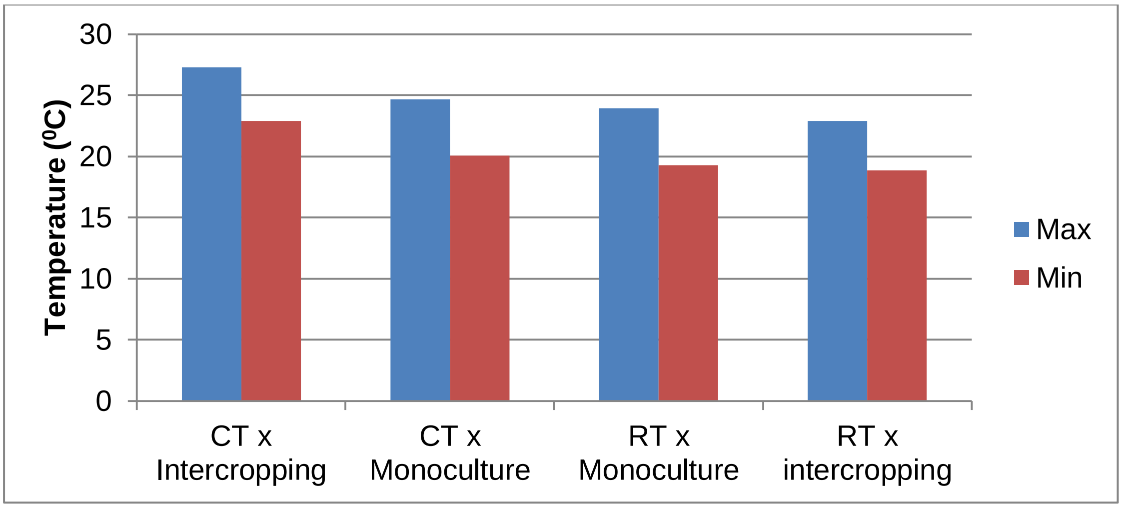


Fig 5.9: Soil temperature at 100 mm depth in response to tillage x cropping pattern effects. (LSD values in Appendix 6).

The temperature differences were not significantly affected by interaction of tillage x cropping patterns. However, at 100 mm depth during the 2011/12 growing season, for example, when the two cropping patterns are compared under tillage systems, there was a larger temperature variation between cropping patterns under CT (monoculture = 9.35^{o}C; intercropping = 6.75^{o}C) compared to RT (monoculture = 8.3 ^{o}C; intercropping = 7.3) (Appendix 9B). It seems that RT resulted in more moderate conditions for both cropping patterns. Also when comparing the cropping systems, maize monoculture presented the highest temperature variation in both tillage systems.

As expected, soil temperatures were lower at 40 cm depth and at 80 cm depth than at 10 cm-depth, regardless of cropping system. Temperatures measured close to the exchange surface have fewer time lags and larger amplitude than those farther from the surface. The amplitude of the diurnal temperature wave becomes smaller with increasing distance from the exchange surface Campbell & Norman (1998).

5.5 Conclusions

The tendency observed during both growing seasons was consistently the same for SWC and soil temperatures, although differences were not always significant. The lowest SWC was found in treatments under CT compared to RT and therefore, RT has the potential to enhance soil water collection and storage. This is the results of combined effects of crop residues left on the soil surface and minimal mechanical soil disturbance under RT. The water content under RT was always higher, even when some water amounts were taken up by plant, thus confirming the improved water storage capacity of the soil under RT. The intercropping practice resulted in lower water content due to increased water uptake by two crops with different characteristics (e.g rooting system and growth habits), compared to monoculture. It seems that intercropping is more efficient in water utilization compared to monoculture, where water may evaporate due to absence of soil cover between the rows (by intercrops).

Reduced tillage was effective in reducing both maximum and minimum soil temperatures, but failed to reduce temperature extremes (difference between maximum and minimum). This shows that RT has potential to cool the soil temperatures when air temperatures are very hot. The higher temperatures were also observed under intercropping practice, probably due to lower water content in the soil. In conclusion, RT has the potential to enhance soil water holding capacity and reduce soil temperature, while intercropping practice was not effective in improving soil water content and was further associated with higher minimum soil temperatures.

CHAPTER 6: THE EFFECT OF TILLAGE, CROPPING SYSTEMS AND FERTILIZERS ON DRYLAND MAIZE GROWTH AND YIELD

6.1 Introduction

Dryland maize production relies to a large extent on rainfall, which is inherently erratic and poorly distributed in most semi-arid areas. Crop production under dryland conditions is in fact a risky initiative, and the situation is worsened by prevalent soil infertility and inappropriate farmers' soil and crop management practices (Jensen *et al*., 2003; Kutu, 2008). Smallholder resource-poor farmers often face a challenge of adding inorganic fertilizers, due to their high costs, and that place even greater pressure on them to to improve crop productivity (Kutu, 2012). Among the several solutions that may contribute to reduce the possibility of crop failure and low grain yield in dryland maize production, the FAO (2004) suggested conservation cropping systems and making more efficient use of natural resources.

The success of first critical growth stages of maize (germination and seedling establishment) requires oxygen, sufficient water, and adequate temperatures (Singer & Munss, 1992). The soil micro climate should therefore be conducive to provide such requirements. It is generally believed that tillage practices that leave crop residues on the soil surface (e.g reduced tillage (RT)) could lead to wetter soil and reduced soil temperatures (FAO, 2010). Lower soil temperatures are often linked to delays in seed germination and emergence as well as slow crop development during the early vegetative growth stage (Hayhoe *et al*., 1993, 1996; Zhang *et al*., 2011). However, as plant growth progresses, cooler soil temperatures and improved soil water in RT are beneficial and can compensate for the downsides encountered during early crop development (Verhulst *et al*., 2011; Van Donk & Klocke, 2012). This is particularly important in semi-arid areas where summers are hot and dry. Van den Putte *et al.* (2010) indicated that crop response to tillage is still subject to different soil types, yield outcomes therefore usually differ, even under the same soil environments.

Satisfactory maize biomass and grain yields call for sufficient supply of inorganic fertilizers (O'Keeffe, 2009). Law-Ogbomo & Law-Ogbomo (2009) conducted a study on the response of maize grain yield to various fertilizer levels. The authors reported highest grain yield at fertilized (60 kg ha^{-1} N + 27.16 kg ha^{-1} P + 49.80 kg ha^{-1} K) and lowest yields at unfertilized treatments. Resource-poor farmers often apply low to sub-optimal amount of mineral nutrients to the soil, the most important of which are nitrogen, phosphorus and potassium in an attempt to marginally enhance yield outputs (Bot & Benites, 2005). Although nutrient requirements are not critical during early days after planting, as plants grow, the need for nutrients, especially N, increase linearly. This is because stored nutrients inside the seeds are used up during seed germination and seedling establishment (O'Keeffe, 2009).

As fertilizer costs rise, smallholder resource-constrained farmers struggle to maintain or improve yields. According to Bot & Benites (2005), practices that improve soil organic matter (SOM) and inclusion of legumes in the cropping system will help to improve soil fertility and hence crop productivity. High soil organic matter encourages efficient utilization of fertilizers in the soil (Bot & Benites, 2005) which may also benefit crops in soils with low water holding capacity because water use efficiency is improved, possibly due to greater root growth (O'Keeffe, 2009).

Cereal-legume intercropping, for example maize-cowpeas, is commonly practiced by smallholder farmers in an attempt to minimize risks in semi-arid environments (Tsubo *et al*., 2003, Kutu & Asiwe, 2010). Inclusion of legumes in a cropping system is known to positively influence soil physical and biological properties, thus enhancing soil productivity (Belay *et al*., 2002). Legumes could increase organic matter and nitrogen (N) content in the soil by fixing N from the atmosphere (Havlin *et al*., 1990), thus benefiting the subsequent maize crop (Adu-Gyamfi *et al*., 2007). This is mainly helpful on N poor soils (Vesterager *et al*., 2008). Moreover, intercropped legumes can conserve soil and water through ground cover (Ghanbari *et al.,* 2010), thus improving soil water utilization by maize crops (Norwood & Currie, 1997). In monoculture, root systems tend to explore the soil to the same layers, which can lead to a decrease in availability of nutrients for crop growth, leading to a gradual decline in maize yields.

Under dryland conditions, those conservation effects should result in improved yield potential and stability. However, practically, this is not always realized. As a result, these practices remain weakly adopted by farmers mainly because the benefits of RT and cover crops are not immediately evident (may take four to 6 years) fairly well documented in the literature for many environments (Wilhelm *et al*., 1987; Lal (1991). For this reason, the objective of this chapter was to establish how tillage practices, cropping patterns and fertilizers will affect dryland maize growth and grain yield.

The following hypothesis was tested:

$H_0$1: Reduced tillage, intercropping practices and optimum fertilizer levels have the potential to improve dryland maize growth and therefore, biomass and grain yield.

6.2 Materials and methods

This chapter focused on two tillage systems (whole plots) and then each whole plot (reduced and conventional tillage) was subdivided into four treatments (two fertilizer levels x two cropping patterns). These eight treatments were replicated three times. Full details on experimental design, treatments and crop husbandry applied are presented in Chapter 3.

6.2.1 Data collection

Maize germination and plant height data were only collected for the 2011/12 growing season.

6.2.1.1 Emergence rate

Emerging plants were counted on day 4, 6, 8, 10, 11, 12, 13, 16 and 20 after planting. A 1m x 1m square grid was used, and two square metres (subsamples) per plot were selected. To eliminate biased sampling, the subsamples were taken on fixed points: one subsample starting on the south eastern corner and the other starting from the north western corner of each plot. From both corners, three rows across the plot were counted and from there 3 m into the plot was measured out. The average plant count was used as a composite sample to represent the specific plot. Subsamples of maize monoculture and maize seedlings in maize/cowpea intercropping were monitored. If, however, there were no viable plants to be counted on the fixed point (for example in the case of tramline planting, where some rows were not planted), an alternative area was used instead. The average number of plants in these sub-samples was used as a composite sample to represent the specific plot.

6.2.1.2 Plant height

Maize height was measured at 42 days after planting (DAP), 54 DAP and 65 DAP. Two subsamples, each consisting of four plants were selected in all plots where maize plants were planted. The plants in subsamples were measured and then marked for future measurements. The subsample sites were selected similar to the germination sites. If, however there were no viable plants to be measured on the fixed point (for example in the case of tramline planting, where some rows were not planted), an alternative plant would be measured instead. The average height of eight plants per plot was calculated and used to represent the specific plot.

6.2.1.3 Biomass yield

Biomass was determined on 10 March 2011 and 6 March 2012 (about 95 DAP). Above-ground maize biomass yield was determined using a 1 m x 1 m square grid per plot. During the 2010/11 growing season, two square metre subsamples per plot were selected whilst only one square metre was sampled per plot during 2011/12. This decision was made to conserve some plants for yield harvest due to poor stand. The average of two subsamples was used as a composite sample to represent the specific plot. The subsamples were bagged and oven dried at 50ºC to constant mass. The dried plant material was then weighed to determine the total dry mass. Biomass values were converted into kilogram per hectare. In the case of intercropping, only maize plants were considered.

6.2.1.4 Grain yield

Maize was harvested in late April in both growing seasons. Grain yield was determined by harvesting two x 5 m rows of maize plants per plot. The number of plants and total cobs were counted for the harvested rows. The harvested maize samples were threshed by using hand maize strippers. The grain was weighed and moisture content determined using a grain moisture analyser (Farmex Moisture Master). Yields were adjusted to a grain moisture content of 12.5%.

6.2.1.5 Harvest Index

Harvest Index (HI) is a parameter that gives an indication of how efficiently assimilates stored are partitioned to the grain and was calculated by dividing the maize grain yield by the above-ground biomass.

6.2.2 Data analysis

A split-plot ANOVA over two tillage systems was done using Genstat 14.1 to test for differences between high and low fertilizer levels as well as the two cropping systems. The data were normally distributed with acceptable homogeneous variances. The means were separated using Fishers' unprotected t-test least significant difference (LSD) at the 5% level of significance.

6.3 Results and discussion

6.3.1 Seed emergence rate

The first plants emerged six days after planting, and by the 19th day, no more new plants were observed. At the final seedling emergence count, 19 days after planting, no significant effect of any of the treatments tested was observed on maize germination (Table 6.1). Although tillage effect was not significant ($p = 0.058$) probably due to the high coefficient of variation (CV) of 43.5% (Table 6.1), seedlings under conventional tillage (CT) tended to emerge first, with 15% higher germination percentage than reduced tillage (RT) (Appendix 10). This situation could be ascribed to higher seedbed temperature (Monneveux *et al*., 2006; Giller *et al*., 2009) or by enhanced contact between seed and the soil under CT (Hayhoe *et al.,* 1996). Hayhoe *et al.* (1993) also observed slow seedling emergence in RT treatments and concluded that seeds needed a few more days to reach 50% emergence rate compared to treatments under CT. This response was attributed to lower soil temperatures under RT. In the present study, it was also found that soil temperature was higher under CT during the early stage of maize growth (Fig, 5.7, in Chapter 5)

Table 6.1: PR> F probability values from the analysis of variance indicating significant differences in germination, plant height, biomass and grain yield of maize during the 2010/11 and 2011/12 growing seasons

Treatment effects	2010/11 growing season		2011/12 growing season			
	Biomass	Grain yield	Germination	Plant height	Biomass yield	Grain yield
Tillage	0.958	0.151	0.058	0.183	0.338	0.147
Fertilizer	0.796	0.524	0.629	0.574	0.007*	0.629
Cropping pattern	0.091	0.049*	0.057	0.080	0.702	0.008*
Tillage x fertilizer	0.478	0.565	0.629	0.853	0.907	0.359
Tillage x cropping pattern	0.912	0.485	0.287	0.159	0.523	0.364
Fertilizer x cropping pattern	0.023*	0.195	0.809	0.010*	0.299	0.018*
Tillage x fertilizer x cropping pattern	0.642	0.57	0.472	0.918	0.904	0.435
Coefficients of variation (%)	27	35.6	43.5	11.5	27.5	27.8

* indicates significant treatment effect on growth parameters at $P < 0.05$

The germination percentage was weakly affected by cropping patterns ($p = 0.057$), with monoculture having 20% higher germination percentage compared to the intercropping system (Fig 6.1; Appendix 10). During the maize germination period, legumes were not yet planted in the maize-cowpea system, and therefore were not expected to have any effect. The fertilizer regimes also did not show any significant effect on crop germination (Table 6.1) and this shows that seeds utilize their own reserves during germination and this process is not influenced by variable fertilizer levels (O'Keeffe, 2009).

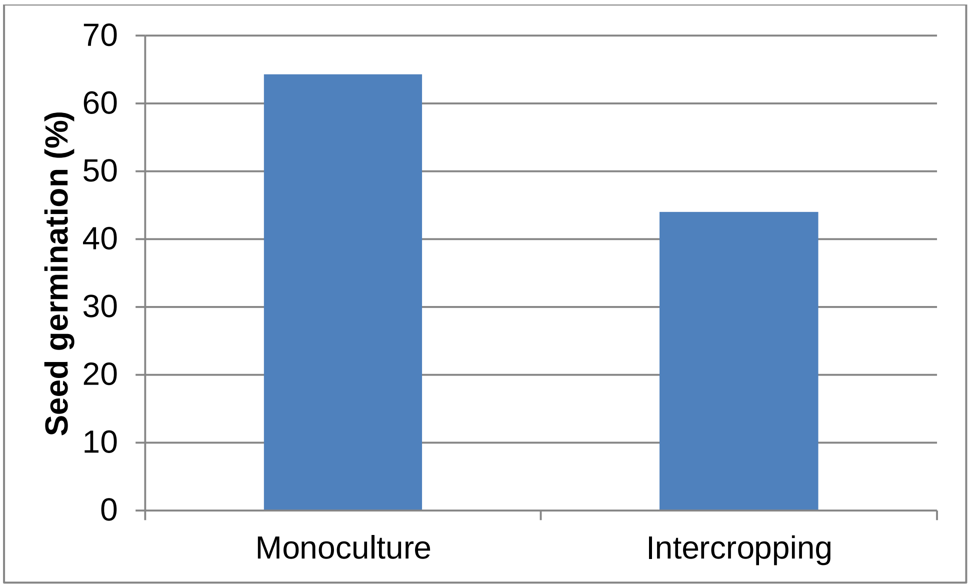


Fig 6.1: Effect of cropping pattern on seed germination percentage. (LSD values shown in Appendix 12).

6.3.2 Plant height

Statistical analysis on maize plant height data indicated that the main effects (tillage, fertilizer and cropping patterns) had no significant effect on plant height (Table 6.1). The maize plant height was on average higher under CT (176.7 cm) than RT (149.7 cm). These findings correspond with results of studies conducted by Verhulst *et al*. (2011) and Memon *et al*., (2012). The shorter maize plants could probably be due to restricted roots because of soil compaction that may be found on the RT plots (Giller *et al*., 2009), while conventionally tilled plots could improve root development because seedbeds are prepared adequately (Varsa *et al*, 1997), and result in taller plants (Khurshid *et al.,* 2006).

The effect of cropping pattern on plant height was also weak (p = 0.08, Table 6.1). However, intercropping resulted in taller plants (170.5 cm) compared to monoculture (155.9 cm). It seems the drier last part of the growing season resulted in poor fertilizers response due to draught stress, especially that water content was low in the soil under intercropping treatments. There was also no significant difference due to fertilizer application level. This is contrary to the expectation that high fertilizer application would result in taller plants. Several authors found increased maize plant height with high N application (Liu & Wiatrak, 2012). The poor response to fertilizer application could be attributed to the poorly distributed low rainfall in the 2011/12 season (Fig 5.1) at this stage. Available soil water was probably a bigger constraint than nutrients, and thus the maize did not significantly respond to higher fertilizer at that stage.

There were, however, significant differences when the interaction between Fertilizers x Cropping pattern was tested. The mean plant height for maize under monoculture system and low fertilizer level, were significantly lower (142.0 cm), compared to maize in an intercropping system and low fertilizer level, as well as maize under monoculture and with high fertilizer level (169.8 cm) (Fig 6.3). The maize under monoculture and high fertilizer level did not differ from the maize under intercropping (for both fertilizer levels). This shows the potential of intercropping system in improving crop growth due to efficient use of natural resources compared to monoculture (Ghanbari *et al*., 2010).

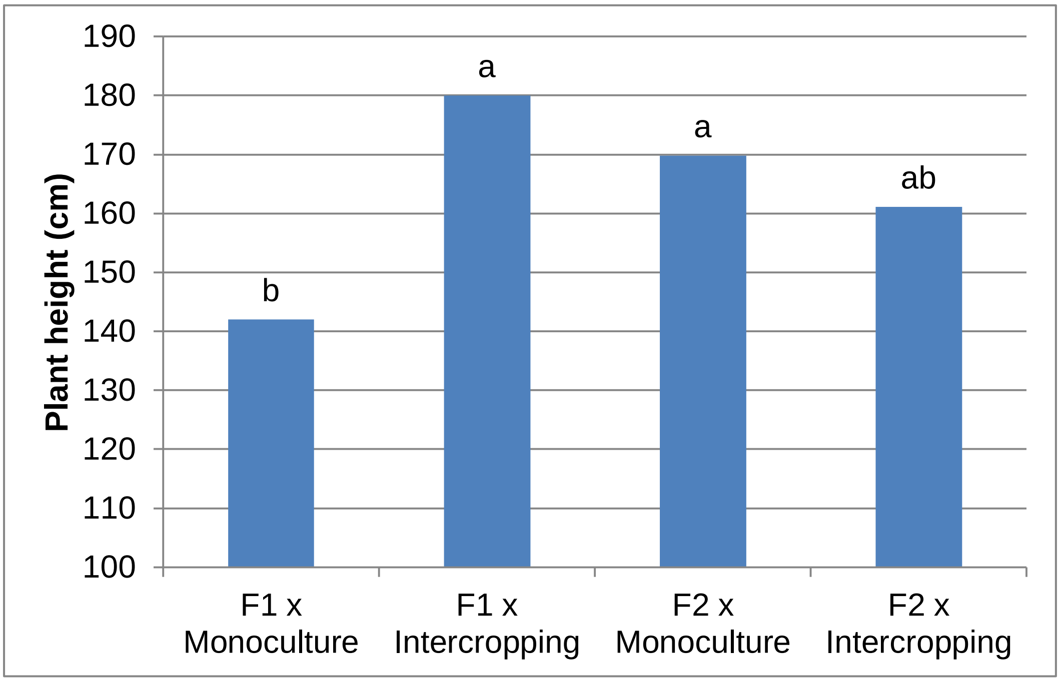


Fig 6.2 Effect of fertilizer x cropping pattern on maize plant height in the 2011/12 season. *F1 = low fertilizer, F2 = high fertilizer (LSD values shown in Appendix 12).*

6.3.3 Maize biomass yield

During both seasons, tillage and cropping patterns had no significant effect on total biomass yield (Table 6.1). However, biomass from maize under CT tended to be higher compared to RT, and the biomass yield from the intercropping system was slightly higher (5,559 kg/ha) compared to monoculture (5,320 kg/ha) in 2011/12 (Table 6.2). Several authors also found increased biomass production in maize-legume intercropping systems (e.g Dahmardeh, 2010; Ngwira *et al*., 2012).

During the 2011/12 growing season, a significant effect on maize biomass production was observed for different fertilizer levels. Plants that received high fertilizer application had high maize biomass yield (6,432 kg/ha), while low fertilizer treatments produced lower biomass yield of 4,447kg/ha (Table 6.2). It was noted in the study that there was generally good rainfall during February 2012 compared to other months (week nine to twelve, Fig 5.1). This suggests that at this time, water was not a limiting factor for plants, and as a result fertilizers were used efficiently. The nutrient uptake by plants in the soil happens through the process of diffusion which requires water, and therefore may not be limited if there is sufficient water in the soil (Suriyagoda *et al*., 2014). These results are similar to the findings of Sharma (1991), who found that high fertilizer application increased maize biomass yield compared with low application.

Significant effect of fertilizer x cropping pattern was observed on biomass yield in 2010/11. Maize biomass yield under monoculture and low fertilizer was significantly lower (Table 6.2) compared to other fertilizer x cropping pattern treatments. These results confirm the beneficial effect of intercropping (with legumes) on maize in terms of atmospheric nitrogen fixation and efficient use of resources (Tsubo *et al*., 2003). Murungu *et al*. (2011) also found increased maize productivity under intercropping compared to maize in monoculture.

Table 6.2: Means of maize biomass and grain yield for growing seasons 2010/11 and 2011/12.

Treatments	2010 /11 growing season		2011 /12 growing season	
	Biomass yield (kg/ha)	Grain yield (kg/ha)	Biomass yield (kg/ha)	Grain yield (kg/ha)
RT	7927 a	1070a	4618a	2060a
CT	8035 a	2130a	6261a	2740a
F1	8099a	1680a	4447b	2460a
F2	7863a	1530a	6432a	2330a
Monoculture	7161a	1340b	5320a	1970b
Intercropping	8801a	1860a	5559a	2830a
RT x F1	7718a	1080a	3589a	2000a
RT x F2	8136a	1060a	5647a	2120a
CT x F1	8479a	2280a	5305a	2930a
CT x F2	7590a	1990a	7217a	2540a
RT x Monoculture	7157a	900a	4699a	1760 b
RT x Intercropping	8697a	1250a	4537a	2360a b
CT x Monoculture	7164a	1790a	5941a	2180 b
CT x Intercropping	8905a	2470a	6582a	3290a
F1 x Monoculture	6113 b	1260 b	3996b	1660 b
F1 x Intercropping	10084a	2100a	4898ab	3270a
F2 x Monoculture	8208a b	1430a b	6644a	2270 b
F2 x Intercropping	7518a b	1620a b	6220a	2390 b

Means within a column (per main effect / interaction) followed by different letters are significantly different at P<0.05 (LSD values shown in Appendix 12).

6.3.4 Grain yield

Grain yields achieved under RT and CT practices were similar during both seasons (Tables 6.1 and 6.2). During both seasons higher soil water storage at sowing and throughout the seasons under RT (Fig 5.2 and 5.3) plots did not enhance maize development and growth. This might have been due to soil compaction in treatments under RT. Soil compaction is often realized in soil which were not ploughed, especially in clay soils, and this often leads to poor root development and therefore reduced plant stand and lower yields. (Hayhoe *et al*., 1993; 1996). However, there was little evidence that increased soil penetration resistance prohibited roots growth and nutrient uptake as it was not measured.

In some studies, lower soil temperatures under RT system led to delayed maize development and growth (Zhang *et al*., 2011). In this study, it was observed that lower soil temperature under RT encountered during the early stage (seed germination and establishment) never improved as the growing season progressed (Fig 5.7). However, maximum soil temperatures in this study were generally within the range that would not be expected to reduce plant growth and yield. Although final plant population was not measured in this study, it was observed that reduced germination percentage in fact led to reduced final plant population and this was particularly evident in 2010/11 when rainfall was not so low. According to Namken *et al.* (1974), good plant stands and fast seedling growth are vital to obtain higher yields.

It has been found in several studies that increases in crop yields under RT compared to CT may take about five years or more before they become significant (Thierfelder *et al*., 2013). That means grain yields under RT may remain nil or negative compared to CT in the short term. For example, Mupangwa *et al*. (2007) also found no differences in yield among RT and CT, even though there was high water content under RT. In a study conducted by Govaerts *et al.* (2009), yield improvements under RT were found after 10 years of practice. Although the short-term yield benefits of RT may be zero or negative, in the long term, accumulation of SOM gradually improves soil physical and biological properties (Dumanski *et al*., 2006). These include biological tillage, where micro-organisms improve soil porosity, leading to high water holding capacity and unrestricted rooting systems (Shaxson & Barber, 2003).

In both seasons, cropping patterns had a significant effect on maize grain yield production; with maize in the intercropping system giving higher yields (Table 6.1). Inclusion of legumes in intercropping has been reported to improve maize productivity through atmospheric N fixation (Murungu *et al.,* 2011) and improved soil water use efficiency. Several authors have reported higher productivity of cereal-legume intercropping systems than maize monoculture in several regions of South Africa (Tsubo *et al*., 2003).

Fertilizer levels had no significant effect on maize grain yield in either season. In the present study, there was higher total biomass accumulation for treatments that received high fertilizer levels (F2) but that did not result in improved grain yield. A possible explanation is that in both seasons (but especially in 2011/12) the last part of the growing season was very dry (Fig 5.1). The result is that the crop that received high levels of fertilizer (F2) grew more vigorously early in the growing season (high total biomass), but during reproductive stage, the crop ran out of water (because of a bigger canopy) and then the result is a high total biomass but low grain yield (low harvest index). This means the water shortage coincided with the water sensitive reproductive stages. These results are in conformity with findings of Kutu (2012), who found the same maize grain yield at optimum fertilizer as in adjusted low fertilizer rate under dryland conditions. This differs from the view of Grigoras *et al*. (2011), who reported that fertilization is generally the main factor affecting maize yield, in both conventional and reduced tillage systems. Wang *et al*. (2011) found highest dryland maize grain yields under RT, with no significant yield increase above the optimum N and P (105 kg N and 46 kg P ha^{-1}) fertilizer application rates.

A significant fertilizer x cropping system interaction effect on maize grain yield was observed in the 2011/12 growing season. The mean grain yield of maize under intercropping with low fertilizer application gave significantly higher yields (3.27

ton/ha) compared with other fertilizer x cropping pattern treatments (Fig 6.3). It seems the drier last part of the growing season resulted in poor fertilizers response due to draught stress, especially that water content was low in the soil under intercropping treatments (Fig 5.5). According to Bennett *et al.* (1989) and Suriyagoda *et al*. (2014), drier soil leads to inefficient use of nutrients. These findings suggest that the low fertilizer rate could be considered the optimal application rate for intercropping systems under the current conditions. Bennet *et al*. (1989) found no effect of N level on maize grain yield under severe water stress during reproductive stage. Bennett *et al.* (1989) conducted a study on the interactive effects of different levels of nitrogen and water stresses on maize biomass and grain yield. The authors found that even with high N, the 10-day wilting period prior to silking reduced grain yields by about 75%, in the rainfed treatment.

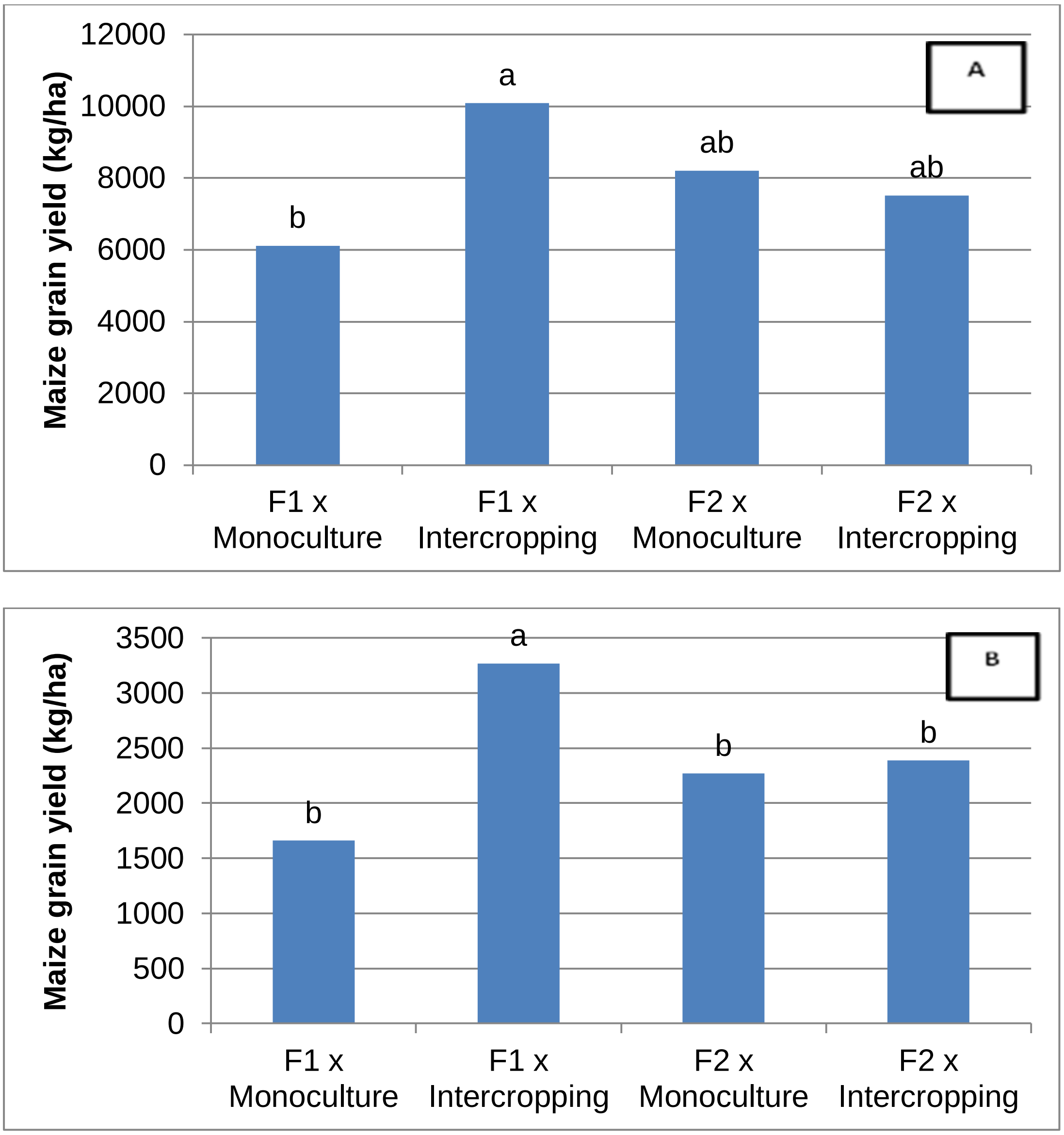


Fig 6.3 Effect of fertilizer x cropping pattern on maize grain yield during (A) 2010/11 and (B) 2011/12 (LSD values are shown in Appendix 12).

6.3.5 Harvest index

Harvest index is an important parameter that gives an indication of how efficiently assimilates stored in the stems are partitioned to the grain (harvestable part). A good HI is reported to be about 0.40 (Passioura & Angus 2010). The HI values are presented in Table 6.3. The higher biomass yield and low grain yield observed under treatments that received high fertilizer resulted in low harvest indexes. This was particularly evident in 2011/12. In 2010/11, the HI values were exceptionally low for both F1 and F2. The reason is probably that the first part of the season was very wet, stimulating big canopies, while the latter part of the season (especially in February) was very dry. The crop ran out of water at a critical time and therefore grain filling was very poor, eventually resulting in low grain yields and low HI values for all treatments. The results have shown that water shortage during pollination and grain filling is a major constrains responsible for reduced maize production (Guelloubi *et al*., 2005).

A good HI of about 40% (Passioura & Angus, 2010) was achieved under the intercropping system. The greater biomass growth was linked to greater interception of solar energy and greater photosynthesis which ultimately resulted in greater yield development (Nielsen *et al*., 2010). In this study, it was found that higher biomass under intercropping system resulted in higher grain yield and therefore higher harvest index. This suggests that water was used efficiently under intercropping even when it was low due to low rainfall and the soil temperatures were probably favourable. Very high harvest index of 66.76 under F1 x intercropping was found relative to F1 x monoculture (41.54), due to higher biomass accumulation and higher grain yield.

Table 6.3: Harvest Index values* for cropping systems during both seasons.

Treatments	2010 / 11 growing season	2011 / 12 growing season
RT	13.50	44.61
CT	26.51	43.76
F1	20.74	55.32
F2	19.46	36.23
Monoculture	18.71	37.03
Intercropping	21.13	50.91
RT x Low fertilizer	13.99	55.73
RT x High fertilizer	13.03	37.54
CT x Low fertilizer	26.89	55.23
CT x High fertilizer	26.22	35.19
RT x Monoculture	12.58	37.45
RT x Intercropping	14.37	52.02
CT x Monoculture	24.99	36.69
CT x Intercropping	27.74	49.98
Low fertilizer x Monoculture	20.61	41.54
Low fertilizer x Intercropping	20.83	66.76
High fertilizer x Monoculture	17.42	34.17
High fertilizer x Intercropping	21.55	38.42

* HI data was not analysed statistically

6.4 Conclusions

Cropping patterns were mostly responsible for significant differences in terms of maize growth and yield. Intercropping maize with cowpeas generally improved maize growth and grain yield. These results show that intercropping has the potential to increase maize growth and yield whereas under maize monoculture grain yields were significantly lower. The results of this study suggest little grain yield benefits when RT is applied instead of CT in dryland areas. The non-significant effect of tillage systems on maize yield could be explained by obstructed rooting systems in RT treatments, due to possible soil compaction under the RT systems in the short-term. In the short-term, lower or comparable yield benefits under RT are mostly observed, because beneficial physical and biological properties usually only accumulate in the long run. The lower soil temperature under RT may also have been a limiting factor due to its negative effects on germination, early establishment and final plant population. The combined effect of RT, crop residue retention and intercropping did not significantly improve maize growth and yield in the present study.

Maize plant height and biomass accumulation in response to fertilizer levels was greatly determined by water supply by rain. Effective fertilizer use by plants was observed when there was sufficient water in the soil. Higher rainfall during the vegetative growth stages resulted in higher total biomass yield, but the occurrence of water shortage during the reproductive stage resulted in lower grain yield. The harvest index was then lowered in treatments that received high fertilizers compared to those that receive low fertilizers. In conclusion, intercropping and optimum fertilizer levels are recommended for farmers to obtain improved maize yields.

CHAPTER 7: THE RELATIONSHIP BETWEEN MONTHLY SOIL WATER CONTENT AND SOIL TEMPERATURE AND MAIZE GRAIN YIELD.

7.1 Introduction

Water is crucial for maize production, and any scarcity within the growing season has an effect on its yields. Under rainfed conditions, crops depend on water conserved in the soil after rainfall and this has a potential of limiting yields if rainfall is insufficient (Peterson *et al*., 2006). Maize responds differently to water stress according to the stage of development (Çakir, 2004). If shortage of rainwater or dry-spells coincides with the maize growth stage of reproduction, it can seriously reduce grain yield. Water stress also leads to reduced photosynthetic capacity of the crop (Shaxson & Barber, 2003). Çakir (2004) found that during vegetative growth, occurrence of water stress resulted in stunted growth and therefore reduced biomass accumulation.

Maize grain yield is not only affected by soil water, but also soil temperature. Soil temperature plays a critical role in maize seed germination and establishment. Du Plessis (2003) reported that faster germination of seeds may be observed at minimum temperatures of 16 to 18 ºC, although the minimum is 10 ºC. According to Belfield & Brown (2008), minimum soil temperature of 12°C or greater, is ideal for germination and establishment, while the optimum of 18 to 32°C is required for growth and development.

Improving soil water storage and use efficiencies of dryland maize is a necessity for maintaining maize production. Optimum minimum and maximum soil temperatures are also important to obtaining improved yields (da Veiga *et al*., 2010). The objective of this chapter was to investigate the effect of soil water and soil temperature on maize yield, with the hypothesis that linear relationships exist between mean monthly soil water and soil temperature and maize grain yield.

7.2 Materials and methods

General methodology was discussed in chapter 3 of this dissertation.

7.2.1 Statistical analysis

Forward regression analysis was done on the soil water and temperature dataset with the dependent variable (Y) taken as maize grain yield vs. the independent variables (X) being monthly SWC (SWC in December, SWC in January, SWC in February and SWC in March). The mean monthly soil temperature (Maximum soil temperature December to March, minimum temperature December to March and temperature differences December to March) were also taken as independent variables (X) vs. dependent variable taken as maize grain yield. Other categorical variables which were also used by creating dummy variables are: Tillage, Cropping pattern, Fertilizer levels and Year. The probability for allowing these variables into the model was 0.2.

7.3 Results and discussion

It is well known that the most sensitive growth stages to water stress are early growth of seed germination and establishment (Huang *et al.*, 2006) and reproductive stage of cob development and grain filling (Guelloubi *et al*., 2005). In this study, there was generally higher rainfall during the first part of the season in December for the 2011/12 and 2010/11 (although poorly distributed) seasons, with the best rainfall month being January for 2010/11 (Fig 5.1). It has been found in the present study that maize grain yield was significantly affected by SWC in December and in March (Table 7.1). The higher water content is associated with good stand (when other factors are not limiting) and therefore are important to obtain higher yield (Namken *et al.*, 1974). During the reproductive stage, which occurred in March, there was very low rainfall during both growing seasons. The dry spell occurred in mid-February and mid-March during 2010/11 and March during 2011/12 (Fig 5.1). Therefore, a low grain yield in both seasons is attributed to water stress at reproductive stage. According to Hall (2001) and Zaidi *et al.* (2004), even a water shortage for a short period may lead to poor grain filling due to the negative effects on anthesis and silking.

Table 7.1: Summary of Forward Selection on the effect of monthly SWC on grain yield

Step	Variable Entered	Partial R-Square	Model R-Square	F-value	Pr > F[1]
1	Cropping pattern	0.225	0.225	8.930	0.019*
2	Tillage	0.139	0.363	5.758	0.044*
3	SWC in March	0.095	0.458	4.217	0.076*
4	SWC in December	0.078	0.537	3.292	0.089*

[1] All variables not significant at 10% significance level to be rejected from the model.

There was a linear relationship between grain yield and minimum soil temperatures in December and in March (Table 7.2). In this study, there were higher minimum soil temperatures under CT and under Intercropping, than under RT and under CT respectively. The same trend was observed during both seasons and generally throughout the seasons (Fig 5.7 and 5.8, Appendix 8 and 9A). With such soil temperature conditions under the said treatments, higher maize grain yields were also realised (Table 6.2). The higher soil temperatures have been shown to be critical for successful seed germination and growth by Hayhoe *et al.* (1993) and Giller *et al*., (2009). According to du Plessis (2003), maize seed germination increases at minimum temperatures of 16 to 18 ºC. This was also evident in this study (Appendix 10). This suggests that higher minimum soil temperatures were important during the early and reproductive stages to obtain successful yield production.

According to Cairns *et al*. (2012) and (FAO, 2012), water stress combined with high temperatures during reproductive stage could account for significant reduction in grain yield. Even though, higher minimum temperature might not have been the limiting factor during reproductive stage (March) in this study, water stress was most probably the limiting factor.

Table 7.2: Summary of Forward Selection on the effect of mean monthly soil temperature on grain yield.

Step	Variable entered	Partial R-square	Model R-square	F Value	Pr > F
1	Cropping pattern	0.1677	0.1677	2.62	0.129
2	Tillage	0.1284	0.2961	2.19	0.1648
3	Minimum soil temperature in March	0.1844	0.4805	3.91	0.0737*
4	Year	0.1697	0.6502	4.85	0.0522*
5	Minimum soil temperature in December	0.1482	0.7984	6.62	0.0301*

*Indicates significant effect at 10% significance level.

7.4 Conclusions

There was a high linear relationship between maize grain yield and soil water content and minimum soil temperatures in December and March. The shortage of water during March, which coincided with the reproductive stage, was greatly responsible for grain yield reductions. The higher minimum soil temperatures (under CT) were highly correlated to maize grain yield. There was no linear relationship between maximum soil temperatures as well as temperature differences and maize grain yield.

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CHAPTER 8: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The conservation of soil water has become the main issue in the dryland areas of sub-Saharan Africa due to low rainfall, which is often poorly distributed within the growing season (Peterson *et al*., 2006; World Bank, 2010).

It is important that water content in the root zone is correctly measured to avoid over or under estimation of soil water content (SWC). The quality of SWC data may be reduced due to the effect of soil physical and chemical properties on the field calibration of neutron water meters (NWN). In the present study, the abundance of soil concretions at different layers was found to increase soil bulk density. However, the exclusion of concretions from soil bulk density values had no significant effect on the calibration functions of the NWM. These results suggest that changes in soil bulk density have little effect on the relationship between NWM count ratio and volumetric soil water content.

The results of this study showed that average soil water content was higher in all depth layers in the RT plots than in conventionally ploughed plots throughout both growing seasons (although differences were not always significant). Govaerts *et al*. (2007) as well as Giller *et al.* (2009) attributed this to the insulating effects of crop residues left on the surface which lead to reduced evaporation and vapour transfer near the soil surface. Crop residues also act as barrier which traps rainwater on the surface and thus encourage infiltration. These changes lead to overall enhanced water content (Power *et al*. 1986; Van Donk & Klocke, 2012). According to Rockstrom *et al.* (2010), systems that capture more rainwater and encourage water infiltration can lead to improved yields of dryland maize.

Significantly lower ($p > 0.05$) soil water content under intercropping was found in the present study at all depths during both seasons (except top soil SWC in 2011/12) compared to monoculture. Similar results were also reported by Miriti *et al*. (2012). This effect was probably due to increased water uptake by two crops in the intercropping system. According to Karuma *et al*. (2014) different crops with different rooting systems increases water utilization from different soil horizons and as crops transpire, more water is used.

The maximum and minimum soil temperatures were significantly reduced in RT system during both growing seasons. Higher soil temperatures in conventionally tilled plots were also reported by Power *et al*. (1986), Fabrizzi *et al.* (2005) and Licht & Al-kaisi (2005). The authors explained that the soil under RT plots has high resistance to heat and there is less air movement between the soil beneath the residues and atmosphere, thus resulting in reduced soil temperatures. Licht & Al-kaisi (2005) stated that soils with low water content tend to warm faster than wet soil because soil particles are good conductors of heat compared to water. In this study, the soil under CT was drier compared to soil under RT and that also explains higher temperature in soil under CT. However the RT did not result in reduction of soil temperature extremes (too high and too low) in the present study.

Higher maximum and minimum temperatures were recorded in plots under intercropping than under monoculture. Although the effect (on maximum soil temperature) was only significant at 100 mm depth during the 2011/12 growing season, the trend persisted throughout both seasons. These results suggest that more heat was able to penetrate into the soil under intercropping and less heat was lost when incoming radiation energy was absent. These effects can be attributed to low soil water content under intercropping, which lead to increased conductivity of heat (Licht and Al-Kaisi, 2005). Furthermore, it seems that the higher canopy cover of the intercrops was effective in trapping heat in the soil. The differences in soil temperature (maximum - minimum) were mostly non-significant, except at 400 mm during 2011/12, where monoculture have shown high temperature extremes. This indicates the insulating ability of intercrops in trapping the heat and not getting too cold during the night (Baver *et al*., 1972).

In terms of water content, RT system has shown great potential to alleviate the effects of water shortage during the growing season, as higher soil water content is associated with higher yields (Thierfelder *et al*., 2013). The increased water content under RT was combined with lower soil temperatures, but those soil characteristics failed to improve seed germination and crop establishment (and therefore resulted in reduced stand) which is one of the most important factors that determines maize crop productivity (Namken *et al.*, 1974). Although the effect was not significant (p = 0.058), low germination percentage was recorded under RT compared to CT. This was probably due to other factors associated with RT such as higher soil penetration resistance. Several authors have also reported slow germination and seedling establishment under RT due to soil compaction compared to CT (e.g, Hayhoe *et al*., 1993; 1996). The germination percentage under intercropping was not significantly different from that under monoculture. This is because during the maize germination period, legumes had not yet been planted in the maize-cowpea plots, and therefore were not expected to have any effect. The effect of fertilizers on germination percentage was also not significant and this is because seeds mainly use their own reserved nutrients during germination (O'Keeffe, 2009).

According to Hayhoe *et al.* (1993) RT can lead to poor soil-seed contact and soil compaction, especially in clay soil. The author has associated these changes with reduced stand establishment. It was found in this study that low germination percentage under RT (possibly due to low temperature) led to low biomass accumulation and subsequently low grain yield. This was found despite high water content found under RT. These results suggest that there was more water in the soil, but the plants could not extract water from deeper layers due to poor root development under RT. This, in combination with the lower plant stand then resulted in lower yields under RT. However, in this study there was no tangible evidence that soil compaction prevented seedlings from emerging or that it restricted root growth.

From the results in this study, it seems that water was not enough to satisfy the crop demand, due to insufficient rainfall during the critical growth stages. The dry spells occurred in mid-February and mid-March during 2010/11. There was generally low rainfall with poor distribution during the 2011/12 growing season, with dry-spell during mid-summer in January and in March. The three most sensitive growth stages of maize that potentially reduce grain production if they coincide with dry-spells during the season are crop establishment, flowering and grain filling (Guelloubi *et al*., 2005). There was a significant effect due to soil water content in December and in March on grain yield in the present study. That confirms the limiting effect of water shortage during reproduction stages, which was in March.

The increased water use and higher soil temperatures under intercropping led to higher plant height and subsequently high biomass, grain yield as well as harvest index. The trend was the same during both seasons and the effect was significant on grain yield during both seasons. Compared to monoculture, intercropping with legumes improved the subsequent crop growth rate and yield through improved light interception, improved water and nutrient uptake and increased nitrogen content due to ability of legumes to fix atmospheric nitrogen. Furthermore, intercropping may result in reduced weed and pest populations (Mousavi & Eskandari, 2011). These results are consistent with results found by Walker and Ogindo (2003).

Biomass was significantly affected by fertilizer regimes in 2011/12, with higher biomass achieved in plants under optimum fertilizer (F2) than under half-optimum (F1). However, for grain yield the trend was the opposite. During 2011/12, there was generally better rainfall during February compared to the last part of the growing season (from March until harvest). This suggests that plants which received high fertilizer levels were able to extract nutrients from the soil successfully (when water was not limiting) (Suriyagoda *et al*., 2014) and then grew vigorously and accumulated high biomass, but during critical stage of water requirements for successful grain yield production (flowering and grain filling stage), there was not enough water (Guelloubi *et al*., 2005). The higher biomass but lower grain yield in response to higher fertilizer was also confirmed by the low harvest index values. The harvest index values were very low under higher fertilizer (HI = 36 %) compared to treatments with low fertilizers (55 %). Water stress can reduce efficiency of nutrient uptake by 26% and consequently grain yield by up to 75 % if water shortage is prolonged (Bennett *et al*., 1989).

8.1 Conclusions and recommendations

Higher soil water storage at an early stage and throughout the seasons under RT plots did not enhance maize development and growth. This is attributed to soil compaction under RT which affected the initial crop growth of maize and resulted in more variable emergence rates and lower plant stand compared with those of CT. Insufficient rainfall in March, during the reproductive stage, and generally low and poor rainfall distribution throughout 2011/12, contributed to lower grain yields. From this study, it can be concluded that maize can benefit from intercropping with cowpeas. It is therefore recommended that small-holder farmers in dryland areas take the advantage of intercropping maize with legumes to obtain higher maize productivity. Further studies are required to investigate the possibility of poor root development and restrictions under RT under various environmental and soil conditions. Furthermore, long term experiments based on conservation agriculture practices are thus required at different areas and under various soil conditions to determine whether RT may give positive results after many years of continuous practice.

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Appendix 1 – Trial layout

CONCERVATION AGRICULTURE TRIAL TREATMENTS

1. Tillage (whole plots - 2 treatments)

   a) Reduced tillage (**RT**)

   b) Conventional (**CT**)

2. Fertilizer (2 treatments)

*a) Low-input (**F1**):*

Maize

Type – with plant: 2:3:2 (22)

Amount: 2 bags (50kg x 2); 6.3kg N : 9.6 kg P : 6.3 kg K

Type / amount – top dress: 0

Legume

Type – with plant: Mixture LAN and KCl (ratio of 2:1)

Amount: 1 bags Supers (100kg) and 0.5 bag KCl (50kg)

Type / amount – top dress: 0

*b) High input (**F2**): (Potential of 4 ton ha^{-1})*

Maize

Type – with plant: 2:3:2 (22)

Amount: 4 bags (200kg); 12.6 kg N : 19.2 kg P : 12.6 kg K

Type / amount – top dress: 4 bags LAN (200 kg) (54 kg N)

Legume

Type – with plant: Mixture LAN and KCl (ratio of 2:1)

Amount: 2 bags Supers (100kg) and 1 bag KCl (50kg)

Type / amount – top dress: 0

3. Cropping systems (6 treatments)

a) 1 x Maize monoculture – **C1**

b) 2 x Maize / Legume rotation

   a. Maize + Cowpeas – **C2**

   b. Maize + Soybean – **C3**

c) 1 x Maize / Legume intercropping (Legume: Cowpeas) – **C4**

d) 2 x Maize delayed intercropping with temperate crops

   a. Maize + oats – **C5**

   b. Maize + vetch – **C6**

Total number of treatments (plots):

Three blocks x Two tillage systems x two fertilizer levels (Fert) x 6 (crops) = 72 plots

Treatment Number (T)	**Treatment Combination (Crop + Fert)**
1	F1C1
2	F1C2
3	F1C3
4	F1C4
5	F1C5
6	F1C6
7	F2C1
8	F2C2
9	F2C3
10	F2C4
11	F2C5
12	F2C6

ZEEKOEGAT CA Trial layout

BLOCK A	**Reduced Tillage**	**1** / 7 / *1*	PIT 1	**13** / 7 / *2*	**Conventional Tillage**
		2 / 2		**14** / 2	
		3 / 9 / *4*		**15** / 9 / *3*	
		4 / 3 / *5* / AC		**16** / 3 / *6* / AC	
		5 / 1 / *8* / AC		**17** / 1 / *7* / AC	
		6 / 11		**18** / 11	
		7 / 4 / *9* / AC		**19** / 4 / *10* / AC	
		8 / 12		**20** / 12	
		9 / 6		**21** / 6	
		10 / 8		**22** / 8	
		11 / 10 / *12*		**23** / 10 / *11*	
		12 / 5		**24** / 5	
BLOCK B	**Reduced Tillage**	**25** / 5	PIT 2	**37** / 5	**Conventional Tillage**
		26 / 11		**38** / 11	
		27 / 10 / *13*		**39** / 10 / *14*	
		28 / 8		**40** / 8	
		29 / 1 / *16* / AC		**41** / 1 / *15* / AC	
		30 / 2		**42** / 2	
		31 / 9 / *17*		**43** / 9 / *18*	
		32 / 6		**44** / 6	
		33 / 7 / *20*		**45** / 7 / *19*	
		34 / 4 / *21* / AC		**46** / 4 / *22* / AC	
		35 / 3 / *24* / AC		**47** / 3 / *23* / AC	
		36 / 12		**48** / 12	
BLOCK C	**Conventional Tillage**	**49** / 1 / *25* / AC	PIT 3	**61** / 1 / *26* / AC	**Reduced Tillage**
		50 / 11		**62** / 11	
		51 / 2		**63** / 2	
		52 / 5		**64** / 5	
		53 / 10 / *28*		**65** / 10 / *27*	
		54 / 8		**66** / 8	
		55 / 9 / *29*		**67** / 9 / *30*	
		56 / 3 / *32* / AC		**68** / 3 / *31* / AC	
		57 / 12		**69** / 12	

	58 / 7 / *33*		**70** / 7 / *34*	
	59 / 6		**71** / 6	
	60 / 4 / *36* / AC		**72** / 4 / *35* / AC	

1-72 / 1-12 / *1-36* = **Plot /** Treatment / *NWM access tube* / AquaCheck probe (AC)

Key plots (yellow)

Appendix 2A: Soil nutrient status of 0-30 cm layer (topsoil) 2007-2011

Year	pH Water	P mg/kg	Ca mg/kg	K mg/kg	Mg mg/kg	Na mg/kg	N-NO3 mg/kg	Org C %	C %	N %
2007	6.073	4.674	1199.0	502.0	267.4	37.056	15.564	1.244	1.291	0.104
2008	6.170	8.873	973.1	599.6	227.6	11.035	9.077	1.314	1.389	0.122
2009	6.277	8.291	1101.9	486.9	239.5	11.194	4.066	1.313	1.357	0.115
2010	6.199	9.400	1115.7	575.6	240.3	5.012	4.596	1.422	1.458	0.120
2011	6.243	8.026	1113.3	520.7	234.6	17.444	6.769	1.356	1.413	0.118

Appendix 2.B**:** Soil nutrient 30-60 cm, 2007-2011

Year	pH Water	P mg/kg	Ca mg/kg	K mg/kg	Mg mg/kg	Na mg/kg	N-NO3 mg/kg	Org C %	C %	N %
2007	6.288	0.880	1247.7	288.3	317.7	58.3	9.517	1.030	1.110	0.086
2008	6.390	0.482	1033.3	279.8	282.8	39.7	1.630	1.095	1.145	0.110
2009	6.453	0.716	1123.9	250.1	303.6	38.6	1.447	1.078	1.104	0.096
2010	6.427	0.875	1175.0	260.6	307.4	35.0	1.742	1.122	1.168	0.097
2011	6.413	0.566	1159.2	289.9	291.6	22.7	1.746	1.124	1.173	0.099

Appendix 3A: Calibration equations for NWM for different replicates and soil horizons (0 – 750 mm) after corrections for concretions

Depth Increment (mm)	Block	Calibration Equation ($\theta v = a + bCR$)	Df	t-test: Regression coefficient (b)	Variance explained (R^2, %)	Correlation coefficient (r)
0-225	1	$\theta v = 3.1816 + 15.8189CR$	24	10.90***	77	0.8780***
	2	$\theta v = 3.3148 + 14.8221CR$	24	10.94***	77	0.8758***
	3	$\theta v = -0.0032 + 19.0540CR$	23	11.29***	80	0.8923***
225-375	1	$\theta v = -0.5539 + 13.6994CR$	24	8.76***	67	0.8201***
	2	$\theta v = -3.1695 + 15.5323CR$	24	12.72***	78	0.8823***
	3	$\theta v = -1.6569 + 15.9077CR$	24	14.52***	79	0.8862***
375-525	1	$\theta v = 3.3709 + 10.3946CR$	24	5.88***	46	0.6772***
	2	$\theta v = 3.6732 + 11.3585CR$	24	0.73***	53	0.7269***
	3	$\theta v = -0.3510 + 14.6010CR$	24	18.96***	75	0.8640***
525-750	1	$\theta v = 6.4318 + 7.5759CR$	22	5.32***	37	0.6090***
	2	$\theta v = 7.2169 + 9.9897CR$	24	7.91***	56	0.7477***
	3	$\theta v = -0.0878 + 14.3263CR$	22	66.61***	80	0.8935***

Appendix 3B: Calibration equations for NWM for different replicates and soil horizons (750 – 1350 mm) after corrections for concretions

Depth Increment (mm)	Block	Calibration Equation ($\theta v = a + bCR$)	Df	t-test: Regression coefficient (b)	Variance explained (R^2, %)	Correlation coefficient (r)
750-1050	1	θv = 5.6364+ 10.0277CR	23	5.91***	40	0.6275***
	2	Y = 5.4704+ 10.7185CR	24	13.55***	64	0.8012***
	3	Y =-1.8132+ 12.5236CR	24	23.44***	74	0.8597***
1050-1350	1	Y = 5.9638+ 9.8782CR	21	5.68***	39	0.6261***
	2	Y = -2.1404+ 13.3124CR	24	9.03***	61	0.7803***
	3	Y = -2.8791+ 13.1196CR	24	28.74***	71	0.8446***

Appendix 4A: Calibration equations for NWM for different replicates and soil horizons (0 – 750mm) before corrections for concretions

Depth Increment (mm)	Block	Calibration Equation ($\theta v = a + bCR$)	Df	Variance explained ($R2$, %)	Correlation coefficient (r)
0-225	1	$\theta v = 4.5 + 14.318\ CR$	24	79	0.888819442
	2	$\theta v = 4.722 + 13.959CR$	24	78	0.883176087
	3	$\theta v = 2.248 + 16.322CR$	23	81	0.9
225-375	1	$\theta v = -0.6123 + 15.069CR$	24	67	0.818535277
	2	$\theta v = -3.2734 + 15.559CR$	24	78	0.883176087
	3	$\theta v = -1.6375 + 15.679CR$	24	77	0.877496439
375-525	1	$\theta v = 4.0375 + 12.421CR$	24	46	0.678232998
	2	$\theta v = 3.6842 + 11.397CR$	24	53	0.728010989
	3	$\theta v = -0.3597 + 14.7464CR$	24	75	0.866025404
525-750	1	$\theta v = 8.2336 + 11.076\ CR$	22	42	0.64807407
	2	$\theta v = 7.3399 + 10.172CR$	24	55	0.741619849
	3	$\theta v = -0.0841 + 14.595CR$	22	80	0.894427191

Appendix 4B: Calibration equations for NWM for different replicates and soil horizons (750 - 1350mm) before corrections for concretions

Depth Increment (mm)	Block	Calibration Equation ($\theta v = a + bCR$)	Df	Variance explained (R2), %)	Correlation coefficient (r)
750-1050	1	θv =13.109+ 9.2681CR	23	24	0.489897949
	2	Y = 5.8963+ 11.54CR	24	64	0.8
	3	Y =-0.2491+ 16.11CR	24	79	0.888819442
1050-1350	1	Y =6.4555+ 10.687CR	21	39	0.6244998
	2	Y = -2.5722+ 16.036CR	24	61	0.781024968
	3	Y = -2.9548+ 16.689CR	24	76	0.871779789

Appendix 5A: Table of means for NWM soil water content (for some treatments) during 2010/11 and 2011/12 growing season

		2010/11 growing season			2011/12 growing season		
Treatments		Top soil (0-300mm)	Subsoil (300-1350mm)	Profile water (0-1350mm)	Top soil (0-300mm)	Subsoil (300-1350mm)	Profile water (0-1350mm)
Tillage	RT	27.682a	28.101 a	27.966 a	23.681a	26.574a	25.609a
	CT	27.072a	26.779 b	26.867 b	21.069a	24.862b	23.598b
Fertilizer	F1	27.363a	27.708a	27.588a	22.477a	25.746a	24.656a
	F2	27.390a	27.172 b	27.245a	22.273 a	25.690a	24.551a
Cropping pattern	Monoculture	28.238a	28.042a	28.105a	22.880a	26.157a	25.065a
	Intercropping	26.516b	26.838b	26.728b	21.870a	25.279b	24.142 b
Tillage x	RT x F1	27.818a	28.375a	28.192a	23.476a	26.580a	25.543a
Fertilizer	RT x F2	27.545a	27.826a	27.740ab	23.886a	26.569a	25.675a
	CT x F1	26.909 a	27.040b	26.983bc	21.478ab	24.913b	23.768b
	CT x F2	27.235a	26.518b	26.751c	20.660b	24.812b	23.427b
Tillage x Cropping pattern	RT x Monoculture	28.634a	28.706a	28.683a	24.605a	27.266a	26.379a
	RT x Intercropping	26.729ab	27.495b	27.249b	22.757ab	25.883b	24.839b
	CT x Monoculture	27.841ab	27.377b	27.526b	21.155b	25.049bc	23.751bc
	CT x Intercropping	26.303b	26.180c	26.208c	20.983b	24.676c	23.445c

Means within columns (per main effect / interaction) followed by different symbols are significantly different at ≤ 0.05

Appendix 5B: Table of means for NWM soil water content (for some treatments) during 2010/11 and 2011/12 growing season

		2010/11 growing season			2011/12 growing season		
Treatments		Top soil (0-300mm)	Subsoil (300-1350mm)	Profile water (0-1350mm)	Top soil (0-300mm)	Subsoil (300-1350mm)	Profile water (0-1350mm)
Fertilizer x Cropping pattern	F1 x Monoculture	27.580ab	28.554a	28.226a	22.422a	26.545a	25.170a
	F1 x Intercropping	27.147 ab	26.861b	26.949ab	22.533a	24.947b	24.141a
	F2 x Monoculture	28.895a	27.530b	27.983ab	23.338a	25.769ab	24.959a
	F2 x Intercropping	25.886b	26.814b	26.507c	21.208a	25.612ab	24.143a
Fertilizer x cropping pattern x Tillage	F2 x Monoculture x RT	29.34a	28.06 b	28.48ab	25.64a	26.75ab	26.38a
	F1 x Monoculture x RT	27.93 ab	29.35 a	28.88a	23.57ab	27.78a	26.37a
	F1 x Intercropping x RT	27.71ab	27.40bc	27.50 abc	23.39ab	25.38bc	24.71ab
	F2 x Intercropping x RT	25.75 b	27.59bc	27.00bcd	22.13ab	26.38ab	24.96ab
	F1 x Monoculture x CT	27.23ab	27.76bc	27.57 abc	21.28b	25.31bc	23.97b
	F2 x Monoculture x CT	28.45 ab	27.00cd	27.48 bcd	21.03b	24.78c	23.53b

Means within columns (per main effect / interaction) followed by different symbols are significantly different at ≤ 0.05

Appendix 6: LSD values for treatment effects on SWC

	2010/11 growing season			2011/12 growing season		
Treatments	0-300 mm	300 -1350 mm	0-1350 mm	0-300mm	300-1350 mm	0-1350 mm
Tillage	1.69	0.50	0.83	2.99	1.56	1.70
Cropping pattern	1.72	0.53	0.75	1.76	0.71	0.89
Fertilizer	1.72	0.53	0.75	1.76	0.71	0.89
Tillage x crop pattern	1.89	0.58	0.85	2.43	1.18	1.34
Tillage x fertilizer	1.89	0.58	0.85	2.43	1.18	1.34
Cropping pattern x fertilizer	2.43	0.76	1.06	2.49	0.99	1.26
Tillage x cropping pattern x fertilizer	3.06	0.95	1.34	3.31	1.45	1.75
Week	0.54	0.36	0.36	0.61	0.30	0.34
Tillage x week	1.27	0.55	0.68	2.31	1.20	1.32
Cropping pattern x week	1.84	0.70	0.87	1.91	0.80	0.98
Week x fertilizer	1.84	0.70	0.87	1.91	0.80	0.98
Tillage x cropping pattern x week	2.12	0.88	1.07	2.62	1.25	1.43
Tillage x week x fertilizer	2.12	0.88	1.07	2.62	1.25	1.43

Appendix 7: Stratum standard errors (s.e) and coefficients of variation (CV%) of treatment effects on SWC

		2010/11 growing season					
		0-30 mm		300 -1350 mm		0-1350 mm	
Stratum	d.f.	s.e.	cv%	s.e.	cv%	s.e.	cv%
Block	2	4.2260	15.4	1.0847	4.0	1.5816	5.8
Block.Tillage	2	0.4799	1.8	0.1422	0.5	0.2376	0.9
Block.Tillage.Cropping pattern.Fertilizer	12	1.9339	7.1	0.6005	2.2	0.8394	3.1
Block.Tillage.Cropping patterns.Fertilizer.Week	323	0.9516	3.5	0.6248	2.3	0.6353	2.3
		2011 /12 growing season					
		0-30 mm		300 -1350 mm		0-1350 mm	
Stratum	d.f.	s.e.	cv%	s.e.	cv%	s.e.	cv%
Block	2	5.2656	23.5	0.7853	3.1	1.7738	7.2
Block.Tillage	2	0.8508	3.8	0.4387	1.7	0.4842	2.0
Block.Tillage.Cropping pattern.Fertilizer	12	1.9784	8.8	0.7946	3.1	0.9997	4.1
Block.Tillage.Cropping patterns.Fertilizer.Week	223	1.0762	4.8	0.5324	2.1	0.5982	2.4

Appendix 8: Summary of means for soil temperatures during growing season 2010/11

Treatments		100mm	400mm	800mm	100mm	400mm	800mm
		Maximum temperature (^{0}C)			Minimum temperature (^{0}C)		
Tillage systems	CT	25.72a	23.81a	23.47a	21.19a	23.28a	23.33a
	RT	23.42b	22.28b	22.55b	19.07 b	21.84 b	22.42a
Cropping pattern	monoculture	24.34a	22.57a	22.64a	19.71a	22.10a	22.51a
	Intercropping	24.80a	23.59a	23.44a	20.60a	23.08a	23.30a
Tillage x cropping pattern	CTx Intercropping	27.30a	25.17a	24.75a	22.90a	24.55a	24.59a
	CT x Monoculture	24.68 b	22.91b	22.62b	20.05 b	22.44b	22.49 b
	RT x Monoculture	23.94 b	22.17b	22.66b	19.31 b	21.71b	22.53 b
	RT x intercropping	22.91 b	22.39b	22.45b	18.85 b	21.97b	22.32 b

Means within columns (per main effect / interaction) followed by a same letter are not significantly different at the 10% probability level, according to LSD.

Appendix 9A: Summary of means for soil temperatures during growing season 2011/ 12

Treatments		100mm	400mm	800mm	100mm	400mm	800mm
		Maximum temperature (^{0}C)			Minimum temperature (^{0}C)		
Tillage systems	CT	29.0703a	25.167 a	24.15487 a	20.99a	24.47 a	23.931a
	RT	27.2773b	23.9705 b	23.60471 b	19.57 a	23.25a	23.44a
Cropping pattern	monoculture	28.008a	23.7842 a	23.1998 b	19.0925b	23.0473 b	23.0064 b
	Intercropping	28.433a	25.3274 a	24.5079 a	21.4106a	24.6438 a	24.3128 a
Tillage x cropping pattern	CT x Intercropping	29.54 a	26.128 a	25.0123 a	22.791 a	25.497 a	24.8075 a
	CT x Monoculture	28.628 a	24.250 ab	23.3403 ab	19.280 b	23.489 ab	23.1020 ab
	RT x Monoculture	27.123a	23.119 b	22.9990 b	18.825 b	22.416 b	22.8698 b
	RT x intercropping	27.385a	24.57 ab	24.0287 ab	20.10 ab	23.834 ab	23.8428 ab

Means within columns (per main effect / interaction) followed by a same letter are not significantly different at the 10% probability level, according to LSD.

Appendix 9B: Summary of means for soil temperatures (Maximum - Minimum (^{0}C))

Treatments		100mm	400mm	800mm	100mm	400mm	800mm
		2010/11 growing season			2011/12 growing season		
Tillage systems	CT	4.54a	0.53a	0.14a	8.0806 a	0.60308 a	0.16111 a
	RT	4.34b	0.44b	0.13a	7.7033 a	0.66529 a	0.12176 a
Cropping pattern	Monoculture	4.63a	0.47a	0.13a	8.9163 a	0.70980 a	0.16078 a
	Intercropping	4.20a	0.51a	0.14a	7.0232 a	0.56427 b	0.12709 a
Tillage x cropping pattern	CTx Intercropping	4.40a	0.62a	0.16a	6.746 a	0.48596 b	0.13825 a
	CT x Monoculture	4.63a	0.47ab	0.13a	9.348 a	0.71433 a	0.18283 a
	RT x Monoculture	4.64a	0.46ab	0.13a	8.299 a	0.70333 a	0.12929 a
	RT x intercropping	4.06a	0.42b	0.13a	7.286 a	0.63867ab	0.11650 a

Means within columns (per main effect / interaction) followed by a same letter are not significantly different at the 10% probability level, according to LSD.

Appendix 10: Means of maize germination percentage and plant height for growing season 2011/12

Treatments		Germination (%)	Plant height (cm)
Tillage	RT	46.4a	149.7a
	CT	61.9a	176.7a
Fertilizer	F1	51.8a	161.0a
	F2	56.5a	165.4a
Cropping	Monoculture	64.3a	155.9a
	Intercropping	44.0a	170.5a
Tillage x Fertilizer	RT x F1	46.4a	146.7a
	RT x F2	46.4a	152.6a
	CT x F1	57.1a	175.3a
	CT x F2	66.7a	178.2a
Tillage x Cropping system	RT x Monoculture	61.9a	148.1ab
	RT x Intercropping	31.0b	151.3ab
	CT x Monoculture	66.7a	163.7b
	CT x Intercropping	57.1a	189.8a
Fertilizer x Cropping system	F1 x Monoculture	63.1a	142.0b
	F1 x Intercropping	40.5a	180.0a
	F2 x Monoculture	65.5a	169.8a
	F2 x Intercropping	47.6a	161.1ab

Means within columns (per main effect / interaction) followed by a same letter are not significantly different at the 10% probability level

Appendix 11: Coefficient of determination (R^2) on the grain yield response to monthly SWC.

Coefficients of determination (R^2):

Variables	Year	Tillage	Crop	Fertilizer	SW_Dec	SW_Jan	SW_Feb	SW_Mar	Yield_1
Year	**1**	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tillage	0.000	**1**	0.000	0.000	0.048	0.049	0.092	0.087	0.139
Crop	0.000	0.000	**1**	0.000	0.006	0.001	0.006	0.023	**0.224**
Fertilizer	0.000	0.000	0.000	**1**	0.001	0.000	0.002	0.000	0.006
SW_Dec	0.000	0.048	0.006	0.001	**1**	**0.963**	**0.968**	**0.951**	0.014
SW_Jan	0.000	0.049	0.001	0.000	**0.963**	**1**	**0.944**	**0.936**	0.022
SW_Feb	0.000	0.092	0.006	0.002	**0.968**	**0.944**	**1**	**0.983**	0.019
SW_Mar	0.000	0.087	0.023	0.000	**0.951**	**0.936**	**0.983**	**1**	0.012
Yield_1	0.000	0.139	**0.224**	0.006	0.014	0.022	0.019	0.012	**1**

Appendix 12: LSD values for treatment effects on maize growth and yield

	2010/11 growing season		2011/12 growing season			
Treatments	Biomass	Grain yield	Germination percentage	Height	Biomass	Grain yield
Tillage	2.007	7745.6	16.80	58.18	5656.9	1.260
Cropping pattern	0.513	1945.1	20.94	16.69	1331.5	0.592
Fertilizer	0.513	1945.1	20.94	16.69	1331.5	0.592
Tillage x crop pattern	1.633	6308.9	22.25	46.13	4672.7	0.971
Tillage x fertilizer	1.633	6308.9	22.25	46.13	4672.7	0.971
Cropping pattern x fertilizer	0.726	2750.8	29.61	23.60	1883.0	0.837
Tillage x cropping pattern x fertilizer	1.539	5926.4	36.90	45.25	4319.0	1.206