Water management for rainfed maize in semi-arid Zimbabwe

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Table of contents

Chapter 1

Introduction

Introduction

1.1 Food insecurity in Sub-Saharan Africa

The present food insecurity and projected population growth in Sub-Saharan Africa (SSA) demand change from low yielding farming systems towards greater production and sustainability (Cai and Rosegrant, 2003; Kauffman et al., 2003 ; Rockström et al., 2002; Wallace, 2000), particularly in semi-arid tropics where food security is threatened by frequent droughts, dry spells (Steiner et al., 2003) and infertile soils (Sanchez, 2002). Food production has to increase under dwindling water resources (Bouman, 2007; Cai and Rosegrant, 2003). Therefore, water productivity in rain-fed agriculture must improve if food production is to keep pace with population growth (Rockström et al., 2002). The priority crops should include maize (*Zea mays* L.), the most important cereal crop in Eastern and Southern Africa (Barron, 2004; Magorokosho et al., 2003).

Semi-arid zones of SSA cover about 41% of the region (Sanchez, 2002). In Zimbabwe, 64% of the total land area is semi-arid agroecological regions (Natural Regions) (IV and V), annual rainfall 450-650 mm and < 450 mm respectively, and 74% of the communal area land is located in these areas (Whitlow, 1980). Low crop yields in semi-arid areas are mainly due to poor temporal and spatial rainfall distribution rather than absolute water shortage (Barron, 2004; Barron and Okwach, 2005; Kahinda et al., 2008; Muhammad and Reason, 2004; Ochola and Kerkides, 2003; Rockström, 2000). Even though rainfall is marginal, low productivity in rainfed smallholder agriculture in semi-arid tropics is more due to management-related sub-optimal performance than low physical potential (Rockström and Falkenmark, 2000; SIWI, 2001). Stable yield increases from 0.5-2 t ha^{-1} (Rockström et al., 2003) are achievable. Over 50% of rainwater is lost by surface runoff and evaporation (Steiner et al., 2003). The green water fraction is only 15-30% of the total rainfall in SSA (Falkenmark and Röckstrom, 2004), yet it may exceed 50% in comparable climates in the USA (Stroosnijder, 2009; Stroosnijder et al., 2008). Water productivity can be improved through maximizing plant water availability and plants' water uptake capacity, and dry spell mitigation using supplementary irrigation (Rockström et al., 2003). However, limited areal extent, competing claims for water (Cai and Rosegrant, 2003; Vohland and Barry, 2009) and prohibitive development and maintenance costs limit the role of irrigation.

Wallace (2000) bemoans the global focus on climate change at the expense of the more pressing need to feed the growing population. In SSA in addition to the shift in focus recurrent political and economic instability interrupt research impetus. For example, in Zimbabwe there has not been sustained research in the smallholder farming areas. Prior to independence in 1980 agricultural research mainly focussed on large-scale commercial farming. After independence the focus shifted to smallholder communal areas with more research activities in the larger semi-arid southern region than the semi-arid northern part, but research activities slowed at the turn of the 21st century due economic problems. Non-Governmental Organisations (NGOs) backed by their financial prowess emerged as "new gods" due inadequate resources from government and minimal international development cooperation. In the absence of adequate supporting research NGO interventions became largely generic and evaluations of interventions were largely biased towards NGOs' perspective.

1.2 Maize production in Zimbabwe

Prior to the land reform in 2000 Zimbabwe's agricultural sector was dualistic with 4500 commercial farms and just over 1 million smallholder farmers (Rukuni, 1994). Even after the land reform programme, most smallholder farming takes place on communally owned land (communal areas) and is typified by a mixture of rainfed small-scale subsistence and commercial production (Wright et al., 1998). Size of land holdings for smallholder farmers generally range from 2 to 4 ha (Cobo et al., 2009; Eicher, 1995).

In Zimbabwe maize is the staple and an important cash crop. Unfortunately it is a high-risk crop because it is susceptible to drought as well as to water logging (Mashingaidze, 2006). Despite, its susceptibility to drought maize ranks first in terms of area planted and the number of households who grow the crop even in the semi-arid areas. Smallholder farmers account for more than half the total national maize production (Stanning 1989) on ± 1.5 million hectares of land. Maize's status as the staple food crop makes it important for food security, hence research and extension naturally target the crop.

The national average yield of maize in communal areas is 1.5 t ha^{-1} compared with about 5.0 t ha^{-1} in the large-scale commercial farming sector (Mashingaidze, 2006). Trends in national average maize yield for the decade 2001-2010 depict a decline from a peak of 1.2 t ha^{-1} in 2001 to just above 0.7 t ha^{-1} in 2010 (United Nations and Government of Zimbabwe, 2010). The decline in yields is linked to socio-economic problems that affected the country during the period under review.

Due to regional differences in climate and soil there is no universal tillage or cropping system that is best for all situations (Wang et al. 2006). Therefore recommendations for semi-arid areas should be based on research done in these areas as opposed to extrapolations from work done in better rainfall areas (Nyamudeza, 1999). There should, however be no standard recommendation or package for soil and water management promotion in semi-arid areas.

Various interrelated soil and water conservation options ranging from those that are applied in the crop growing area (in-field practices) to those that are applied at field edges (field-edge practices) have been explored for optimising maize yields in semi-arid Zimbabwe. These options include conservation tillage, rainwater harvesting (RWH) and more recently conservation agriculture technologies. There is need for continuous search for viable tillage options and fine tuning of existing options to meet farmers' biophysical and socio-economic conditions. The need for co-management of soil fertility has been reiterated (Giller et al., 2006a; Rockström, 2000; Tittonell et al., 2007; Vanlauwe and Giller, 2006; Zingore et al., 2007). It is envisaged that rainwater management will lower the risk of crop failure and encourage investments in soil fertility (Rockström, 2000). However, the benefits have to be realised within a short period since poor people cannot afford to invest in the long-term (Stroosnijder et al., 2008).

1.3 Rainwater management in semi-arid Zimbabwe

The dilemma in semi-arid tropics is to balance between two vital but opposing requirements with respect to water management. On one hand, there is need to harvest and conserve every drop of rain in order to mitigate effects of dry spells; on the other hand there is need for safe disposal of excess water caused by heavy storms or incessant rains in order to conserve soil and protect growing plants. Although the cumulative seasonal rainfall is low in normal years, large rainstorms of high intensity even in dry years and recurring wet (La Niña) years often associated with tropical cyclones make implementation of surface drainage measures imperative. Therefore, there is need to combine the larger field-edge structures and in-field structures. The techniques complement each other by virtue of their different dimensions and locations (Hagmann, 1996; Nyagumbo, 1999). The larger field-edge structures regulate runoff water particularly from heavy storms by slowing it down, partially redirecting it for safe disposal and allowing it to filter into the cropping area in less erosive quantities. In Zimbabwe the field-edge structures are recommended on slopes greater than 2%.

Unfortunately in recent years field-edge structures have been marginalised in favour of in-field practices. Emphasis is on conservation agriculture whose three principles: (1) minimum or no mechanical soil disturbance, (2) permanent soil organic cover, and (3) diversified crop rotations, are wholly based in-field. In our view conservation agriculture based only on in-field practices is incomplete and vulnerable to large single-day rainfall events.

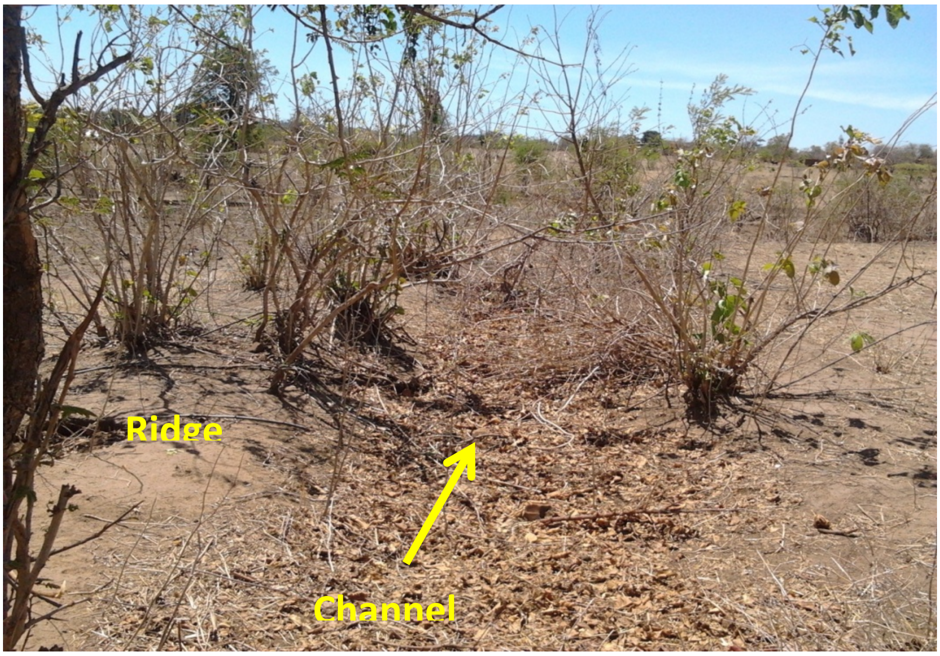


Figure 1.1: Picture showing an unmaintained contour ridge; a remnant of pre-independence (1980) construction in Rushinga district Zimbabwe

Among the field-edge technologies is the contour ridge (Figure 1.1) which is an important historical symbol of rainwater management in Zimbabwe. Contour ridges are hydraulic structures with an upstream channel and downstream ridge constructed at 0.4% gradient in order to safely discharge runoff water (Elwell, 1981). Contour ridges exist in most crop fields either as remnants of pre-independence constructions or as more recent constructions. They have been in existence since their enforcement by the colonial government in the 1950s (Whitlow, 1988; Wilson, 1995).

In recent years contour ridges have been modified in order to adapt them to a new role of RWH through construction of infiltration pits and *fanya juus* (bench terraces with retention ditches). Infiltration pits are rectangular trenches of varying dimensions excavated at intervals in the channels of contour ridges for collecting runoff water, storing it and allowing it to infiltrate and presumably flow through the soil layers (Figure 1.2). These field-edge structures have been largely promoted by NGOs and have been reported to increase crop yields through an increase in soil moisture content in the crop growing area (Motsi et al., 2004 ; Mugabe, 2004; Mutekwa and Kusangaya, 2006). Whilst *fanya juus* have been tried and tested especially in Eastern Africa (Makurira et al., 2009), the benefits of infiltration pits in increasing soil moisture and crop yields has not been adequately quantified.

Although farmers and NGOs claim benefits of improved crop yields, intuitively it is difficult to conceive how infiltration pits located at field edges benefit crops growing in fields which are on average 20-25 m wide. Based on knowledge from soil physics and hydrology we contend that in a homogenous and deep soil profile most of the water may infiltrate downwards below the pit to recharge the water table without significant lateral movement into the rootzone of the maize cropping area (Figure 1.3). Subsurface lateral flow in the crop rootzone will dominate only when the lateral hydraulic conductivity of the surface soil horizons exceeds the overall vertical hydraulic conductivity through the soil profile (Boonstra, 1994; Ward and Robinson, 2000). The subsurface lateral flow is predominant just above the less permeable or impermeable layer (Miyazaki, 2006) and this may not benefit shallow rooted crops including maize. Vogel (1993) observed that where maize growth was not restricted by limited topsoil depth or restrictive subsoil horizons the bulk of the roots grew to 30 cm only with a few growing to 45 cm. Furthermore, if the subsurface lateral flow occurs at shallow depths the water is prone to non-productive evaporation losses. Ward and Robinson (2000) state that normal subsurface lateral flow has a maximum rate of 5-6 m d^{-1}, thus it takes 4-5 days to cover the field width. Water may also travel downslope through macropores and fissures. However, such flow is unpredictable and varies in spatial terms and is therefore not by design.

Figure 1.2: Picture showing a contour ridge with an infiltration pits in a maize crop field

Thus, besides the various in-field water management options this thesis focusses on contour ridges modified by construction of infiltration pits, a RWH technique adopted by most farmers in southern Zimbabwe (Hagmann et al., 1999; Hughes and Venema, 2005 ; Mutekwa and Kusangaya, 2006), and Motsi et al. (2004) and Mutekwa and Kusangaya (2006) report that they were preferred to *fanya juus* by farmers.

For the combination of field-edge (infiltration pits) and in-field structures we selected planting pits which resemble zaï pits used in West Africa (Anschütz et al., 2003; Shaxson and Barber, 2003). The planting pits, 20-25 cm diameter and 15 cm deep (FACHIG, 2009) are located inside the cropping area whilst infiltration pits, usually ≥1.5 m^3 at 5-20-m intervals are constructed along field edges. In West Africa, zaï pits are often combined with stone bunds or grass strips for the same reasons (Anschütz et al., 2003). We selected planting pits because they were the least researched; were being promoted across the country by Zimbabwean Conservation Agriculture Task Force (ZCATF); and they courted controversy as they were viewed by some academics and politicians as taking people back to ancient times.

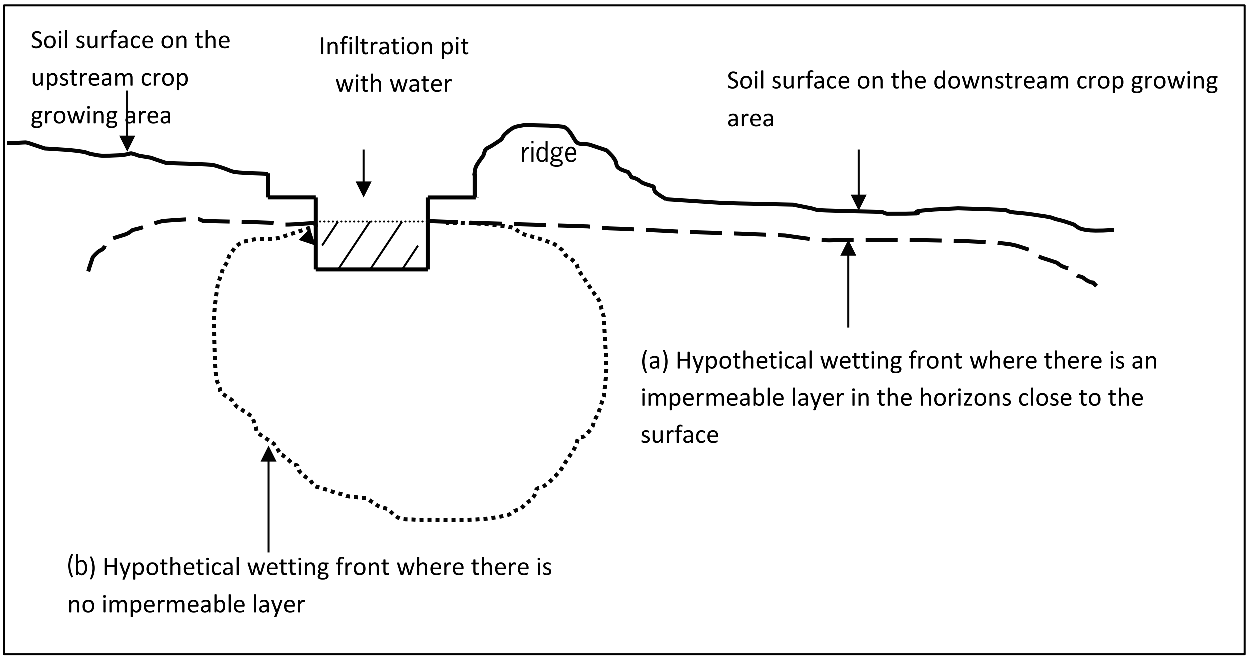


Figure 1.3: Hypothetical development of wetting front in contour ridges with infiltration pits

1.4 Theoretical concepts

1.4.1 Water use efficiency

In rainfed crop production systems water deficiency is a major limitation (Nielsen et al., 2005; Stanhill, 1986; Stewart and Steiner, 1990) therefore, focus is on increasing efficiency of water use.

Precipitation use efficiency has been used as a surrogate for water use efficiency (WUE) in rainfed agriculture because soil management practices that increase soil water storage have a positive impact on water use efficiency (Hatfield et al., 2001). Although the terms are often used interchangeably, there is a difference between precipitation use efficiency and WUE. Precipitation use efficiency is a measure of the biomass or grain yield produced per unit precipitation while water use efficiency is based on evapotranspiration. If all precipitation during the growing season is used for evapotranspiration then precipitation use efficiency and water use efficiency will be equal (Hatfield et al., 2001). From a physiological perspective, crop water use efficiency is the ratio of biomass to consumed water (Blum, 2005; Hatfield et al., 2001; Sinclair et al., 1984). Thus, water use efficiency is described according to Equation 1.1.

$$WUE = Y/ET \quad [1.1]$$

Where:
Y is either total biomass or yield of the crop, and
ET is the evaporation of water from the soil surface and transpiration from the crop.

In calculating WUE (Equation 1.1), the productive flow of vapour (transpiration) is combined with non-productive evaporation losses of water. The combined vapour fluxes as evaporation and transpiration constitute the total consumptive water use in biomass production called the green-water flow (Falkenmark and Rockström, 2006). The other complementary flow is the liquid blue-water flow through rivers and aquifers.

Another parameter used to measure efficiency of water use is the green-water use efficiency (GWUE) expressed as a ratio: transpiration/precipitation (Stroosnijder, 2009). The advantage of GWUE is that it avoids the compounding effect of the non-productive evaporation losses. The opportunities available to improve WUE can be assessed by comparing average values currently being achieved with those obtained under the best field practices and with estimates of potential values (Stanhill, 1986). For example, according Stroosnijder (2009) GWUE in dryland systems in sub-Saharan Africa ranges from 5 to 15% but may be above 50% in comparable climates in the USA. Falkenmark and Rockström (2006) estimate the GWUE for sub-Saharan Africa at 10 to 30% for tropical grains including maize sorghum (*Sorghum bicolor* L. (Moench)) and millet (*Pennisetum glaucum* (L.) R. Br.) and non-productive evaporation at 50% of seasonal rainfall.

According to Rockström et al. (2010) the productive flow of water as transpiration can be enhanced by integrated soil, crop and water management and through the following management options: conservation agriculture, early planting, improved crop cultivars, optimum crop geometry, soil fertility management, optimum crop rotation, intercropping, pest control and organic matter management. This is in agreement with Tittonell and Giller (2013) who also state under smallholder farming systems in Africa yield gaps may be reduced through proper agronomic management including planting dates, spacing, cultivars and early weeding.

1.4.2 Available water during a dry spell

Field water balance

The field water balance for rainfed crop production in a semi-arid area (assuming a deep water table > 15 m and net subsurface lateral flow of zero) has five components namely precipitation (P) as input into the system, and surface runoff (R), evaporation from the soil surface (E), transpiration (T) and drainage below the rootzone (D) as outputs arranged in an equation following the generic water balance (input = output + change in storage) according to Equation 1.2.

$$P = R + E + T + D + \Delta S \qquad [1.2]$$

Where:
ΔS is change in soil water storage in the rootable layer.

Through agronomic management smallholder farmers can influence the relative proportions of the output components to maximize the productive flow of water as transpiration and minimise the non-productive flows. The last two terms (D + ΔS positive) form the infiltration component. In order to achieve maximum benefits from infiltration soils must be able to store more water and deep percolation must be minimized. Infiltration depends on the duration of the shower and soil's infiltration capacity (mm h^{-1}) which is high for sand (> 50 mm h^{-1}) and low for clay (< 10 mm h^{-1}) (Stroosnijder, 2009).

Available water capacity and plant available water

During precipitation the soil moisture content may approach saturation. After the rain stops soil water content in the rootzone decreases due to internal drainage until the soil water potential is between -10 kPa (-0.1 atmospheres) (pF 2.0) and -33 kPa (- 0.33 atmospheres) (pF 2.5) at this suction level the moisture content is at field capacity (Panigrahi and Panda, 2003; Stroosnijder, 2009). Field capacity is the upper limit for the soil water content available for plant growth. During a dry spell the water content in the rootzone is depleted by the outputs (E + T) and may reach a lower limit at which plants start to wilt and die (the wilting point (WP)) i.e. soil water content at potentials equal to -1.6 MPa (pF 4.2) (Stroosnijder, 2009). The difference between the moisture contents FC and WP is called the available water capacity. The available water capacity depends on soil texture. Typical values of available water capacity (mm m^{-1}) for different soil textures are as follows: sand (55); sandy loam (120); clay loam (150), and clay (135) (Anschütz et al., 2003). Soil organic matter affects soil's water storage capacity. Soil water retention at -33 kPa is affected more by organic matter than water content at -1500 kPa (Rawls et al., 2003). The same authors observed that at low initial carbon contents (1-3%) an increase in organic carbon leads to an increase in water retention in coarse-textured soils and to a decrease in water retention fine-textured soils. At high initial carbon contents (5%), an increase in carbon contents results in an increase in water retention of all textures. Soil organic matter contents in semi-arid Zimbabwe are generally low, less than 5% (Mapfumo and Giller, 2001) corresponding to organic carbon content less than 3%.

The maximum amount of water in the rootzone available for plant growth is important because it determines the period for which plants can survive during a dry spell (period of consecutive days without effective rainfall). The total plant available water (PAW) is calculated using the Equation 1.3.

$$PAW\ (mm) = RD \times (FC - WP), \qquad [1.3]$$

Where:
RD is the rootable depth (mm).

Reckoning that when soil water content reaches WP plants die, Stroosnijder (2009) introduced a safety factor of 0.9 in the calculation of plant available water. Stroosnijder (2009) uses an example to illustrate that land degradation may cause total plant available water to drop drastically from 70 mm for a rootable depth of 600 mm enough to meet crop water requirements for 28 days to 36 mm only for a rootable depth of 400 mm adequate to meet crop water requirements for only 14 days. In an environment where the soil physical properties are continuously declining farmers then interpret the reduced length of dry spell that plants can endure as a 'drought' problem (Wilson, 1995). Indeed it is, but induced (pseudo) drought (Nyakudya and Stroosnijder, 2011).

Growth of plant roots responds to soil water conditions. When all their requirements are effectively supplied, plants do not need a deep root, hence root systems under very productive drip irrigation systems are relatively shallow. However, under conditions of unsecured soil resources, a potentially deep root is required to ensure capture of resources under erratic conditions (Blum, 2005). For a crop to achieve its genetic potential of rooting depth, the rootable soil profile should not be limiting. Thus, soil management practices that affect rooting depth will ultimately have some effect on WUE and GWUE (Hatfield et al., 2001; Stroosnijder, 2009).

1.4.3 Co-management of soil fertility: the paradigm of integrated soil and water management

The need to pay special attention to soil fertility management in soil and water management interventions in order to improve crop yields and water productivity has long been recognized; for example see Unger et al.(1991). As stated in section 1.1 this has increasingly been reiterated. Innovative and adaptive integrated soil and water management, encompassing soil fertility and tillage management and water harvesting (Falkenmark and Rockström, 2006; Rockström et al., 2010) should be developed. To some extent integrated soil and water management converges with the paradigm of ecological intensification (Tittonell and Giller, 2013). The two authors single out soil quality as the most urgent of the three pillars of ecological intensification in Africa (the other two being yield potential and precision agriculture), and note that in some regions most poor farmers' fields have degraded and poorly responsive soils. They argue that substantial investment to build soil organic matter is needed to restore the soils to a responsive state. However, the storage capacity of soil organic matter in most soils depends on the amount of sand and silt. Sandy soils are not good at protecting soil organic matter because of poor aggregation. Therefore, in sandy soils there is limited potential to store soil organic matter and resulting in little potential to build organic soil nitrogen capital (Mapfumo and Giller, 2001) and crop production has to largely rely on mineral fertilizers.

1.4.4 Long-term rainfall analysis

To plan and improve management of agricultural and environmental activities including various options for increasing water use efficiency under rainfed crop production, an analysis of climatic data is essential. According to Stewart et al. (1990) a first step is to conduct an agroclimatic analysis to determine the amount of water available for crop use through dependable rainfall or as stored soil water. Integration of agroclimatic data with detailed soil data is essential to take advantage of plant available soil water that buffers the crop against dry spells as explained in section (1.4.2). Food security and environmental conditions can be improved if better use is made of rain (Stroosnijder et al., 2008). For agriculture, important aspects which relate to rainfall include the days of the start and the end of the rainy season and hence its length, rainfall amounts and risks of dry spells within the season (Hassan and Stern, 1988). The longest dry spell analysis is essential for selecting coping strategies including RWH and largest rainfall amount analysis is crucial for designing soil erosion, flood control and RWH structures (Biamah, 2005; Ochola and Kerkides, 2003). The latter is often associated with the longest wet spell. In Zimbabwe, climate data is often used for forecasting crop yields with little if any attempts to plan and manage rainwater.

1.4.5 Crop modelling

Computerized procedures greatly facilitate the estimation of crop water requirements from climatic data and allow the development of standardized information and criteria for planning and management of rainfed and irrigated agriculture (Smith, 2000). For example, benefits of different crop management adaptation options can be analysed through crop simulation models; Matthews et al. (2013). In this study, FAO's crop water productivity model, AquaCrop(Raes et al., 2012)was used to simulate the field water balance and crop productivity using long-term rainfall data. AquaCrop partitions evapotranspiration (Raes et al., 2012), thus enabling determination of GWUE. According to (Raes et al., 2009) an important application of AquaCrop is to compare the attainable against actual yields in a field, farm, or a region, to identify the constraints limiting crop production and water productivity (benchmarking tool). Measurement of actual evapotranspiration or in the separate forms of evaporation and transpiration under partial soil cover during growing seasons is not easy practically (Panigrahi and Panda, 2003). Hence, application of simple but robust models like AquaCrop could be of paramount importance. Basic input data for the model includes daily climate variables, soil properties, crop parameters and management practices.

1.5 Aim of study and research questions

This PhD study aims to untangle previous controversial research results and determine strategies that can be used by policy makers and farmers to optimise rainwater management for improving maize crop yields in semi-arid Zimbabwe by combining literature review of maize conservation tillage research, long-term rainfall analysis, field experimentation and crop modelling. This aim resulted in the following research questions:

a. Which conservation tillage options are worthy pursuing in semi-arid Zimbabwe?
b. What are the water management options for rainfed maize production based on long-term rainfall for Rushinga district in semi-arid Zimbabwe?
c. Do infiltration pits really improve soil water content and maize crop yields?
d. Are planting pits a viable tillage option for cultivating maize in semi-arid Zimbabwe?
e. How useful is FAO's AquaCrop as a decision making tool for adaptive practices in rainfed maize production?

The ultimate objective is to develop recommendations for optimal rainwater management for maize production in semi-arid areas of Zimbabwe in order to cope with dry spells and droughts, and improve food security.

1.6 Methodology

1.6.1 Literature review of maize conservation tillage research

Literature review of maize conservation tillage research done in semi-arid Zimbabwe was done in order to synthesise information and develop a consolidated body of knowledge on status quo of maize conservation tillage. Through literature review the two most promising conservation tillage methods based on maize yields were identified and discussed based on resources and levels of management required. The literature review helped to answer the first question.

1.6.2 Long-term rainfall analysis

Long-term rainfall analysis for Rushinga district in semi-arid Zimbabwe was done to assess opportunities and limitations for rainfed maize production using 25 years of rainfall data (between 1980 and 2008). Rainfall analysis was used as a tool that provides a framework for selection of feasible management options and selection of appropriate cropping systems. In order to generate sufficient information for policy makers and farmers other than just departures from the mean, a variety of statistical methods were employed. The methods included graphic trends analysis, t-test for independent samples, rank-based frequency analysis, Spearman's correlation coefficient tests and Mann-Whitney's U-test. The rainfall data were important input data for subsequent modelling with FAO's AquaCrop model. Long-term rainfall analysis answered the second research question.

1.6.3 Field experimentation

In order to quantify the benefits of infiltration pits in improving soil moisture content and maize yields we set up field experiments at three farmers' fields during three cropping seasons 2010/11, 2011/12 and 2012/13. We tested the hypothesis that infiltration and planting pits do not improve soil moisture content and maize yields. The experiment was conducted during a period when there was widespread promotion of planting pits (planting basins) by the ZCATF as part of a conservation agriculture package under a programme coordinated by the FAO Emergency Office in Zimbabwe with various NGOs as implementing partners (section 1.3). We therefore incorporated planting pits in our experimental design. In the study area, the implementing partner, Sustainable Agricultural Trust promoted planting pits and set up demonstration plots. The project ran concurrently with our experiments and thus fostered learning of the farmers in the area.

The experiment was laid out in a split-plot design with the field-edge structures (contour ridges only or contour ridges with infiltration pits) constituting the main-plot factor and the tillage methods (conventional tillage and planting pits) the split-plot factor. Treatments were replicated three times giving a total of 36 plots for the three sites. The Seed-CO SC513 maize cultivar recommended for the study area was planted throughout the duration of the experiments.

Soil moisture content was measured at two of the three sites. At one site moisture measurements were taken weekly (Barron, 2004; Makurira et al., 2009) using the TRIME-PICO IPH (TDR method) (IMKO, 2010) at 0.2 m depth intervals (Wiyo et al., 2000) up to 1.4 m. At the second site the gravimetric method soil moisture content determination was used at an interval of 7-10 days. Soil samples were taken using the Dutch Edelmann soil auger to maximum depth of 0.4 m.

An automatic weather station for measurement of precipitation, solar radiation, air humidity, temperature, wind speed and direction was set-up near the experimental sites. Climate data from the weather station was input into the AquaCrop model, for simulating field water balance and crop water productivity (Raes et al., 2012). Additional rain gauges were installed at each experimental site in order to have accurate rainfall data.

Maize was harvested from sub-plots of 10 m × 10 m in the centre of the plot in order to avoid border effects. Field experimentation addressed the third and fourth research questions.

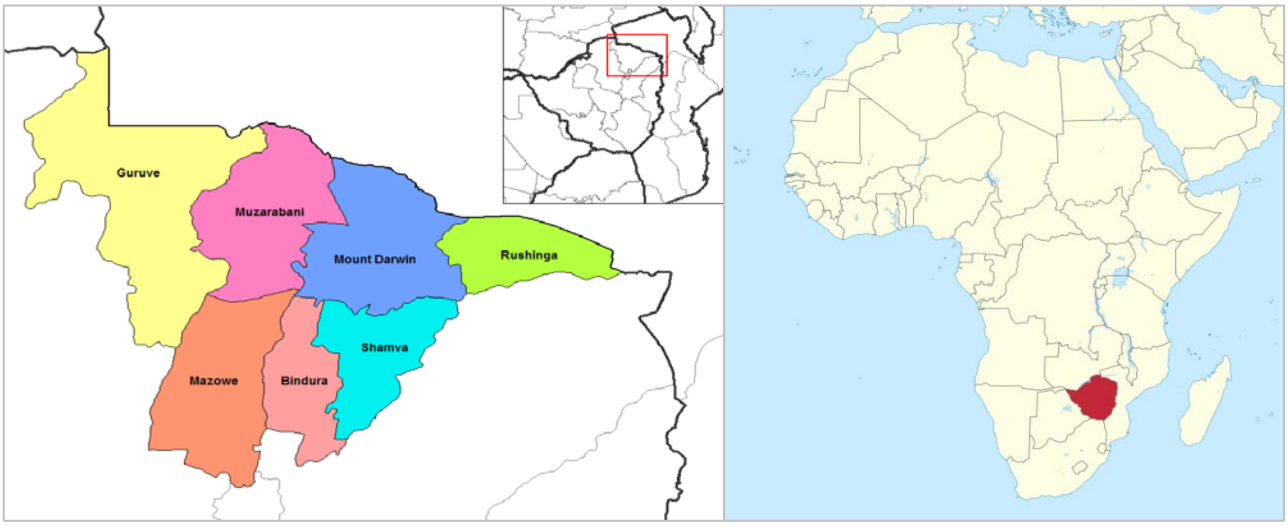
1.6.4 Modelling with FAO's AquaCrop

AquaCrop model has already been calibrated for maize and validated at multiple locations worldwide including Zimbabwe (Biazin and Stroosnijder, 2012; Heng et al., 2009; Hsiao et al., 2009; Mhizha, 2010). The model was used for scenario simulations (Raes et al., 2009) using long-term rainfall data. The AquaCrop model was run using 25 years of seasonal daily rainfall data for years between 1980 and 2009 for three soil types at the experimental sites. Simulations were performed for the following agronomic practices or parameters: (i) maximum effective rooting depth (m) at four levels (0.30, 0.35, 0.40 and 0.60), (ii) plant density (plants ha^{-1}) at three levels (17500, 25000 and 32500), (iii) curve number (representing different infield water management practices) at three levels (40, 65 and 79), (iv) planting criterion at two levels (Agritex and Depth criteria) and planting date for the first and second planting opportunities within a season based on Agritex criterion. For the long-term modelling with rainfall data, planting dates were mostly based on the depth criterion (Raes et al., 2004) and were obtained from (Raes et al., 2012). Through the scenario simulations possible rainwater management adaptive practices were explored. Crop modelling addressed the last question.

1.7 The study area

Rushinga District (16.7^{0}S, 32.3^{0}E, altitude 730 m above sea level) was the site for long-term rainfall data and field experiments (Figure 1.4). Rushinga district covers approximately 229 800 ha of which 7% is Natural Region III (annual rainfall, 650-800 mm) and the rest is Natural Region IV (annual rainfall, 450-650 mm). Rainfall data source and experimental sites were located in Natural Region IV. The rainy season is unimodal generally extending from mid-November to end of March. No rainfall of agricultural significance is received during the cold dry season from April to July and in the hot dry season August to the beginning of the rainy season (Raes et al., 2004). Mean minimum and maximum temperatures are 14.1°C and 28.6°C, respectively.

Agriculture in the district is based on a mixed crop-livestock system. Major crops grown are maize, cotton (*Gossypium hirsutum* L.), groundnuts (*Arachis hypogaea* L.) and millets and cattle and goats are the major livestock species. According to district Agricultural Technical and Extension Services Department (Agritex) the mean maize yield ranges from 0.1 to 2.5 t ha^{-1}. The soil parent materials in this area are associated with the Zambezi mobile belt and include gneisses, paragneisses and mafic granulites (Anderson et al., 1993).



Rushinga district in Zimbabwe

Zimbabwe in southern Africa

Figure 1.4: Map showing geographical location of Rushinga district in Mashonaland Central Province Zimbabwe

1.8 Thesis outline

After the General introduction (Chapter 1), Chapter 2 is literature review that synthesizes maize conservation tillage results from experiments in semi-arid Zimbabwe and identifies the most promising tillage methods in terms of maize yields. The promising tillage methods are discussed with respect to resource constraints under semi-arid areas smallholder farming. The relationship between maize yields and seasonal rainfall is explored using results from experiments and areas needing further research are highlighted.

As a follow-up to Chapter 2, realising the significant influence of rainfall on maize yields, Chapter 3 is based on long-term rainfall analysis to assess opportunities and limitations for rainfed maize production. In this chapter the incidence of dry (El Niño) and La Niña years is determined. Recommendations for maize-based sustainable crop production are drawn.

Chapter 4 is based on field experiments where benefits of infiltration and planting pits are quantified on basis of soil moisture content and maize yields measurements. Some of the soil moisture and yield data are used for modelling with FAO’s AquaCrop in Chapter 5.

Chapter 5 draws its input data from Chapters 3 and 4. In this chapter, we simulate maize yield response to water of using AquaCrop under different rainfall scenarios (normal, dry and wet seasons) using long-term rainfall data from Chapter 3, soil and crop data from Chapter 4 and we apply AquaCrop as an adaptive management tool.

Chapter 6 finally summarizes the major conclusions and discusses their implications. Findings from this thesis are put into the broader context of smallholder farming in semi-arid areas. Finally recommendations for future research are highlighted.

Chapter 2

Conservation tillage of rainfed maize in semi-arid Zimbabwe: A review

This paper is under review as:
Nyakudya, I.W., Stroosnijder, L. (2013). Conservation tillage of rainfed maize in semi-arid Zimbabwe: A review.
Soil & Tillage Research

Conservation tillage of rainfed maize in semi-arid Zimbabwe: A review

Abstract

In Zimbabwe, 74% of smallholder farming areas are located in semi-arid areas mostly in areas with soils of low fertility and water holding capacity. The dominant crop in these areas, maize (*Zea mays* L.), is susceptible to drought. Under smallholder farming in Zimbabwe, conventional tillage entails ploughing with the mouldboard plough which cuts the soil and buries weeds and crop residues. Seed is planted by hand into a furrow made by the plough, ensuring that crops germinate in relatively weed free seedbeds. Inter-row weed control is performed using the plough or ox-drawn cultivators and hand hoes. Conventional tillage has been criticised for failure to alleviate negative effects of long dry spells on crops and to combat soil loss caused by water erosion estimated at 50 to 80 t ha^{-1} y^{-1}. Therefore, conservation tillage has been explored for improving soil and water conservation and crop yields. Our objective was to determine the maize yield advantage of the introduced technology (conservation tillage) over conventional tillage (farmers' practice) based on a review experiments in semi-arid Zimbabwe. Eight tillage experiments conducted between 1984 and 2008 were evaluated. Conventional tillage included ploughing using the mouldboard plough and digging using a hand hoe. Conservation tillage included tied ridging (furrow diking), mulch ripping, clean ripping and planting pits. Field-edge methods included *fanya juus* (bench terraces) and infiltration pits. Results show small yield advantages of conservation tillage methods below 500 mm rainfall. For grain yields ≤ 2.5 t ha^{-1} and rainfall ≤ 500 mm, 1.0 m tied ridging produced 144 kg ha^{-1} and mulch ripping 344 kg ha^{-1} more than conventional tillage. Above 2.5 t ha^{-1} and for rainfall > 500 mm, conventional tillage had ≥ 640 kg ha^{-1} yield advantage. Planting pits had similar performance to ripping and conventional tillage but face digging labour constraints.

Keywords: Conservation tillage, maize yield, semi-arid Zimbabwe, experiments, smallholder farmer, resource constraints.

2.1 Introduction

Zimbabwe's semi-arid areas, known as Natural Regions (NR)) IV and V, annual rainfall 450-650 mm and less than 450 mm respectively (Vincent and Thomas, 1960), cover 64% of the country (25 million hectares) (Whitlow, 1980). The rainy season is unimodal and stretches from November to March and the dry season occurs from May to October. A few showers may fall during the dry period but high evapotranspiration results in no effective rainfall and the soil undergoes complete desiccation except at the foot of slopes where the water table is close to the soil surface.

Although fertile soils occur including the Vertisol group (total exchangeable bases per 100 g clay (S/C) and cation exchange capacity per 100 g clay (E/C) > 60), Eutric vertisols in FAO classification, and Silliatic group (Zimbabwean classification), S/C ≥ 31 and E/C ≥ 35 including Chromic luvisol and Chromic Cambisol in the FAO classification (Nyamapfene, 1991); most soils in semi-arid Zimbabwe are infertile sands derived from basic gneiss (Grant, 1981; Vogel, 1992). These less fertile soils include Fersiallitic group (Zimbabwean classification) with S/C values 6 to 30 and E/C 12 to 35, Ferralic Cambisol and Ferralic Arenosol in the FAO classification, and Regosol group (Zimbabwean classification) characterised by a deep sandy profile with less than 10% silt plus clay within the upper 2 m, Ferri-Luvic Arenosols in FAO taxonomy. The Lithosol group, which includes soils having < 0.25 m depth equivalent to Eutric Leptosol in FAO classification (Nyamapfene, 1991) constitutes soils whose agronomic potential is limited mostly by shallow depths.

Prior to the land reform in 2000 Zimbabwe's agricultural sector was dualistic with 4500 commercial farms and just over 1 million smallholder farmers (Rukuni, 1994). The large-scale commercial farmers (LSCF) occupied over 10 million hectares of land mainly in areas with better soil fertility and rainfall than the estimated 18 million hectares for the smallholder farmers. The dual structure was created by the colonial regime from the 1890s through 1970s. Even after the land reform programme, most smallholder farming takes place on communally owned land (communal areas) and is typified by a mixture of rainfed small-scale subsistence and commercial production (Wright et al., 1998). Communal ownership confers individual rights to plots for houses, gardens and fields with shared but unlimited access to grazing land. Due to the systematic segregation by the colonial regime, an estimated 74% of the communal land is located in the semi-arid areas (Muir, 1994) mostly in areas with soils of low inherent fertility and water holding capacity. Tillage methods discussed in this paper are targeted at these smallholder farmers.

Maize (*Zea mays* L.), the staple food crop of Zimbabwe and an important cash crop is a high-risk crop because it is susceptible to drought as well as to waterlogging (Mashingaidze, 2006). Despite, its susceptibility to drought maize ranks first in terms of area planted and the number of households who grow the crop even in semi-arid areas. In the 1990s, before Zimbabwe's economic crisis at the turn of the 21st century, smallholder farmers produced over 50% of the maize delivered to the Grain Marketing Board; there was a trend among LSCF to move out of maize production of into horticulture, wheat, oilseeds and minor commodities, including wildlife (Muir, 1994).

The national average yield of maize in communal areas is 1.5 t ha^{-1} compared with about 5.0 t ha^{-1} in the LSCF sector (Mashingaidze, 2006). In line with the rest of semi-arid SSA, most of the yield-limiting factors could be overcome by better management and it is possible to double yields in communal areas by using recommended high-yielding technologies. The recommendations for semi-arid areas should be based on research done in these areas as opposed to extrapolations from work done in better rainfall areas (Nyamudeza, 1999). There should, however be no standard recommendation or package for soil and water management promotion in semi-arid areas. There is need to recommend technology options that use the blending of traditional and modern technologies reconciling traditional resource-extensive and resource intensive systems (Twomlow et al., 1999).

Smallholder farmers in semi-arid Zimbabwe rely heavily on draught animal power and ox-drawn mouldboard ploughs for primary tillage and crop establishment (Twomlow et al., 1999). Achieving timely planting and good germination can be difficult for those without access to adequate draught animal power. Farmers recognise the need for weed control because weeds compete with crops for light and water and opening the soil to allow enhanced capture of rainfall (Twomlow et al., 1999). Weed control is achieved through the mouldboard plough which cuts the soil and turns the furrow "slice" burying weeds and crop residues. Seed is planted by hand into a furrow made by the plough and covered, ensuring that maize germinates in a relatively weed free seedbed (Twomlow et al., 1999). Where available, ox-drawn cultivators are used for inter-row weed control. This system of cultivation is referred to as conventional tillage and it is the current farmers' practice.

Conventional tillage has been criticised for its failure to alleviate the destructive effects of long dry spells on rainfed crops and its failure to combat land degradation due to soil erosion (Bultena and Hoiberg, 1983; Whitlow, 1988; Willcocks and Twomlow, 1993; Wilson, 1995). An estimated 50 to 80 t ha^{-1} of soil is lost in crop fields (Munodawafa and Zhou, 2008). Hagmann (1996) measured 59.2 t ha^{-1} soil loss through rill erosion from arable land in semi-arid southern Zimbabwe with the first 25-mm storm causing soil loss up to 40 t ha^{-1} in 1992/93 season. In a bid to circumvent the short-comings of conventional tillage there has been a continuous search for more sustainable tillage methods. Sustainability is about being able to recover from stresses (meteorological dry spells in this case) and being resilient in the face of natural and human induced processes (Twomlow et al., 1999). In semi-arid areas, such methods should increase the infiltration rate of water into the soil profile, conserve or use water sparingly to enable crops to survive under low rainfall and during long dry spells (Nyamudeza, 1999; Stroosnijder, 2009; Temesgen et al., 2012). To this end conservation tillage methods have been explored as strategies for soil and water conservation in semi-arid Zimbabwe (Mupangwa et al., 2006).

Conservation tillage definitions vary but in most cases they reflect a focus on soil and water conservation, thus making conservation tillage an attractive option for semi-arid Zimbabwe. Fowler and Rockström (2001) define conservation tillage as soil management systems which aim to conserve natural resources. Willcocks and Twomlow (1993) define conservation tillage broadly as a tillage system which conserves energy inputs (i.e. labour and draught power) as well as water and soil resources. Nyagumbo (1999) define conservation tillage as any tillage sequence which reduces soil and water loss. According to Unger et al. (1991), in the USA, conservation tillage is defined as any tillage or planting system that maintains at least 30% of the soil surface covered by residues after crop planting to reduce soil erosion by water. Conservation tillage as applied in smallholder farming systems in semi-arid Zimbabwe does not necessarily adhere to the 30% soil surface cover by residues. Emphasis is more on conservation soil and water and reduction in labour and draught power requirements with or without crop residues. Conservation tillage uses some of the principles of conservation agriculture (CA) but may have more soil disturbance (Hobbs et al., 2008). The principles of conservation agriculture (CA) mostly applied are (1) minimum or no mechanical soil disturbance, and (2) permanent organic soil cover with crop residues or growing plants. In fact CA evolved from conservation tillage.

According to Unger et al. (1991), in many cases the most dominant soil-degrading processes are erosion and organic matter decline and the authors identify crop residue management and tillage as the two practices that have a major impact on soil conservation. However, residue availability decreases sharply in hot and dry regions like semi-arid Zimbabwe. Besides low production, residues are often used for feeding livestock during the dry season and as fuel. The amount of residues retained as mulch therefore depends on total residue production and other residue uses with mulching being least in priority (Erenstein, 2002).

An example of a residue management system is the stubble mulch tillage that was developed in the US Great Plains (Unger et al., 1991). Crop residue management is a technology whereby at the time of planting at least 30% of the soil surface is covered by organic residue of previous crop (Erenstein, 2002). The timing aspect relates to the limited soil cover at the onset of the season, which predisposes the soil to water erosion. In stubble mulching, sweeps or blades undercut the soil surface at 0.05-0.10 m to control weeds and to prepare a seedbed, but most crop residues are retained on the surface. Unger et al. (1991) and Erestein (2002) indicate that crop residue management helps to control water erosion, by dissipating the energy of falling raindrops, thus minimizing soil particle detachment, dispersion and surface sealing, thereby maintaining favourable water infiltration rates and minimizing particle transport. Crop residues also add organic matter that stimulates soil fauna and leads to higher aggregate stability. The tillage component in stubble mulching, loosens soil and enables greater water infiltration into soils having dense surface layers; tillage also roughens the surface and creates depressions for temporary water storage, thereby providing more time for infiltration. This results in reduced water flow and particle transport, thus minimising erosion.

In addition to reducing erosion stubble mulching provides water conservation benefits by reducing evaporation by water from the soil surface. Conservation tillage produced positive results in areas with low rainfall and on soils with low water holding capacity such as light and well-drained silty loam soil (Wang et al., 2006). Nyamapfene (1991) reported evidence of sheet erosion on the fertile Siallitic soils caused by the high intensity storms on sloping land leading to shallow soil profiles; thus, even on fertile soils benefits can be derived from conservation tillage through reduced soil erosion. Fowler and Rockström (2001) cite examples from Zimbabwe where conservation tillage reduced soil loss to < 10 t ha^{-1} from 60 t ha^{-1} under conventional tillage. Unger et al. (1991), whilst stating that conservation tillage compared with conventional tillage enhances water conservation and crop yields in many cases; cite studies where opposite results or no differences were reported. Crop yield is the most common and useful parameter used to evaluate the acceptability by farmers of production practices (Abeyasekera et al., 2002), hence it is important to evaluate benefits of conservation tillage in terms of crop yield.

Tillage without surface residue maintenance (clean tillage) can be used to increase infiltration or convey excess water at non-erosive velocities (Unger et al., 1991). This is achieved through tillage that ridges or roughens the surface in conjunction with graded furrows, contouring or furrow diking (tied ridging), and terracing.

Advocacy for conservation tillage systems began in the 1930s but in Zimbabwe's smallholder farming sector momentum towards conservation tillage only gathered in the early 1980s. Maize's status as the staple food crop makes it important for food security; hence conservation tillage research and extension interventions mostly target the crop. There is need to take stock of what has been done to date and to answer the question: "Which alternative tillage methods are worthy pursuing?"

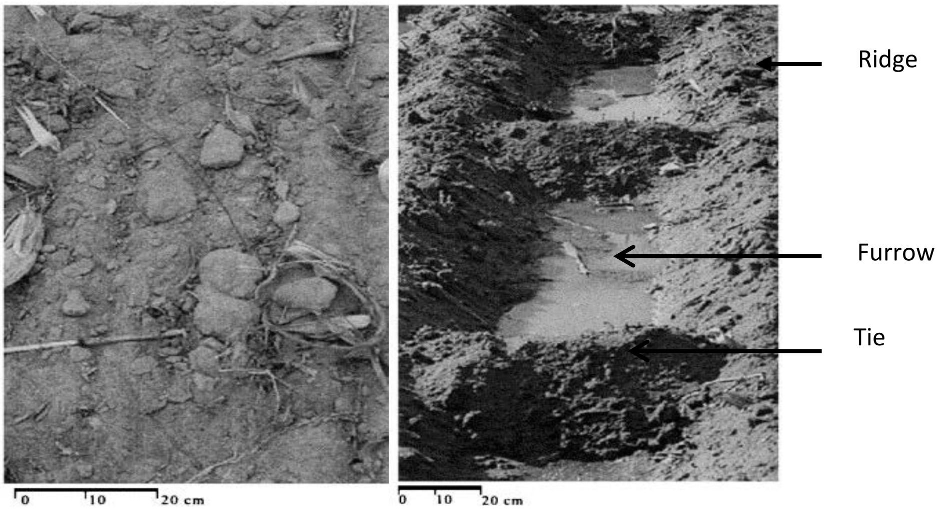
Therefore, the objective of this paper is to compare the performance of conventional tillage with conservation tillage methods in terms of maize yield based on a review of tillage experiments which were carried out in semi-arid Zimbabwe. In comparing performance of different tillage methods we remain cognisant of the fact that for any alternative system to be adopted, its yield should be higher or at least equal that of conventional tillage in the short term and that smallholder farmers face resource constraints. We embrace the assertion by Willcocks and Twomlow (1993) that ".......development of improved cultural practices will not only be based on technical soundness but also that the prescribed tillage practices will meet real farmer needs and thereby be adopted.........." However, the prescriptions should come in the form of options. Giller et al. (2011) aptly state the need for targeting in a "best fit" approach from a basket of options as opposed to "silver bullet" solutions. We, therefore aim to enrich the debate on the future of tillage research in semi-arid Zimbabwe. It is hoped that results of this review will also benefit areas with similar agro-ecological and socio-economic conditions.

2.2 Tillage methods in semi-arid Zimbabwe

Tillage methods used in the smallholder sector in Zimbabwe range from manual to animal draught power driven technologies (Table 2.1). In all research experiments the conservation tillage methods were compared with conventional tillage. We adopt the definition by Kaumbutho et al. (1999) who define tillage as manipulation of soil for any purpose.

Table 2.1: Overview of tillage methods used in maize experiments in semi-arid Zimbabwe targeted at smallholder farmers

Type of tillage method	Tillage method	Description	References
In-field	Conventional	Land is cleared of previous season crop residues, weeds, and shrubs are either stumped or coppice regrowth is cut; ploughing is done to a depth of 0.10 to 0.25 m using an ox-drawn single-furrow mouldboard plough; planting is done in furrows made by the mouldboard plough; row spacing is usually 0.9 to 1.0 m; successive operations may include harrowing with a spike-toothed harrow and weed control using an inter-row cultivator or mouldboard plough, and hand hoe.	Riches et al. (1997), Nyamudeza (1999), Munodawafa and Zhou (2008)
	Holing out	Land is cleared of previous season crop residues, weeds, and shrubs coppice regrowth is cut; planting holes are dug using a hand hoe (*badza*); and usually digging is restricted to preparing planting stations without soil disturbance in between the planting holes.	Vogel (1993), Wilson (1995)
	Ridging	Ridge/furrow system at 1% slope; spacing ranges from ≤ 1.0 to 2.0 m and ridge height ranges from 0.1 to 0.4 m with narrower spaced ridges being shorter; 1.0 m-spaced ridges can be constructed using an high wing ridger or a mouldboard plough but wider-spaced ridges require tractor-drawn ploughs; and planting is done on top of the ridge.	Vogel (1993), Nyamudeza (1999),Motsi et al. (2004), Munodawafa and Zhou (2008)
	Tied ridging (Furrow diking)	Semi-permanent ridge/furrow system with annual ties usually 0.5 to 0.65 times the height of the ridges at intervals ranging from 1 to 3 m; spacing of ties is shorter on steeper slopes than on gentle slopes. Planting is done in the furrow or on top of the ridge.	Vogel (1993), Nyamudeza (1999), Munodawafa and Zhou (2008), Motsi et al. (2004)
	Mulch ripping	Previous season's crop residues are retained on the soil surface and the land is ripped in between the previous season's crop rows with a rigid ripper tine attached to an animal-drawn plough frame; planting is done in the rip mark line; ripping depth ranges from 0.15 to 0.25 m; and spacing is usually similar to that in conventional tillage	Grant et al. (1979), Vogel (1993), Munodawafa and Zhou (2008)
	Clean ripping	Clean ripping entails ripping land in between the previous season's crop rows with a rigid ripper tine attached to animal-drawn plough frame; no crop residues are left in the field; planting is done into the rip mark line; ripping depth ranges from 0.15 to 0.25 m and spacing is usually similar to that in conventional tillage.	Nyagumbo (1999), Vogel (1993), Mupangwa et al. (2012b)
	Planting pits (planting basins)	Hand dug planting holes; recommended dimensions: 0.9 m x 0.6 m (spacing); 0.15 m (length); 0.15 m (width) and 0.15 m (depth); soil dug from the planting pit is placed downslope creating a 'damming effect' for harvesting rainwater.	Mupangwa (2006), Twomlow et al. (2008)
Field-edge	Contour ridges	Graded ridges with an upstream channel designed to convey water from fields at less or non-erosive velocities; standard dimensions: gradient: 1:250; channel width: 1.70 m; channel depth: 0.23 m; ridge height: 0.23 m and ridge width: 1.70 m.	Elwell (1981), Wilson (1995), Hagmann (1996), Whitlow (1988)
	Fanya juus (bench terraces)	Bench terraces with retention trenches where excavated soil is placed upslope to form terraces; channel depth is usually 0.5 to 0.6 m with ties at 10-m intervals; channels are usually constructed on a dead level contour and grass may planted on the embankment to stabilize.	Twomlow et al. (1999), Motsi et al. (2004), Mutekwa and Kusangaya (2006)
	Infiltration pits	Rectangular trenches of varying dimensions excavated at intervals in the channels of contour ridges; pits may be filled with grass or stover covered by a thin layer of soil so that the organic material can decompose to form compost.	Motsi et al. (2004), Mugabe (2004), Mutekwa and Kusangaya (2006)



(a) conventional tillage (b) ridge-furrow system with ties

Figure 2.1: Tillage methods on Makoholi sandy soils: (a) conventional tillage creating a flat soil surface, and (b) ridge/furrow system with ties (tied ridges) (Twomlow and Bruneau, 2000)

2.2.1 In-field tillage methods

In-field tillage methods are implemented in the crop growing area. Stroosnijder (2009) referred to in-field tillage methods as area practices because the methods are applied over the full area of a farmer's field.

Conventional tillage

Conventional tillage is the technique commonly used by smallholder farmers with access to animal draught power i.e. cattle or donkeys. Initially the land is cleared of remaining large pieces of previous season crop residues, weeds and shrubs deemed to interfere with tillage operations and planting. Shrubs are stumped or only coppice growth is cut before or just after the onset of rains. Usually the organic material cleared from the field is burnt *in situ*, but some twigs and stumps may be removed from the field and used as firewood. The land is then ploughed using an ox-drawn single-furrow mouldboard plough. Ploughing depth ranges from 0.10 m to 0.25 m depending on the soil's draught power requirements and the strength of the draught animals. Conventional tillage is usually done soon after receiving the first effective rains but some farmers practice early ploughing at the end of the preceding cropping season after crop harvests (end of March to early May) when the soil is still moist. Post-harvest early ploughing facilitates infiltration of early rain thereby enabling early planting (Willcocks and Twomlow, 1993). The mouldboard plough helps to prepare a weed-free seedbed and facilitates infiltration of water into the soil profile (Riches et al., 1997). Row spacing is usually 0.9 to 1.0 m (Nyamudeza, 1999). Successive operations may include harrowing with a spike-toothed harrow (Munodawafa and Zhou, 2008) and inter-row cultivation with a cultivator. Conventional tillage in Zimbabwe entails crop production with cultivations on the flat, i.e. cultivations which do not significantly change the in-field topography (Figure 2.1). For a summary on reasons for using conventional tillage refer to (Hobbs et al., 2008).

Holing out

Holing out bare ground (digging planting holes into bare ground) using a hand hoe (*badza*) is used by farmers without adequate access to draught animals. Holing out is a traditional tillage method which was used prior to the advent of the plough in the 1920s (Whitlow, 1988; Wilson, 1995). Land is cleared of previous season crop residues and weeds; usually shrubs coppice regrowth is cut without stumping. In most cases, the organic material cleared from the field is burnt *in situ* whilst twigs may be removed from the field and used as firewood. Digging is normally restricted to preparing planting stations without soil disturbance in between planting holes. Delays in holing out may necessitate digging over the whole area in some parts of the field to control weeds for example couch grass (*Cynodon dactylon*) that will have emerged after effective rains. This technique differs with the more contemporary techniques such as planting pits (planting basins) in that the position of the soil mound does not necessarily need to be downslope as this technique is not meant to harvest rainwater but to prepare planting stations only.

Ridging

Ridging is a technique that results in a ridge/furrow system (Figure 2.2 a to c). At construction the ridges have an inverted "V" shape and the furrows are "V" shaped. Both ridges and furrows become less pointed as the cropping season progresses due to the effect of rainfall and practices such as weeding. Ridge spacing ranges from ≤ 1.0 m to 2.0 m and ridge height ranges from 0.1 m to 0.4 m with ridges with narrower spacing being shorter. Wider-spaced and higher ridges therefore use up more top soil during construction and lead to deeper furrows than narrower-spaced and shorter ridges. The 1.0 m-spaced ridges can be constructed using an high wing ridger or a mouldboard plough but wider-spaced ridges require tractor-drawn ploughs. In this paper ridges are identified by their spacing i.e. 1.0 m ridges refers to ridges with a ridge spacing of 1.0 m.

Ridges are established on a slope of 1% (Munodawafa and Zhou, 2008; Vogel, 1993) or at zero gradient. The 1% slope provides a gradient for less erosive flow of water along the furrow. Planting is done on top of the ridge once the ridge is moist throughout (Motsi et al., 2004 ; Vogel, 1993) or in the furrow (Nyamudeza, 1999) (Figure 2.2 a to c).

Tied ridging (Furrow diking)

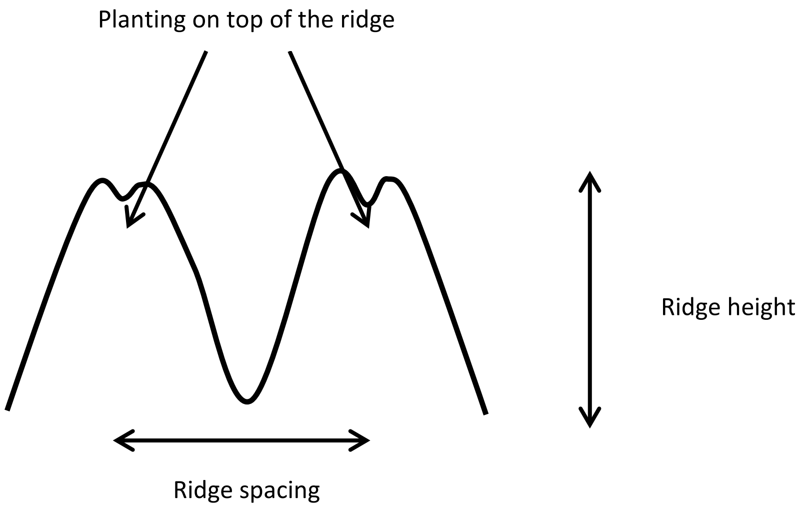
Tied ridging is a semi-permanent ridge/furrow system with annual ties (Figure 2.1b). Ties are usually 0.5 to 0.65 times the height of the ridges (Munodawafa and Zhou, 2008; Vogel, 1993) and are constructed across the furrows annually at intervals ranging from 1 m (Munodawafa and Zhou, 2008), 1.5 m (Vogel, 1993), to 3 m (Motsi et al., 2004) to reduce the possibility of runoff. Thus, water will only flow along the furrow when the depth of water in the furrow exceeds the height of the ties. The spacing of the ties is shorter on steeper slopes than on gentle slopes (Hughes and Venema, 2005).

Mulch ripping

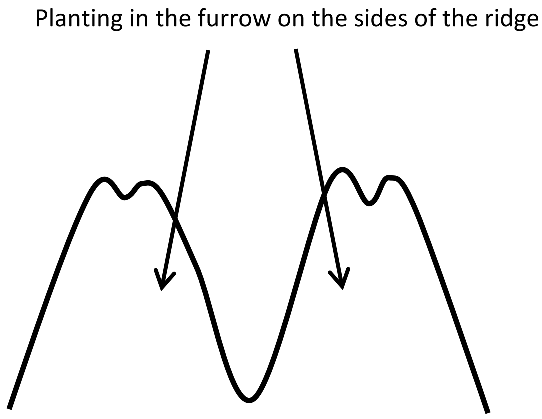
Mulch ripping is a combined minimum tillage and residue management system. In this system, previous season's crop residues remain on the soil surface and land is ripped in between the previous season's crop rows with a rigid ripper tine attached to an animal-drawn plough frame (Munodawafa and Zhou, 2008; Vogel, 1993). The crop is then planted into the rip mark line. Rip line spacing is usually similar to plant spacing in conventional tillage. Ripping depth ranges from 0.15 m to 0.25 m. The ploughing and ripping depth of 0.20-0.25 m has been found to be optimal for maize production on granitic soils (Grant et al., 1979). However, the depth that is usually achieved in farmers' fields ≤ 0.15 m.

Clean ripping

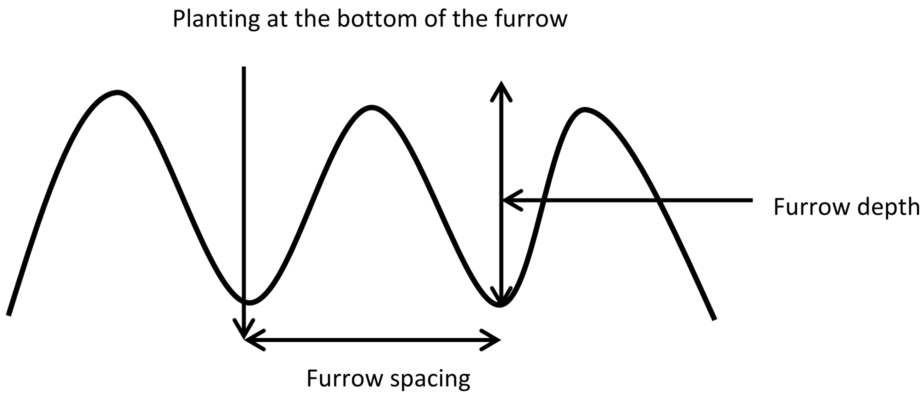
Clean ripping entails ripping land in between the previous season's crop rows with a rigid ripper tine attached to animal-drawn plough frame (Munodawafa and Zhou, 2008; Vogel, 1993), no crop residues are left in the field (Mupangwa et al., 2012b; Nyagumbo, 1999; Vogel, 1993). The crop is then planted into the rip mark line. Rip line spacing and ripping depth are similar to that under mulch ripping. This tillage method could be an option for areas where there is no stover left in the field due to competition with livestock. In the predominantly crop-livestock smallholder farming systems in semi-arid Zimbabwe, most of the stover is removed from the fields for feeding livestock during the dry season and the livestock are left to graze freely in the fields after crop harvests.



(a) ridge dimensions and planting position on top of the ridge



(b) planting position in the furrow on the side of the ridge



(c) dimensions and planting position at the bottom of the furrow

Figure 2.2: Ridge/furrow system with different planting positions

Planting pits (Planting basins)

Planting pits (planting basins) are hand dug planting holes resembling the zäi pits commonly used in West Africa. The recommended dimensions for planting pits are: 0.9 m x 0.6 m (spacing); 0.15 m (length); 0.15 m (width) and 0.15 m (depth) (Mupangwa et al., 2006; Twomlow et al., 2008). Planting pits should be dug in September or October in the same position annually (Mupangwa et al., 2006). Since the 2004/05 cropping season there has been widespread promotion of planting pits throughout Zimbabwe by the Zimbabwean Conservation Agriculture Task Force (ZCATF). The soil dug from the planting pit is placed downslope in order to create a 'damming effect' for harvesting rainwater.

2.2.2 Field-edge tillage methods

These are structures constructed at field edges usually along the contour. Field-edge structures normally have bigger dimensions than in-field tillage methods. Stroosnijder (2009) called them line practices.

Contour ridges

Contour ridges are graded ridges with upstream channels constructed in a cross slope direction in order to safely discharge runoff, i.e. convey excess water from crop fields at less or non-erosive velocities (Figure 2.3). A standard contour ridge has the following dimensions: gradient: 1:250; channel width: 1.70 m; channel depth: 0.23 m; ridge height: 0.23 m and ridge width: 1.70 m.

Contour ridges were enforced in the 1950s as a measure against rill and gully erosion. Soil erosion and land degradation had become severe and the colonial government intervened using the Native Land Husbandry Act of 1951 which enforced compulsory construction of contour ridges (Hagmann and Murwira, 1996; Whitlow, 1988; Wilson, 1995).

Although most farmers still maintain contour ridges in their original state some farmers have modified them into dead level contour ridges, or contour ridges with infiltration pits in order to harvest more rainwater in the fields (Mupangwa et al., 2006; Mutekwa and Kusangaya, 2006).

Fanya juus (Bench terraces with retention ditches)

Fanya juus are ridges within cultivated land where trenches are dug and the excavated soil is placed upslope to form terraces (Makurira et al., 2009; Motsi et al., 2004). The channel depth is usually 0.5-0.6 m with ties at 10-m intervals. Channels are usually constructed on a dead level contour (level *fanya juu*). The trenches act as temporary water stocks that allow infiltration to occur for longer periods during and after rainfall events (Makurira et al., 2009). Grass may planted on the embankment to stabilize it while trees or bananas are planted in the trenches (Motsi et al., 2004 ; Mutekwa and Kusangaya, 2006; Twomlow et al., 1999).

Figure 2.3: A contour ridge with infiltration pits Rushinga district Zimbabwe

Infiltration pits

Infiltration pits are rectangular trenches of varying dimensions excavated at intervals in channels of contour ridges for collecting runoff water, storing it and allowing it to infiltrate (Figure 2.3). The pits may be filled with grass or stover covered by a thin layer of soil so that the organic material can decompose to form compost. The assumption is that infiltration pits trap rain as it falls and then water infiltrates downslope thereby providing moisture to crops in the fields (Motsi et al., 2004 ; Mugabe, 2004).

Infiltration pits were adopted by most farmers in southern Zimbabwe (Hagmann et al., 1999; Hughes and Venema, 2005 ; Mutekwa and Kusangaya, 2006), and Motsi et al. (2004) report that they were preferred to *fanya juus* by farmers. Farmers' preferences of infiltration pits to *fanya juus* may be due to the fact that they are an improvement of an existing practice which they are familiar with. Little is known about the effectiveness of infiltration pits in improving soil moisture content and crop yields, and the risk of waterlogging. It is also difficult to conceive how the infiltration pits benefit crops given their location at field edges.

2.3 Linking conservation tillage to soil fertility management in semi-arid Zimbabwe

Soil quality (physical and chemical fertility) is often a more limiting factor to crop growth than water even in semi-arid tropical agroecosytems (Rockström et al., 2004; Tittonell and Giller, 2013). Thus, integrated soil and water management with a focus on restoring degraded poorly responsive soils to a responsive state is required. Yet, current yield gaps may be reduced through proper agronomic management for example, appropriate planting dates and crop geometry, improved cultivars, early weeding, crop rotation and intercropping (Rockström et al., 2010) even when fertilizers are not applied (Tittonell and Giller, 2013).

In Zimbabwe, smallholder farmers commonly apply fertilizers at sub-optimal rates (Mapfumo and Giller, 2001). According to Nyamudeza (1999) a unique feature of crop production on vertisols and alluvial soils is that smallholder farmers do not apply fertilizers claiming that applying fertilizers is detrimental to their crops due to low and unpredictable nature of rainfall. Ncube et al. (2007) states that farmers claim that manure burns crops. Farmers' perceptions emanate from the fact that, manure and inorganic fertilizers result in more vigorous crop growth which depletes the limited soil water faster than an unfertilised crop and under severe moisture stress manure or inorganic fertilizers increase the osmotic potential in the soil that may cause plasmolysis of plants. However, research in the region shows that addition of mineral and organic fertilizers increases maize yield (Ncube et al., 2007; Nyakatawa, 1996; Nyamangara and Nyagumbo, 2010; Nyamudeza, 1999). Ncube et al.(2007) proposes use of low rates of manure and fertilizer as one option for farmers in semi-arid Zimbabwe and reports that 8.5 kg N ha^{-1} combined with either 3 t ha^{-1} and 6 t ha^{-1} manure increased maize yields both in a good rainfall season and a dry season although the increase was lower in the later.

Fertilizer application rates of major nutrient elements (kg ha^{-1}) reported in maize tillage experiments under review are 12-16 N; 9-12 P; and 9–12 K, and topdressing with N ranges from 0 to 75 kg ha^{-1} for plant densities ranging from 22000 to 44000 plants ha^{-1}. These fertilizer application rates correspond to Agritex recommendations: 200 kg ha^{-1} Compound D (8% N, 14% P_2O_5, 7% K_2O) and 100 kg ha^{-1} ammonium nitrate (34.5% N). Nyakatawa (1996) established that 25 kg N ha^{-1} was on average the optimum for both grain and stover yields. Cattle manure application rates range from 3 to 7 t ha^{-1}, but Nyamangara and Nyagumbo (2010) used 18 t ha^{-1} in a study in central Zimbabwe. In addition to use of fertilizers there is need to design resilient cropping systems that combine soil and water conservation and fertility improvement. Currently under smallholder farming in semi-arid Zimbabwe more land is allocated to cereals than legumes, as a result there are no systematic crop rotations (Ncube et al., 2007). Thus, there is a weak link between crop rotations practised and soil fertility enhancement (Mapfumo and Giller, 2001). Legume-based rotations are underexploited yet they can potentially contribute to the N content of the soil. Mupangwa et al. (2012b) established that maize-cowpea (*Vigna unguiculata* (Walp) L.)-sorghum (*Sorghum bicolor* L. (Moench))-maize (MCSM) rotation had higher grain yield than the other crop sequences. The higher maize yield in the rotation was attributed to the residual N contributed by cowpeas and improved soil bulk density from a mean of all treatments at 0 t ha^{-1} mulch level of 1.55 g cm^{-3} for sole maize to 1.49 g cm^{-3} for MCSM rotation and organic carbon from 0.67% under a sole maize crop to 1.00% under MCSM rotation. Whereas there is flexibility in combination of crops over time (rotations) combinations over space (intercropping) require more innovation in view of negative effects that can occur due to inter-species competition for water.

2.4 Conservation tillage experiments in Semi-arid Zimbabwe

Table 2.2 gives an overview of the tillage experiments and Table 2.3 presents summarised results from the individual experiments. In semi-arid Zimbabwe farming systems, are dominated by mixed crop-livestock systems where besides maize grain, stover yield is required to supplement livestock feed during the dry season and may be required to provide mulch under conservation tillage methods. Therefore, we also present stover yield in this study.

2.4.1 On-station research

On-station research has mainly been confined to the semi-arid southern region at three research stations: Chiredzi Research Station (21^0S, 31^0E, altitude 429 m a.s.l.); Makoholi Research Station (19.8^0S, 30.80E, altitude 1200 m a.s.l.) and Matopos Research Station (28.5^0S, 20.4^0E, altitude 1344 m a.s.l.) (Figure 2.4). No publications on maize conservation tillage were available for Chiredzi Research station but published sorghum conservation tillage results from this site provide important insights and are referred to later in this paper.

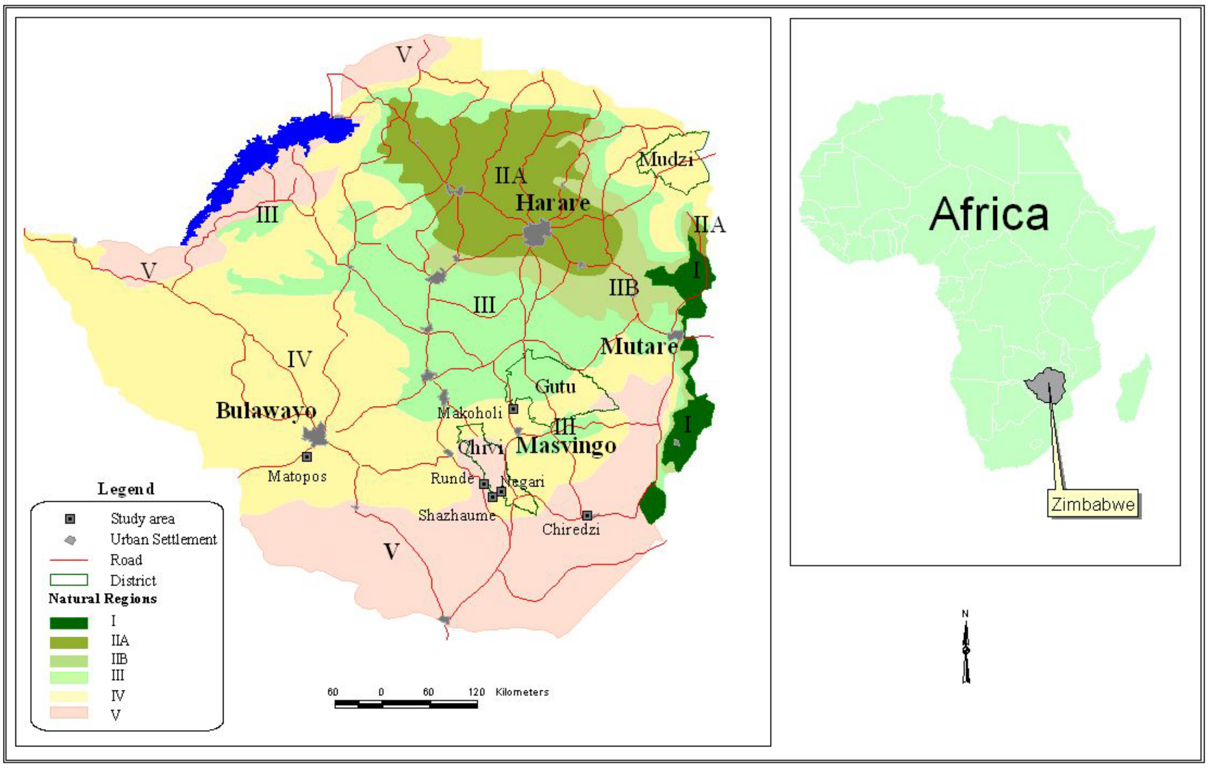


Figure 2.4: Location of conventional and conservation tillage experiments sites in semi-arid Zimbabwe

Table 2.2: Tillage experiments conducted in semi-arid Zimbabwe between 1984/85 and 2007/08 cropping seasons

Research site/Soil type	Season (rainfall (mm))	Description of tillage method	Reference
Makoholi Research Station **Sandy soils derived from granite**	1988/89 (415); 1989/90 (742); 1990/91 (343).	Conventional tillage plough depth 0.2 to 0.25 m; Tied ridge with ties at 1.5 m, planting on the ridge; Mulch ripping at 0.2 to 0.25 m depth; Clean ripping at 0.2 to 0.25 m depth; Holing out (dimensions not specified).	Vogel (1993)
	1993/94 (483); 1994/95 (384); 1995/96 (765).	Conventional tillage at 0.25 m depth Mulch ripping at 0.25 m depth Tied ridges at 0.9 m ridge spacing, ties at 1 m intervals (planting position not specified)	Munodawafa and Zhou (2008)
Matopos Research Station **red silty clay loam derived from basaltic greenstone** **and granite-derived sandy soil**	2004/05 (320[a]); (291[b]); 2005/06 (900[a]); (800[b]) 2006/07 (465)[a] 2007/08 (364)[a]	Conventional tillage (no specifications) Ripping, lines spaced at 0.9 m inter-row and the ripping depth between 0.15 and 0.18 m. Planting pits, spacing 0.9 m x 0.6 m , 0.15 m (length) x 0.15 m (width) x 0.15 m (depth	Mupangwa et al. (2007) Mupangwa et al.(2012)
Matibi 1 Communal Area at Runde, Shazhaume and Negari **granite-derived sandy soils**	1990/91 (375[c])(340[d]) 1991/92 (n/a) 1992/93 (580[c])(395[e])	Conventional tillage (no specifications) Tied ridge at 1.0 and 1.5 m ridge spacing with ties at 2 m intervals, planting in the furrow.	Nyakatawa (1996)
Communal Lands of Zimbabwe (Mudzi, Gutu and Chivi districts) **Sandy loams to sandy soils derived from granite**	n/a	Tied ridge spacing at 0.75 m with ties at intervals between 2 and 3 m, planting on the top of the ridge Conventional tillage (no specifications) Fanya juus, with channel depth 0.5 m to 0.6 m and 10-m ties interval on a dead level contour, grass planted on the embankment Infiltration pits filled with grass or stover covered with a thin layer of soil. Dimensions were not specified.	Motsi et al. (2004)

[a]Site with silty clay loam; [b]site with granite-derived sandy soil
[c]Runde; [d]Negari, [e]Shazhaume
n/a stands for not available.

Makoholi Research Station (Natural Region IV)

Vogel (1993) compared conventional tillage, clean ripping, mulch ripping and tied-ridging from 1988/89 through 1990/91 (Tables 2.2 and 2.3).

In the 1988/89 season, dry conditions prevailed and no statistically significant treatment differences were observed. In addition all treatments except tied-ridging were similar, as they were all on land that had been opened up from virgin land by mouldboard ploughing (Vogel, 1993).

During the 1989/90 season, favourable rainfall (742 mm) provided excellent yields. Conventional tillage and the two ripping techniques produced the highest yields. Holing-out produced significantly lower grain yields than all other treatments and also ranked last with respect to stover yield together with tied ridging.

Table 2.3: Tillage methods and maize grain and stover yields ranges from experiments in semi-arid Zimbabwe

Tillage method	Number of seasons	Grain yield range (kg ha^{-1})	Stover yield range (kg ha^{-1})	Source
Conventional	3	1715-6493	1984-4419	Vogel (1993)
Hand hoeing	2	963-3863	1947-3878	
1.0 m tied ridging	3	926-5407	1845-4356	
Clean ripping	3	1803-5894	1675-4419	
Mulch ripping	3	2313-5933	1951-4743	
Conventional	3	860-4642	n/a	Munodawafa and Zhou (2008)
0.9 m tied ridging	3	1132-3736	n/a	
Mulch ripping	3	2203-3923	n/a	
Conventional	3	0-3104	0-3398	Nyakatawa (1996)
1.0 m tied ridging	3	0-3535	0-3391	
1.5 m tied ridging	3	0-524	0-2977	
[a]**Conventional**	2	203-1262	777-3170	Mupangwa et al. (2007)
[b]**Conventional**	2	2616-2721	3649-6605	
[a]**Mulch ripping**	2	238-1811	834-3723	
[b]**Mulch ripping**	2	2521-2529	3596-5012	
[a]**Planting pits**	2	381-1523	1053-3143	
[b]**Planting pits**	2	2441-3032	2808-6958	
Conventional	2	676-1504	1494-1741	Mupangwa et al. (2012b)
Clean ripping	2	1060-1257	1296-3086	
[c]**Mulch ripping**	2	1162-2030	1333-4086	
[c]**Planting pits**	2	1076-1570	1271-3000	
Conventional	n/a	1500	n/a	[d]Motsi et al. (2004)
0.8 m tied ridge	n/a	3400	n/a	
Fanya juu	n/a	2800	n/a	
Infiltration pits	n/a	2400	n/a	

[a]sandy soil; [b]clay soil: yields are means over crop residue mulch levels (t ha^{-1}):(0, 0.5, 1, 2, 4, 8, 10)
[c]For mulch ripping and planting pits yields presented are for the mulching level of 4 t ha^{-1}.
n/a stands for not available.
[d]Authors presented mean yields for three sites, therefore there is no yield range.

The 1990/91 season was a dry year (rainfall, 343 mm) and treatment performance was as follows: mulch ripping > clean ripping = conventional tillage > tied ridging = hand hoeing. However, there was no significant treatment effect on stover production levels. Tied ridging and hand hoeing produced lower grain yields, largely because these two treatments coped less well with a deliberately delayed first weeding which had allowed prolific weeds to overgrow the maize seedlings (Vogel, 1993). Yields were lower under tied ridges than under conventional tillage because planting was done on top of the ridge which dries out faster because of the large surface area for evaporation.

Maize yields were related to year, reflecting rainfall amount and distribution. Results suggest that mulch ripping is likely to prove the best conservation tillage technique in dry years, mainly due to reduced topsoil water losses. However, the technique faces considerable constraints with respect to required levels of management (timeliness of planting and weeding) and inputs (crop residues) and therefore, may not be readily acceptable to communal farmers (Lal, 2013). Clean ripping on the other hand may pass the test of farmer adoption more easily. While there are no significant differences in mean grain yields between the conventional tillage and clean ripping, there is saving in draught energy requirements and machinery costs for clean ripping (Vogel, 1993). Some farmers skip ploughing and just open planting furrows using the mouldboard as an adaptive strategy to hasten land preparation and plant before the soil loses moisture or when cattle are too weak to perform conventional tillage. However, when selecting treatments for extension in communal areas, the weed problem, the availability of implements such as ripper tines and soil erosion hazard must be taken into account (Vogel, 1993).

In another experiment conducted from 1993/94 through 1995/96 including conventional tillage, mulch ripping and tied ridging, Munodawafa and Zhou (2008) also reported a significant interaction between year and treatment. Conservation tillage treatments performed better in dry years whilst conventional tillage had better yield in the wet year (rainfall, 765 mm). The higher yields recorded under mulch ripping and tied ridging in dry years reflect the moisture conservation potential of the conservation tillage treatments (Munodawafa and Zhou, 2008). The results obtained by Munodawafa and Zhou (2008) are in agreement with Vogel (1993).

Matopos Research Station

Mupangwa et al. (2012b; 2007) conducted experiments with three tillage methods: conventional tillage, ripping and planting pits as the main plot and seven mulch levels (0.0; 0.5; 1.0; 2.0; 4.0; 8.0; and 10.0 t ha^{-1}) arranged as split plots on each tillage method. Thus results reported here are means of each tillage method over the mulch level range.

Mupangwa et al. (2007) observed that on a clay soil in both 2004/05 (dry season, 300 mm rainfall) and 2005/06 (wet season, 900 mm rainfall) tillage method, mulch level, and tillage method-mulch level interactions did not have a significant effect on maize grain yield. However, the tillage method influenced ($P = 0.015$) maize stover production in 2004/05 with planting pits yielding lowest. At the site with sandy soil, in 2004/05 planting pits outyielded ripping and conventional tillage by 153 and 178 kg ha^{-1} respectively but treatments did not perform differently in 2005/06.

Tillage methods did not influence ($P > 0.05$) average seasonal soil water content observed in the top 0.3 m in 2004/05 and top 0.6 m in 2005/06. However, soil water content increased with increasing mulch cover irrespective of tillage treatments ($P < 0.001$) up to 4 t ha^{-1} at both sites.

The 2006/07 and 2007/08 seasons received less rainfall than the long-term average for Matopos Research Station (573 mm) and had poor rainfall distribution during flowering and the grain filling stages of maize.

According to Mupangwa et al. (2012b), in 2006/07 season the tillage method and mulching interaction had no significant influence on grain yield but affected ($P < 0.001$) stover production. Mulching increased grain yield and regression analysis indicated a significant linear relationship between grain and mulch level applied irrespective of the tillage method ($P < 0.001$, $r = 0.59$).

In 2007/08 growing season, neither tillage method nor mulch cover, nor their interaction had significant effect on maize grain and stover production (Mupangwa et al., 2012b). However, conventional and ripping tillage methods had 41 and 52% more grain, 18 and 20% more stover respectively than planting pits across the mulch levels. Mupangwa et al. (2012b) noted that waterlogging in planting pits plots during late December and early January resulted in the suppression of 2007/08 maize yields. Waterlogging was more severe in planting pits plots with > 4 t ha^{-1} mulch levels (Mupangwa et al., 2012b).

Although the highest maize yields were achieved at 8 t ha^{-1} mulch rate, there were no significant yield benefits derived from increasing mulch cover beyond 4 t ha^{-1}. Smallholder farmers using conservation agriculture can target using 2-4 t ha^{-1} (Mupangwa et al., 2012b). However, because of differences in residue density, different amounts of other crop residues would be required for the protection equivalent to that provided by maize residues. The relationship between crop residue weight (kg ha^{-1}) and surface cover (%) according to Sallaway et al. (1988) is: Projected cover = $m[1-e^{-\text{stubble weight}}]$, with m being 98.1 for wheat (*Triticum aestivum* L.), 64.7 for sorghum (*Sorghum bicolor* (L.)), and 49.3 for sunflower (*Helianthus annuus* L.)

2.4.2 On-farm research

Two multisite on-farm experiments were conducted, one with sites in Matibi 1 Communal Area (21.5^{0}S, 31.0^{0}E, altitude 454 m a.s.l.) (Negari, Runde and Shazhaume) and the other with sites in three districts: Chivi (20.1^{0}S, 31.6E, altitude 946 m a.s.l.) and Gutu (19.6^{0}S, 31.2^{0}E, altitude 1142 m a.s.l.) in southern Zimbabwe and Mudzi (17.0^{0}S, 31.6^{0}E, altitude 724 m a.s.l.) in northern Zimbabwe.

Matibi 1 Communal Area (Natural Regions IV and V)

Nyakatawa (1996) reports on performance of conventional tillage, 1.0 m tied ridges and 1.5 m tied ridges in Matibi 1 Communal Area (Negari, Runde and Shazhaume sites) from 1990/91 to 1992/93 (Table 2.2).

A severe drought in 1991/92 destroyed crops at the seedling stage at all sites; hence only data for 1990/91 and 1992/93 were available (Nyakatawa, 1996). The 1.0 m tied ridges performed better than conventional tillage and 1.5 m tied ridges in both grain and stover yields over the two seasons; whilst, conventional tillage and 1.5 m tied ridges had similar performance.

Less response to tied ridging was expected in 1992/93 because it was a wetter year (rainfall, 580 mm) with good rainfall distribution from November to January (Nyakatawa, 1996), hence temporary waterlogging, especially in 1.5 m tied ridges, was observed. The results suggest that tied ridging works best in medium to moderately dry years. On average, maize grain yield in 1.0 m tied ridges was 11 and 25% greater than that under conventional tillage and 1.5 m tied ridges respectively (Nyakatawa, 1996).

Nyakatawa (1996) states two reasons why on sandy soils 1.0 m tied ridges could perform better than 1.5 m tied ridges. The first reason is that more soil is pushed out of the planting zone during the construction of 1.5 m tied ridges compared to 1.0 m tied ridges (section 2.2.1); hence the crops in the former may suffer more from shallow soil depth. However, this is only true when planting is done in the furrow. Secondly, in a wet year, leaching of nutrients will be greater in 1.5 m tied ridges than in 1.0 m tied ridges due to more water collected in the former. Nyamudeza (1999) with reference to vertisols attributed lower sorghum yield in 1.5 m and 2.0 m tied ridges to waterlogging due to more water in the furrows than the 1.0 m tied ridges and possible reduced soil fertility in furrows because more top soil is used to construct the ridges. However, according to Nyamudeza (1999), in years with poorly distributed and low rainfall wider spaced tied ridges performed better than 1.0 m tied ridges, but the author recommended 1.0 m tied ridging due to its yield superiority when averaged over seasons. A disadvantage of 1.0 m tied ridges compared to 1.5 m tied ridges is that they have to be constructed more often because they quickly fill up with sediment from sloughing of the ridges due to their smaller capacity. However, they are easier to construct than 1.5 m tied ridge and farmers can construct them using an ox-drawn plough or ridger because of their smaller dimensions.

Chivi (Natural Regions IV and V), Gutu and Mudzi districts (Natural Region IV)

Motsi et al. (2004) compared conventional tillage with 0.75 m tied ridges, infiltration pits and *fanya juus* in Chivi, Gutu and Mudzi districts and established that yields were better for all alternative treatments than the conventional tillage (Table 2.3).

Motsi et al. (2004) attributed this to less moisture stress in the rainwater harvesting treatments. However, the paper omits essential details on when the experiment was conducted and treatment performance at each site given the large geographical distances among sites and compares technologies that should in fact complement each other, for example infiltration pits and tied ridging or conventional tillage. The techniques complement each other by virtue of their different dimensions and locations (Hagmann and Murwira, 1996; Nyagumbo, 2002). In West Africa, zaï pits are often combined with stone bunds or grass strips for the same reasons (Anschütz et al., 2003).

2.5 Tillage options for smallholder farmers and constraint considerations

Most of the research was done in southern Zimbabwe where the larger part of the semi-arid areas exists. However, important lessons can still be drawn for the northern parts in similar in agro-ecological zones and farming systems. In both the north and the south mixed crop and livestock farming is the major farming system in the semi-arid areas.

2.5.1 Tied ridging and mulch ripping

A prominent feature of all tillage experiments except the most recent by Mupangwa et al. (2007) and Mupangwa et al. (2012b) is the inclusion of tied ridging albeit in different dimensions and planting positions. Motsi et al. (2004) bulked results from three districts, and Mupangwa et al. (2007) presents averages for tillage methods across different mulch levels, therefore data from these sources is not considered in the discussions that follow. In 5 of 13 experiments (Munodawafa and Zhou, 2008; Nyakatawa, 1996; Vogel, 1993), 1.0 m tied ridging produced more grain yield than conventional tillage. The difference was significant ($P < 0.05$) in only two of these experiments. On the other hand, in the other 5 of the 13 experiments conventional tillage outyielded 1.0 m tied ridging, with the yield difference being significant in 3 years. The remaining experiments were conducted during the severe 1991/92 drought and they produced zero yields.

In 4 of 8 experiments (Munodawafa and Zhou, 2008; Mupangwa et al., 2012b; Vogel, 1993), mulch ripping outyielded conventional tillage which also outyielded mulch ripping in the other 4 experiments. Unfortunately information on statistical significance was not available for the chosen mulch levels (zero for conventional tillage and 4 t ha^{-1} for mulch ripping) for Mupangwa (2012b).

Based on the foregoing analysis there is no yield advantage for conservation tillage. A 1:1 plot of conventional tillage versus the 1.0 m tied ridging and mulch ripping gave high values of the coefficient of determination (R^2) and low values of the root mean square error (RMSE): $R^2 = 0.90$, RMSE = 0.33 t ha^{-1}, $P < 0.001$ for 1.0 m tied ridging and $R^2 = 0.87$, RMSE = 0.32 t ha^{-1}, $P < 0.001$ for mulch ripping showing on average good match between yield under conventional tillage and the conservation tillage methods. The smaller differences in yield levels may be attributed to the short durations of experiments in this review averaging less than three years (Table 2.3). Giller et al. (2009) report that for CA yield benefits may start showing after 10 years. It may be more for conservation tillage. However, some trends in yield differences albeit weak ($P > 0.05$), can be observed from Figures 2.5 and 2.6. For grain yields ≤ 2.5 t ha^{-1} and for rainfall ≤ 500 mm on average conservation tillage methods (1.0 m tied ridging and mulch ripping) produced higher grain yields than conventional tillage (Figures 2.5 and 2.6), underlining the influence of rainfall. Excluding zero yields from the 1991/92 drought; in seven years (experiments) with 340 to 483 mm seasonal rainfall, mean (SD) yields (kg ha^{-1}) were 1629 (894) for conventional tillage, and 1773 (1161) for 1.0 m tied ridging representing a yield increase under 1.0 m tied ridging of 144 kg ha^{-1}. Similarly mean yields (kg ha^{-1}) for six experiments were 1742 (740) for conventional tillage and 2086 (529) for mulch ripping giving a yield difference of 344 kg ha^{-1}. Above 2.5 t ha^{-1} and for rainfall > 500 mm conventional tillage has a yield advantage though insignificant ($P > 0.05$).

For three experiments with higher seasonal rainfall (580 to 765 mm) mean yields (kg ha^{-1}) were 4746 (1670) for conventional tillage and 4051 (1230) for 1.0 m tied resulting in a difference of 695 kg ha^{-1}. Similarly for two experiments with higher seasonal rainfall (742 and 765 mm), mean yields (kg ha^{-1}) were 5568 (1309) for conventional tillage and 4928 (1421) for mulch ripping resulting in a difference of 640 kg ha^{-1}. Such yield differences though statistically insignificant may be practically significant from the farmers' point of view. For example, in Zimbabwe households retain about 150 kg maize grain per resident household member to meet their staple consumption requirements (Kinsey et al., 1998), therefore, at higher rainfall the yield advantage of conventional tillage per hectare is enough for four household members.

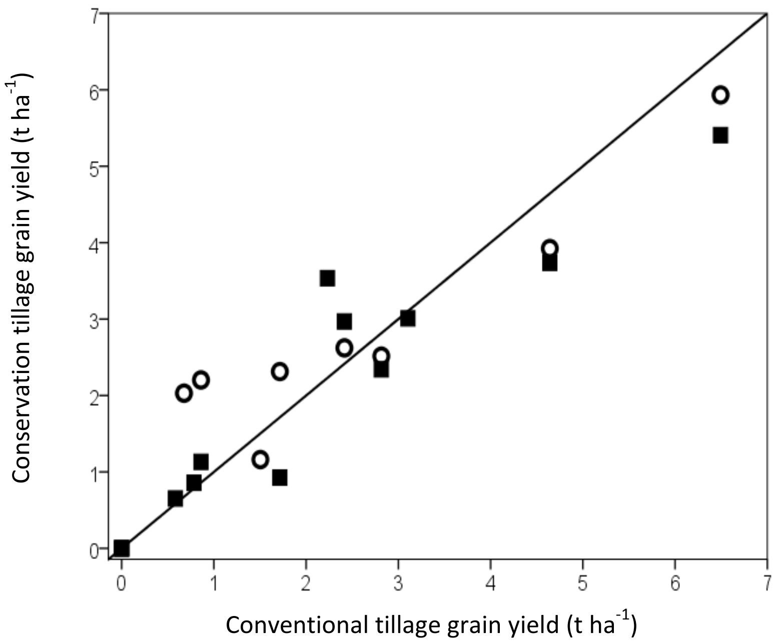


Figure 2.5: Maize grain yield under conventional tillage plotted against maize grain yield under 1.0 m tied ridging (filled squares, n = 13) and mulch ripping (open circles, n = 8) from experiments in semi-arid Zimbabwe. (line represents a 1:1 line)

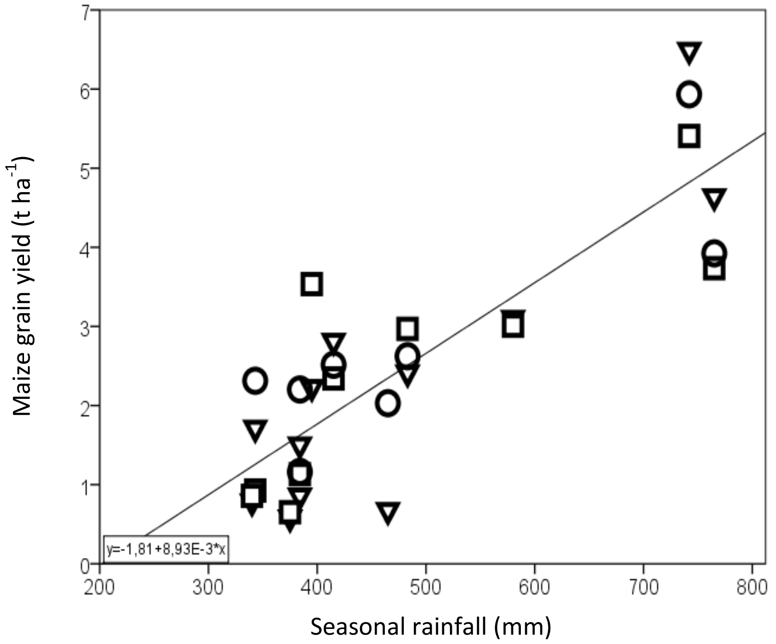


Figure 2.6: Effect of seasonal rainfall on maize grain yield obtained in experiments in semi-arid Zimbabwe under conventional tillage (triangles, n = 12), 1.0 m tied ridging (squares, n = 10) and mulch ripping (circles, n = 8) (coefficient of determination , (R^2) = 0.72, root mean square error (RMSE) =0.74 t ha^{-1}, $P < 0.001$)

Ridge-forming tillage is a proven soil and water conservation practice (Biazin and Stroosnijder, 2012; Unger et al., 1991).Tied ridges retain water within the furrows between ties by reducing surface runoff and increasing infiltration which is critical under low seasonal rainfall. Monodawafa and Zhou (2008) observed that tied ridges retained 62% and mulch ripping 61% of total seasonal rainfall in the field compared to 51% for conventional tillage. The narrower 1.0 m tied ridge performed better than wider 1.5 m and 2.0 m tied ridges in most years (Nyakatawa, 1996; Nyamudeza, 1999). The wider spaced tied ridges have deeper furrows that concentrate larger depths of water and use more topsoil in constructing the larger ridges (both in height and width). The better performance of the 1.0 m tied ridge was attributed to better edaphic conditions because of less topsoil removed from the root zone and less waterlogging or leaching than in wider ridge spacings when planting is done in the furrow (section 2.2.1, Figure 2.2). Removal of topsoil is especially important in sandy soils which are generally shallow, have most organic matter in the top soil and are inherently infertile (Kagabo et al., 2012.; Nyakatawa, 1996). According to Nyamudeza (1999) tied-ridges work best on soils with clay content of 20% and above. Planting in the furrow should be restricted in the driest areas (NR V) while in NR IV planting should be on the ridge (Nyamudeza, 1999). However, this recommendation may need further testing in NR (IV) in order to establish the frequency and severity of aeration stress due to waterlogging under different soil types. Nyamudeza (1999) further recommends changing the position of the furrow every year or once in two years to ensure complete burying of crop residues and improve the organic matter content of the soil. The recommendation to change the furrow position yearly or once in two years exerts pressure on the already constrained labour resource.

Vogel (1993) contends that mulch ripping is likely to prove the best conservation tillage technique, mainly due to reduced topsoil water losses. Mupangwa et al. (2007) and Mupangwa et al. (2012b) reported insignificant differences among ripping, conventional and planting pits; instead it is mulching which increased grain yield and regression analysis indicated a significant linear relationship between grain and mulch level applied irrespective of the tillage system. By reducing evaporation of soil water mulching improves rain water use efficiency (Stroosnijder et al., 2012; Unger et al., 1991). Evaporation of water from the soil occurs mostly from the topsoil, therefore mulching is particularly important under shallow rooting depths. Mulch ripping derives its strength from effective residue management whose positive attributes are discussed in section 2.1.

Thus, based on maize grain yields, among the basket of options for semi-arid Zimbabwe are 1.0 m tied ridging and mulch ripping. The two conservation tillage options are worthy pursuing. However as Vogel (1993) explains both techniques face considerable constraints with respect to resources needed and required levels of management. Successful use of conservation tillage systems requires substantial managerial skills (Bultena and Hoiberg, 1983). For mulch ripping constraints may be faced with respect to timeliness of planting and weeding and large quantities of crop residues needed. Mulch constraints often occur because of competition with livestock under mixed farming systems that are prevalent in most communal areas (Marongwe et al., 2012; Unger et al., 1991). Results from Vogel (1993), Nyakatawa (1996) and Mupangwa et al. (2012b) (not shown) give a mean maize stover yield (SD) of 2537 (1089) kg ha^{-1}. Thus, the recommended stover application rate of 2-4 t ha^{-1} (Mupangwa et al., 2012b) utilises all or leaves very little for livestock. During our work in Rushinga just before the onset of the 2012/13 cropping season (i.e., months of October and November) we observed that whenever cattle heard the sound of an axe cutting a tree they rushed to the site and even helped to bring down the tree by pulling it down as the jostle for the new spring leaves. At this time the ground is almost bare and the situation is worsened by fire outbreaks that are common in the fire season. In Zimbabwe, the area of land affected by fire annually shows a rising trend, increasing from 400 thousand hectares in 2001 to 1 million hectares by September 2012 (Ntandokamlimu, 2012). In a few instances where mulching is practised organic mulch is sometimes obtained from sources external to the field. Collecting mulch from external sources should be carefully monitored as it may adversely affect ecosystems from which the mulch is collected.

The construction of tied ridges is more laborious and time consuming than the ordinary ridge cultivation and much more than conventional tillage (Nyamudeza, 1999).Technologies which increase labour and draught power requirements, or require more than a minimum of capital input, will be rejected by most smallholder farmers (Twomlow et al., 1999). This was confirmed by recent findings in Ethiopia (Araya and Stroosnijder, 2010; Lal, 2013). In an environment where the youthful and capable individuals generally migrate to urban areas to escape the vicious cycle of rural poverty (Whitlow, 1980) leaving behind the elderly and children there is need to search for labour saving technologies.

Conventional tillage does better than conservation tillage methods during relatively wet seasons with more than 700 mm rainfall often yielding greater than 4 t ha^{-1} (Figure 2.6). Monodawafa and Zhou (2008) observed more drainage water beyond the rootzone under conservation tillage treatments (78 mm y^{-1} under mulch ripping and 77 mm y^{-1} under tied ridging) compared to conventional tillage with 64 mm y^{-1} ($P < 0.001$). The high drainage water may lead to yield loss due to leaching under sandy soils and more water retained in the field may cause low yields due waterlogging in heavier textured soils. The strong influence of rainfall is confirmed by the significant linear relationship between rainfall and yields averaged over the tillage methods (R^2 = 0.72, RMSE =0.74 t ha^{-1}, $P < 0.001$). Low maize yields under conservation tillage in wet years may be attributed poor soil drainage, which has an adverse effect on yields under no tillage conditions (Griffith et al., 1988).

Since conservation tillage methods are often outperformed by conventional tillage in wet years they should be improved so that they can cope with wet conditions. This can be achieved by incorporating in the design of the tillage methods a provision for adjustments for improving drainage during the course of the season. The significant influence of rainfall implies that water based crop models for example AquaCrop (Raes et al., 2009) may be used for scenario simulations in maize production under semi-arid Zimbabwe.

2.5.2 Planting pits: an essential fall-back tillage method

Tillage methods based on the hand hoe featured in three experiments as the traditional holing out in Vogel (1993), and planting pits in Mupangwa et al. (2007) and Mupangwa et al. (2012b). These tillage methods, though labour intensive are vital for smallholder farmers without access to adequate draught power and as fall-back tillage methods in the event of a severe drought or cyclone that kills draught animals as what happened in during the 1991/92 drought and Cyclone Eline during the 1999/2000 cropping season. Hagmann (1996) reports that after the 1991/92 drought many draught animals died and farmers tilled the land with hoes. Such devastating droughts occur with a frequency of two in ten years Makarau (1999). Vogel (1993) reported that planting holes had lower performance compared to other tillage methods but Mupangwa et al. (2007) and Mupangwa et al. (2012b) reported yields that were not significantly different from conventional tillage for planting pits. This is because planting pits used by Mupangwa et al. (2012b) are an improvement from the traditional holing out as they are designed to harvest and conserve rainwater. There is a need to further determine the performance of planting pits under farmers' fields.

Our experiences with planting pits in Rushinga district in northern Zimbabwe from 2010/11 to 2012/13 cropping seasons show that planting pits dug before the onset of the rainy season in October are difficult to dig as the soil is very hard at this time of the year. For hardsetting soils planting pits are, therefore, not suitable. "Hard setting soils are soils that set to a hard structureless mass during drying and are thereafter difficult or impossible to cultivate until the profile is wetted" (Mullins et al., 1990). McKyes et al. (1994) characterized hardsetting soils in northern Zimbabwe and states that they usually lie in the sandy clay to loamy sand textural range with a well-graded particle size distribution. Furthermore the planting pits are obliterated by heavy rain storms that fall at the beginning of the season on fields with 5 to 6% slopes on sandy loam to sandy clay loams. Re-digging demands extra labour from the farmer. In response to high labour requirements for digging planting pits the Food and Agriculture organisation of the United Nations (FAO) introduced the 'mechanised' hoe during the 2012/13 season.

2.5.3 Complementarity between tillage methods and the fate of conventional tillage

Motsi et al. (2004) compared in-field technologies (conventional tillage and tied ridges) with field-edge technologies (*fanya juus*) and infiltration pits. As mentioned earlier (section 2.4.2), these two sets of technologies can actually complement each other by virtue of their different locations and dimensions. Thus, future studies should focus on combinations of in-field and field-edge technologies. On sloping land field-edge methods are a prerequisite because they reduce rill and gully erosion that can destroy the smaller in-field conservation tillage methods.

Motsi et al.(2004) report better maize yields under infiltration pits; whilst Mupangwa et al. (2012a) argue that it is not worthwhile investing in these rainwater harvesting structures given the labour and time requirements and limited soil water benefits observed. In view of these contrasting results further research is required in order to ascertain benefits of infiltration pits in areas where there is relatively high potential for large quantities of surface runoff.

It is unfortunate that the plough has been branded as “evil” mostly by advocates of CA but as long as farmers continue to use it researchers and practitioners should embrace the plough in the meantime while they continue to search for alternatives and/or fine tune the existing technologies to match smallholder farmers’ biophysical and socio-economic conditions. Van Ittersum (2011) warns that ‘the low hanging fruit has been harvested’, implying that there are no more easier options that were feasible in the past and innovative options are now required. Best practices under conventional tillage should be promoted and not neglected, for example there is no reason why the CA principle of diversified crop rotations should not be reinforced under conventional tillage when it was even there before CA. Appropriate intercropping systems which circumvent the problem of limited land should be considered. Failure to do so implies that the negative effects may reach critical levels before the appropriate tillage technologies are adopted by the farmers.

2.6 Conclusions and recommendations

For grain yields ≤ 2.5 t ha^{-1} and for rainfall ≤ 500 mm conservation tillage methods produced higher (144 kg ha^{-1} for 1.0 m tied ridging and 344 kg ha^{-1} for mulch ripping) but statistically insignificant grain yields than conventional tillage. Above 2.5 t ha^{-1} and for rainfall > 500 mm conventional tillage has a yield advantage of ≥ 640 kg ha^{-1} though insignificant ($P > 0.05$). Thus, based in low rainfall years 1.0 m tied ridging and mulch ripping are technically viable conservation tillage options for semi-arid Zimbabwe. However, both techniques face considerable constraints with respect to resources needed and required levels of management.

Conventional hand hoeing produced the lowest maize grain yields in one of the two experiments where it was considered but planting pits equalled the performance of ripping and conventional tillage in the other experiment. Planting pits dug using the hand hoe (*badza*) are recommended for farmers without adequate access to draught power and as fall-back tillage method in the event of draught livestock loss to disasters such as severe droughts, cyclones and diseases and fire outbreaks.

In-field technologies (conventional tillage, tied ridging, mulch ripping, clean ripping, planting pits and holing out) and field-edge technologies (*fanya juus* and infiltration pits) complement each other by virtue of their different locations and dimensions. Thus future studies should focus on combinations of in-field and field edge technologies rather than comparisons between them.

Since conservation tillage methods are often outperformed by conventional tillage in wet years; research should focus on developing versatile conservation tillage systems that perform well under both wet and dry conditions.

Further experimental research coupled with modelling is required (i) to establish whether to plant on top of the ridge or not in NR IV and (ii) to further test the threshold seasonal rainfall amounts for conservation tillage methods, and (iii) develop a tool for adaptive soil and water conservation and split application of topdressing fertilizers.

In light of the constraints to adoption of conservation tillage methods by the often resource-constrained smallholder farmers scientists and development practitioners should promote best agronomic practices under conventional tillage while they work on adoption of tested alternative tillage methods or develop new ones.

Chapter 3

Water management options based on rainfall analysis for rainfed maize (Zea mays L.) production in Rushinga district, Zimbabwe

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Water management options based on rainfall analysis for rainfed maize (*Zea mays* L.) production in Rushinga district, Zimbabwe

Abstract

Maize (*Zea mays* L.), the dominant and staple food crop in Southern and Eastern Africa, is preferred to the drought-tolerant sorghum and pearl millet even in semi-arid areas. In semi-arid areas production of maize is constrained by droughts and poor rainfall distribution. The best way to grow crops in these areas is through irrigation, but limited areal extent, increasing water scarcity, and prohibitive development costs limit the feasibility of irrigation. Therefore, there is need for a policy shift towards other viable options. This paper presents daily rainfall analysis from Rushinga district, a semi-arid location in Northern Zimbabwe. The purpose of the rainfall analysis was to assess opportunities and limitations for rainfed maize production using 25 years of data. Data was analyzed using a variety of statistical methods that include trend analysis, t-test for independent samples, rank-based frequency analysis, Spearman's correlation coefficient and Mann Whitney's U test. The results showed no evidence of change in rainfall pattern. The mean seasonal rainfall was 631 mm with a standard deviation (SD) of 175 mm. December, January and February consistently remained the major rainfall months. The results depicted high inter-annual variability for both annual and seasonal rainfall totals, a high incidence of droughts ≥ 3 out of every 10 years and ≥ 1 wet year in 10 years. Using the planting criteria recommended in Zimbabwe, most of the plantings would occur from the third decade of November with the mode being the first decade of December. This predisposes the rainfall to high evaporation and runoff losses especially in December when the crop is still in its initial stage of growth. On average 5 to more than 20 days dry spells occupy 56% of the rainy season. Seasonal rainfall exhibited negative correlation ($p < 0.001$; $R = -0.746$) with cumulative dry spell length, and wet years were free from dry spells exceeding 20 days. The most common dry spells (6-10 days), are in the range in which irrigated crops survive on available soil water. Therefore, they can be mitigated by in-situ rainwater harvesting (RWH) and water conservation. The potential evapotranspiration of a 140-day maize crop was estimated to be 540 mm. Consequently, short season maize cultivars that mature in less than 140 days could be grown successfully in this area in all but drought years. However, sustainable maize production can only be achieved with careful management of the soil as a medium for storing water, which is essential for buffering against dry spells. To this end soil restorative farming systems are recommended such as conservation farming, in-situ RWH techniques for dry spell mitigation and a cropping system that includes drought-tolerant cereal crops as for example sorghum and pearl millet, and perennial carbohydrate sources as for example cassava to provide stable crop yields.

Keywords: Cropping season, dry spell, drought mitigation, rainfed agriculture, soil management

3.1 Introduction

Smallholder farmers in the semi-arid sub-Saharan Africa (SSA) often experience food shortages due to water stress induced crop failure (Barron and Okwach, 2005). The situation will certainly worsen as future water scarcity is inevitable due to increasing population demand for food and development, and environmental maintenance (Barron, 2004; Cai and Rosegrant, 2003; Smith, 2000). The challenge in semi-arid areas is to optimize crop production per unit soil and water (Kahinda et al., 2007; Rockström et al., 2002; Vohland and Barry, 2009), 2009). The climatic conditions with high atmospheric evaporative demand and highly variable rainfall on both spatial and temporal scales make rainfed farming a risky business.

Rockström (2000) distinguishes between an agricultural drought, which occurs when the cumulative plant available soil water is significantly lower than cumulative crop water requirements and a dry spell which occurs as short periods of water stress, often, only a couple of weeks long, during crop growth.

Poor distribution of rainfall over time often constitutes a more common cause of crop failure than absolute water scarcity due to low cumulative annual rainfall (Barron, 2004; Barron and Okwach, 2005; Muhammad and Reason, 2004; Ochola and Kerkides, 2003; Rockström, 2000). During the crop growing duration intermittent dry spells of variable length occur at any stage (Muchow, 1989). A method to characterize the 'goodness' of rainfall distribution is an analysis of the probability of dry spells (Stroosnijder, 2007). Dry spells relate directly to agricultural impacts since their frequency and duration indicate the degree of stress plants are exposed to (Muhammad and Reason, 2004).

In this study the Famine and Early Warning System (FEWS) of the United States' definition of a dry day i.e. day with rainfall < 0.85 mm is adopted (Muhammad and Reason, 2004). The analysis of patterns of dry spells is necessary for planning long-term policies of water resources development and identifying appropriate mitigation measures (Lohani et al., 1998; Ochola and Kerkides, 2003). For agriculture, important aspects which relate to rainfall include the days of the start and the end of the rainy season and hence its length, plus rainfall amounts and risk of dry spells within the season (Hassan and Stern, 1988). In view of climate change, periodical assessment of rainfall and other climate variables in relation to crop production is required in order to develop adaptive strategies timely and to check if recommendations from the past are still relevant.

In meteorological analysis (using Markov chain methods) a dry spell is a period without effective rainfall. In agricultural terms (using a water balance model) a dry spell is a period with consecutive dry days resulting in soil water deficit causing crop water stress (Barron, 2004; Biamah, 2005). According to Stroosnijder (2007) meteorological analysis either over- or under-estimates agricultural dry spells, depending on the soil water holding capacity. Barron et al. (2003) consider a dry spell between 5-15 days to be harmful for sub-Saharan Africa. Stroosnijder (2007) reports that in Kenya and Tanzania, a 10-day dry spell has potential to damage a maize crop due to water deficit. Ochola and Kerkides (2003) define a critical dry spell as the longest duration of dry days and a critical wet spell as the longest duration with uninterrupted rainfall. Knowledge of occurrence of critical dry periods can aid in drought prediction and hence drought disaster preparedness; understanding of the longest wet spells has particular relevance to runoff, soil erosion and flood control (Biamah, 2005; Ochola and Kerkides, 2003).

Plants may become water stressed earlier than needed, even though there is sufficient rainfall for crop water requirements, a phenomenon called induced drought (Shaxson and Barber, 2003). Induced drought occurs when most of the rainwater does not infiltrate into the soil to become plant available water. This leads to more frequent and increased severity of agricultural droughts. Stroosnijder and Slegers (2008) attribute this more frequent occurrence of agricultural droughts to loss of the soil water holding capacity due to land degradation. Maphosa (1994)) stated that anthropogenic activities contribute significantly to land degradation. From an agricultural perspective the only way to combat a meteorological drought is by irrigation (Barron, 2004). An agricultural drought may, however, be prevented to some extent through crop management practices, for example use of drought tolerant cultivars, appropriate cropping systems, increasing plant available water through in-situ rainwater harvesting (RWH) (Shaxson and Barber, 2003).

Stroosnijder and Slegers (2008) argue that although farmers relate their notion of drought mainly to the occurrence of dry spells most recent studies show little evidence that the length and/or frequency of dry spells have increased.

The main cereal crop in savannah agro-ecosystems in Southern and Eastern Africa is maize (*Zea mays* L.) (Barron, 2004; Magorokosho et al., 2003). Maize is favored by farmers compared to more drought-tolerant cereals such as millet or sorghum despite its sensitivity to water deficiency, in particular during flowering and grain filling. At a certain threshold moisture deficit level pearl millet and sorghum can salvage some yield compared to no grain yield at all for maize (Muchow, 1989). In Zimbabwe, even in high potential regions maize may be affected by mid- and late season dry spells (Magorokosho et al., 2003). Maize is grown by almost all crop growing households in Zimbabwe's communal areas because it is the staple food crop despite the fact that most of the communal areas are more suitable for production of sorghum (*Sorghum bicolor* L. (Moench)) and pearl millet (*Pennisetum glaucum* (L.) R. Br.) because the soils and rainfall are marginal (Maphosa, 1994). Communal areas are characterized by largely resource-poor smallholder farmers operating at a subsistence level with maize yield averaging less than 1 t ha^{-1}. The situation in these areas is further compounded by inadequate soil fertility. It is envisaged that the lower risk of crop failure due to water, will trigger investments in soil nutrients (Kahinda et al., 2007; Rockström, 2000).

Rainfall within the semi-arid areas of Zimbabwe is reminiscent of other semi-arid regions (Mbilinyi et al., 2005; Rockström, 2000) typically coming mostly in the form of convective thunderstorms that are highly isolated resulting in a high spatial variability. In these areas severe mid-season dry spells are a common feature. A time series analysis of seasonal rainfall from 1901/02 to 1994/95 illustrates a high year to year variability(Makarau, 1999). According to (Hulme and Sheard, 1999) this makes Zimbabwe a strong candidate for the application of El Niño Southern Oscillations (ENSO) prediction to reduce the risk in agricultural production associated with rainfall variability. Drought or El Niño years are years with rainfall total less than the mean minus the standard deviation. Wet or La Niña years are years with rainfall totals with 10% probability of exceedance. Using 1951-1989 daily climate data, a decrease in seasonal precipitation and slight shortening of the rainy season were observed with the El Niño phase, compared to both neutral and La Niña years (Phillips et al., 1997).

The objective of this study was to assess limitations in terms of rainfall amounts and dry spell occurrences for maize production during the cropping season at a semi-arid location in the Mazowe valley in Zimbabwe. Rainfall analysis is used here as a tool that provides a framework for selection of feasible management options or selection of appropriate cropping systems. More detailed information than just departures from a mean state (Muhammad and Reason, 2004) is required in order to generate adequate information for farmers and policy makers. Therefore, in this study a variety of statistical methods that include trend analysis, t-test for independent samples, rank-based frequency analysis, Spearman's correlation coefficient tests and Mann Whitney's U-test are employed in order to sufficiently explore the rainfall data.

3.2 Materials and methods

3.2.1 Study site

The rainfall data was collected from rainfall records at Rushinga District in the north-eastern part of Zimbabwe. Rushinga is located 16°40′0″ S and 32°15′0″ E at an altitude of 730 m above sea level in Mazowe valley. The area is located in a semi-arid region locally known as Natural Region IV, which is characterized by low annual rainfall (450-650 mm), seasonal droughts and severe intra-season dry spells. The rainy season is unimodal generally extending from mid-November to the end of March (the hot wet summer period). The December to February period is the peak of the growing season and this is typically when the ENSO impact over southern Africa reaches its maximum strength (Muhammad and Reason, 2004). No rainfall of agricultural significance is received during the cold dry season (winter) from April to July and in the hot dry season (spring) from August to the beginning of the rainy season (Raes et al., 2004). Mean minimum and maximum temperatures are 14.1°C and 28.6°C, respectively. Rushinga district covers about 2 259 km^2 with a population of 67 137 according to the 2002 population census. Major crops grown are maize, cotton (*Gossypium hirsutum* L.), groundnuts (*Arachis hypogaea* L.) and millets. The major soil types are granite-derived sandy soils which are inherently infertile with patches of sandy clay loams.

3.2.2 Data collection and analysis

Daily rainfall data from Rushinga district was collected for the period 1980/81 to 20008/09. The rainfall in Rushinga is measured using non-recording gauges (pluviometers), by periodical readings of accumulated rainfall. This is done every 24 hours, which implies that the distribution of rainfall within the interval of observation is unknown (Boonstra, 1994). From the data set four years of rainfall data from the consecutive seasons 1996/97 to 1999/2000 could not be located for the district leaving data for 25 years. This data set was considered adequate for long-term analysis. According to Oosterbaan (1994) if there are approximately 20 years of information available, predictions for ten-year return periods will be reasonably reliable, but predictions for return periods of 20 years or more will be less reliable. For purposes of application of the Markovian model, Ochola and Kerkides (2003) established that a threshold value of 10 years of rainfall records is the minimum required for accurate prediction. Since the investment time horizon of resource-poor farmers is short, predictions beyond 10 year return periods are likely to be less usefull to them.

According to Barron et al. (2003) one way to analyse dry spell occurrence is to characterise long-term rainfall data with regard to mean values, deviations from long-term mean, frequencies and probabilities of rainfall and dry spells during given time periods. Stroosnijder (2007) identifies the following scales for rainfall analysis: annual scale for trend analysis and probabilities; decadal (10-day) scale for calculating the varying lengths of the growing season; one day scale for the size classes of showers, return period (design storm), hydrological and agronomic modeling and dry spell analysis, and with specific reference to land degradation the minute scale for erosivity in El Niño and La Niña years. The rainfall data was analysed using Microsoft Office Excel 2003 and SPSS for Windows Version 17.0. Initially annual and seasonal rainfall time series plots were made in order to detect any discernible shifts in annual and seasonal rainfall trends (Hassan and Stern, 1988).

Frequency analyses were done to predict how often certain amounts of rainfall occurred during the period under review. Rank-based methods according to Oosterbaan (1994) were employed to determine the frequency of occurrences and return periods of rainfall totals at different scales, and number of wet and dry days.

The mean seasonal rainfall, and monthly rainfall for two consecutive data sets 1980/81-1992/93 and 1993/94-2008/09 were compared in order to identify possible change in rainfall pattern. Wet spells were analysed by counting the number of wet days (rainfall amount > 0.85 mm) (Muhammad and Reason, 2004) per rainy season, calculating rainfall amount per wet day, searching for the largest single day rainfall amount, the longest wet spell and the largest wet spell rainfall amount and calculting the long-term decadal rainfall totals.

The earliest recommended maize planting dates using Zimbabwean criteria for commencement of planting (Raes et al., 2004) were determined for all the years in the data set. The end of the rainy season cannot be based solely on rainfall, a soil water balance is required to define the end of the crop growing period more realistically (Hassan and Stern, 1988). Follow-up field trials are planned for the rainy seasons 2010/11 and 2011/12 for determining the water balance. The experiments include simulation of the soil water balance and crop water productivity using AquaCrop, FAO's new crop water productivity model.

Daily rainfall amounts for the three normal years were plotted against day of the year in order to detect any trend in occurrence of dry spells. Frequency of occurrence and timing of dry spells of 5, 6-10, 11-15, 16-20 and > 20 days were established for the entire 25 years. The time stability of the cumulative lengths of dry spells was tested using the t-test for independent samples.

In order to provide an estimate of the evaporative demand of the atmosphere reference evapotranspiration (ET_o) was calculated using monthly temperature data from, a nearby weather station in Mount Darwin town, and average sunshine hours for Zimbabwe using the ET_o calculator (Raes, 2009). The potential crop evapotranspiration (ET_c) for maize was estimated using K_c values generated by CRIWAR 3.0, Alterra ILRI's simulation model for crop irrigation water requirements of a cropped area (Bos et al., 2008). The ET_c was thus determined by the relationship: $ET_c = K_c \, ET_o$.

3.3 Results

3.3.1 Annual rainfall

There is wide variability in annual rainfall amounts ranging from 402 mm in the driest year 1983/84 to 1009 mm in the wettest year 1980/81 (Figure 3.1). The mean annual rainfall amount was 669 mm with a standard deviation (SD) of 181 mm. The median was 680 mm. In a dry year (90% probability of exceedance) the annual rainfall was about 439 mm and in a wet year (10% probability of exceedance) the rainfall amount was about 887 mm.

A t-test for independent samples to compare means of the first thirteen (1980/81-1992/93) mean (SD): 654 (162) mm, and the last twelve years (1993/94-2008/09) mean (SD): 686 (205) mm showed no significant difference t (23) = 0.422, ($P > 0.05$). This suggests that there are no time related changes in the annual rainfall amounts.

3.3.2 Seasonal rainfall

For the seasonal rainfall, November to March (Figure 3.2), the mean (SD) was 631 (175) mm and the median was 662 mm implying that based on the median 97% of the annual rainfall fell during this period. The 10% probability of exceedance rainfall was 858 mm per season and the 90% probability of exceedance was 402 mm per season.

In conformity with the annual rainfall, a t-test for independent samples to compare means of the first thirteen (1980/81-1992/93), mean (SD): 624 (173) mm, and the last twelve years (1993/94-2008/09), mean (SD): 640 (184) mm seasonal rainfall amounts over the 25 years showed no significant difference t (23) = 0.221, ($P > 0.05$).

Seasonal rainfall followed a normal distribution pattern (Figure 3.3). The major rainfall months were December, January and February which accounted for 82% (i.e. 25.8, 28.9 and 27.3% respectively) of the seasonal rainfall. The mean rainfall amounts received during the major rainfall months were not significantly different from each other ($P > 0.05$) but significantly different from the rest ($P < 0.001$). The contribution of the remaining months was as follows: November (7.3%) and March (10.8%).

Figure 3.4 shows that there was no significant shift in the rainy seasons over time. The largest rainfall amounts were consistently received during the major rainfall months.

Seasonal rainfall for typical normal years which seasonal totals are closest to the November to March seasonal mean of 631 mm is shown in Figure 3.5. The total rainfall amounts for the three seasons were 612, 636 and 654 mm for 1986/87, 2003/04 and 2008/09, respectively. These results reveal that there is variability within seasons although they have nearly equal annual rainfall. This confirms the high inter-seasonal variability in distribution of rainfall.

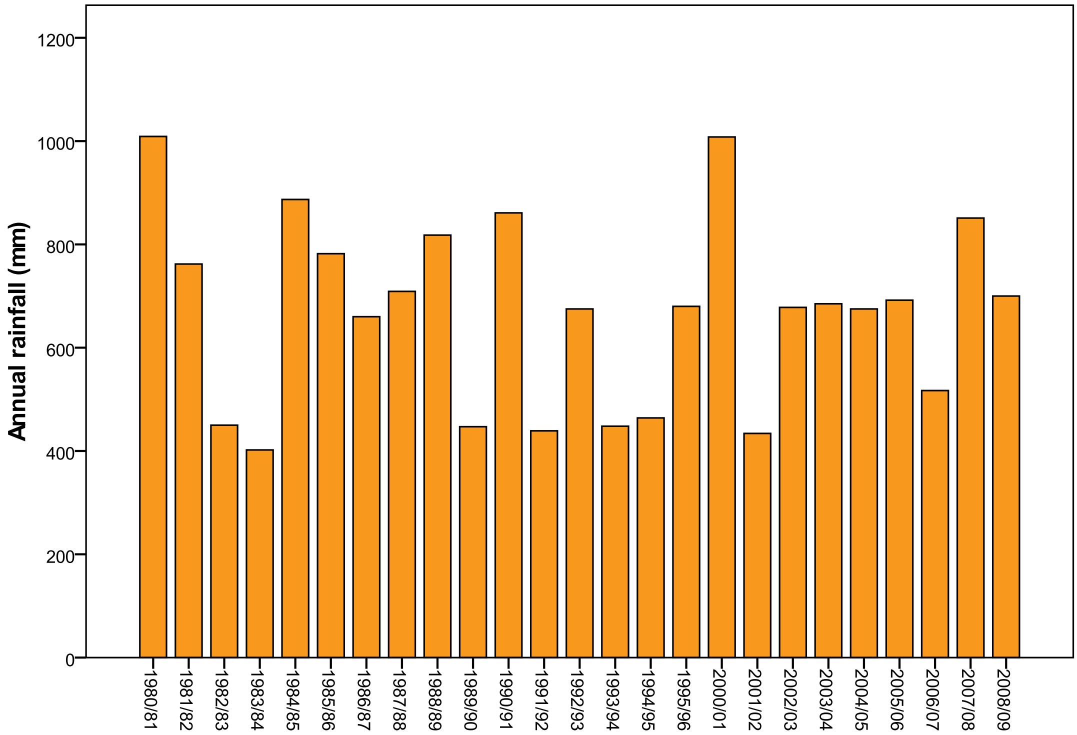


Figure 3.1: Annual rainfall for Rushinga for the period 1980/81 to 2008/09

NB: Four years of rainfall data (1996/97 to 1999/2000) are missing. During the season 1999/2000 Cyclone Eline occurred so *district in Zimbabwe* the rainfall amount for that season is likely to have exceeded the highest depicted here.

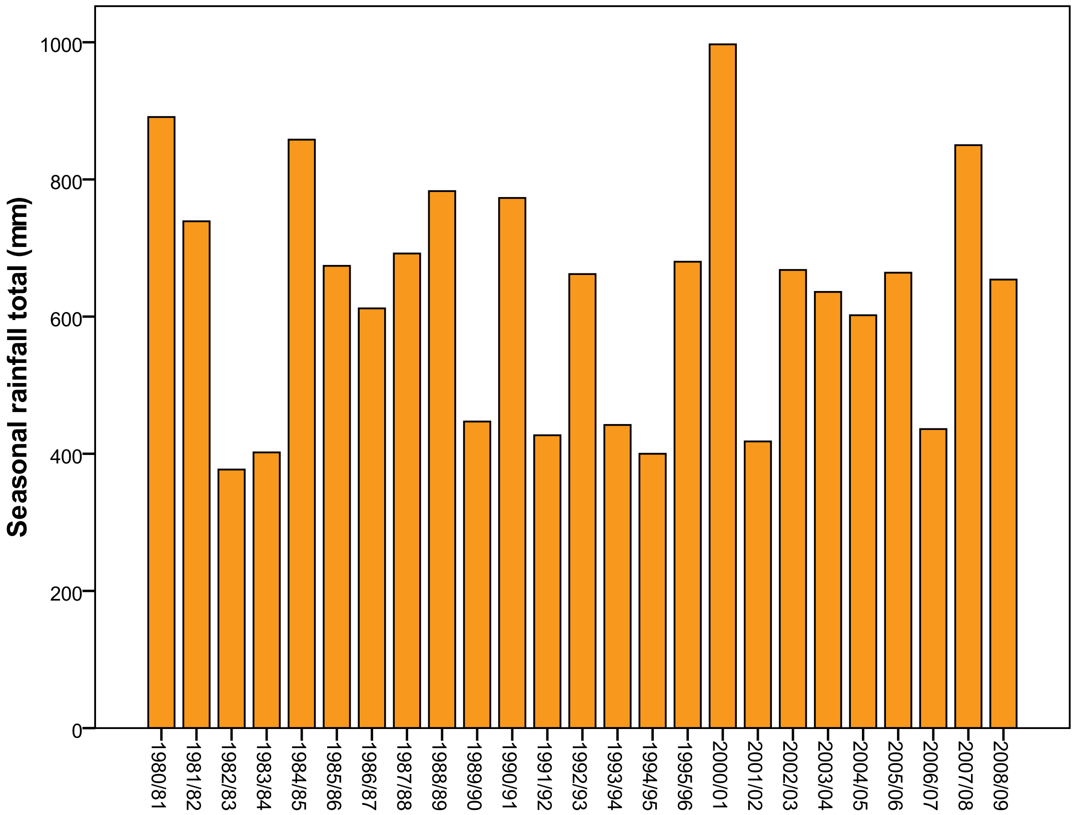


Figure 3.2: Seasonal (November-March) rainfall for twenty five years at Rushinga district

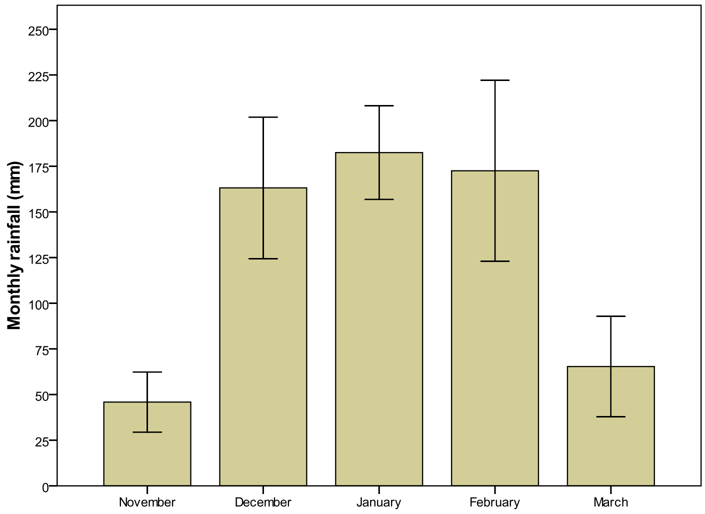


Figure 3.3: Mean monthly rainfall for Rushinga district (Error bars: 95% Confidence Interval)

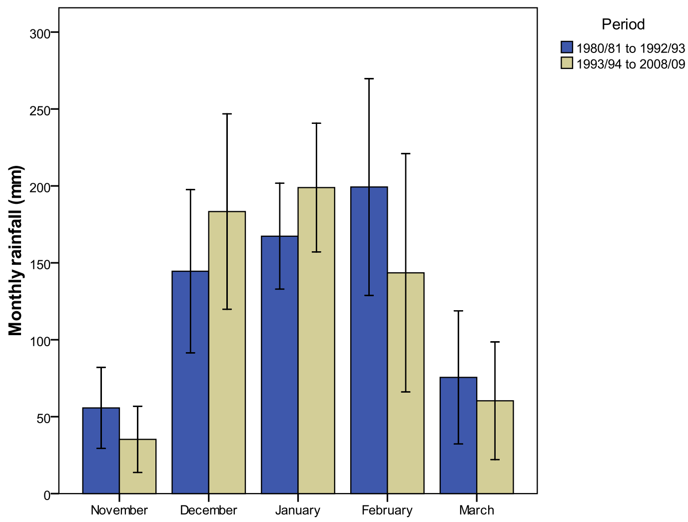


Figure 3.4: Trend in monthly rainfall over two periods (1980/81-1992/93 and 1993/94-2008/09) at Rushinga district. (Error bars: 95% Confidence Interval)

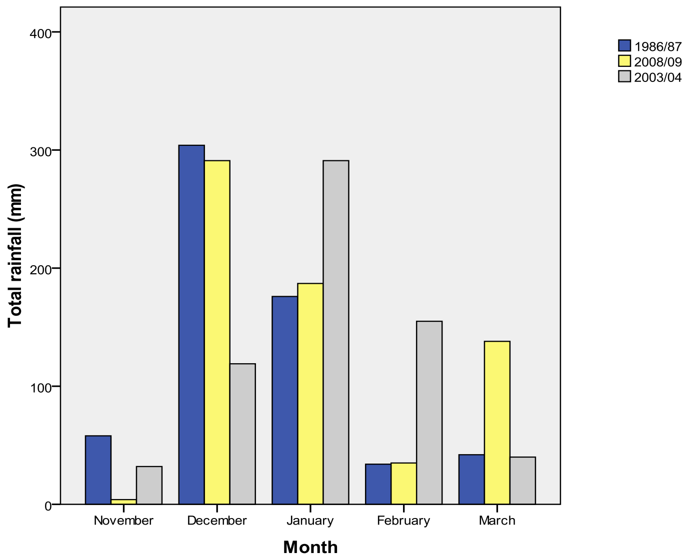


Figure 3.5: Monthly rainfall for three normal years (i.e. with seasonal rainfall closest to November to March mean of 631 mm) at Rushinga district

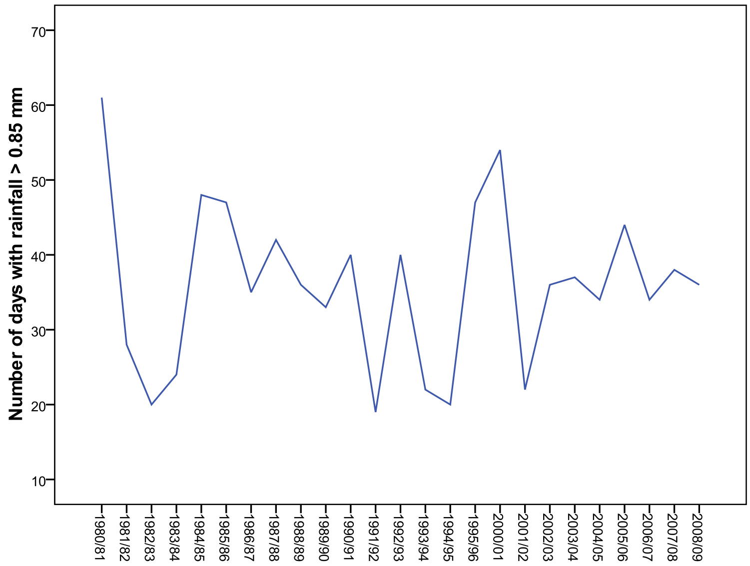


Figure 3.6: Number of wet days in the rainy season for Rushinga district (19980/81-2008/09)

3.3.3. Wet spell analysis

Considering a rainy season of 151 days in a normal year and 152 days in a leap year the mean (SD) number of wet days was 36 (11), giving a probability of a wet day of 0.24. The number of wet days per season ranged from 19 to 60. The mean (SD) rainfall amount per rainy day was found to be 18 (3) mm. A plot of number of wet days and year does not show evidence of a time dependent trend in the number of wet days (Figure 3.6).

The mean (SD) largest single day rainfall amount was 77 (20) mm. The largest single day amounts ranged from 42.5 to 114 mm and the median was 75 mm. Pearson's correlation test for the relation between single day amounts and seasonal rainfall totals yielded a coefficient of 0.344 which is not significant at P = 0.05. Most (76%) of the largest single day amounts fell in the major rainfall months distributed as follows: 36% in December, and 20% in both January and February. The rest fell in November (8%), and March (16%).

Most of the longest wet spells (84%) occur in the main rainfall months, December (24%), January (16%), January-February overlap (8%) February (36%), whilst March and November account for 8% each. The largest rainfall amounts for the wet spells ranged from 35 mm to 276 mm, with a median value of 120 mm and a mean (SD) value of 127 (61) mm. Pearson's correlation coefficient (0.178) for the relation between largest rainfall amount received during wet spells and seasonal totals was not significant, P > 0.05.

The long-term decadal totals for the rainy season (Figure 3.7). If a minimum precipitation per 10-day period is set at 40 mm per day, the amount necessary to trigger growth if one accounts for 50% runoff (Stroosnijder and Hoogmoed, 1984), then on average the rainy season would start during the third decade of November. Even, if a lower limit of 20 mm per 10-day period is set, an amount sufficient for growth if runoff is nil (Stroosnijder, 2007), the season would start during the same period. Similarly, considering two criteria used to advise farmers on commencement of planting (Raes et al., 2004) i.e. the less stringent Department of Agricultural Technical & Extension Services (Agritex) criterion (planting is advised as soon as rainfall exceeds 25 mm in 7 days) and the more strict depth criterion (where planting is advised when a minimum of 40 mm has been received in 4 days) on average planting would start during the third decade of November. Decadal mean number of wet days for the period first decade of December to the first decade of March was ≥ 5 wet days. The rest of the decades had mean number of wet days ≤ 2 except for the third decade of November which had a mean of 3 wet days.

Subjecting the daily rainfall records for each year to the Zimbabwean planting criteria as described earlier, the recommended planting dates ranged from the first decade of November to the first decade of January although the first decade of January was more of an outlier for the Agritex criterion (Table 3.1). Based on the Agritex criterion most plantings (64%) would occur from the third decade of November to the first decade of December. Earlier plantings and later plantings account for 20% and 16% of the plantings, respectively.

Based on the depth criterion, most of the plantings (60%) would occur from the first decade to the second decade of December whilst the earlier and later periods account for 28% and 12%, respectively (Table 3.1). The modal planting period was identical for the two criteria, the first decade of December, accounting for 36% of the plantings in both cases.

Possible planting dates in October based on the Agritex criteria were 12, 17, 20, 21 (twice) and 24 (twice) corresponding to the years 2004/05, 1994/95, 1982/83, 1990/91, 2008/09, 1986/87 and 2006/07, respectively. Based on the depth criterion the October planting days were 12, 19, 20 and 21 for 2004/05,1994/95,1982/83 and 1990/91. These October planting dates are followed by severe dry spells ranging from 18 to 52 days. These plantings result in failure of crop establishment, which often leads to expensive replanting. They would only be suitable for farmers whose fields are in the wetlands. They were discarded due to the obvious high failure rate. In any case most farmers use the first rains for land preparation.

The Mann-Whitney U test for the Agritex criterion, U = 70; (n_1 = 13; n_2 = 12); mean ranks (n_1 = 12.4; n_2 = 13.7) showed that there is no significant shift ($P > 0.05$) in planting dates over time. The same test for depth criterion U = 65; (n_1 = 13; n_2 = 12); mean ranks (n_1 = 12.0; n_2 = 14.1) also showed no significant shifts ($P > 0.05$) in planting dates.

Table 3.1: Recommended planting dates based on Zimbabwean planting criteria (Agritex and depth criteria) for Rushinga district

Rank	Year	Planting dates based on Agritex criterion > 25 mm in 7 days	Year	Planting dates based on the Depth criterion 40 mm in 4 days
1	2002/03	05/11	2002/03	05/11
2	1984/85	10/11	1984/85	10/11
3	1993/94	12/11	1991/92	22/11
4	1991/92	16/11	1990/91	24/11
5	2001/02	18/11	1993/94	25/11
6	1990/91	24/11	2007/08	27/11
7	1983/84	26/11	1981/82	28/11
8	2007/08	27/11	1987/88	01/12
9	[a]2003/04	27/11	1985/86	03/12
10	1981/82	28/11	2001/02	03/12
11	[a]1986/87	28/11	[a]1986/87	06/12
12	1987/88	29/11	2004/05	06/12
13	2000/01	01/12	1988/89	06/12
14	2005/06	01/12	1983/84	07/12
15	1988/89	01/12	2005/06	09/12
16	1980/81	02/12	1982/83	10/12
17	1985/86	03/12	1995/96	11/12
18	2006/07	05/12	1992/93	11/12
19	2004/05	06/12	1994/95	11/12
20	1992/93	09/12	[a]2003/04	12/12
21	1982/83	09/12	2000/01	13/12
22	1994/95	11/12	[a]2008/09	15/12
23	1995/96	11/12	1980/81	28/12
24	[a]2008/09	15/12	2006/07	28/12
25	1989/90	01/01	1989/90	02/01

[a]Years with seasonal rainfall totals that are closest to the long-term mean.

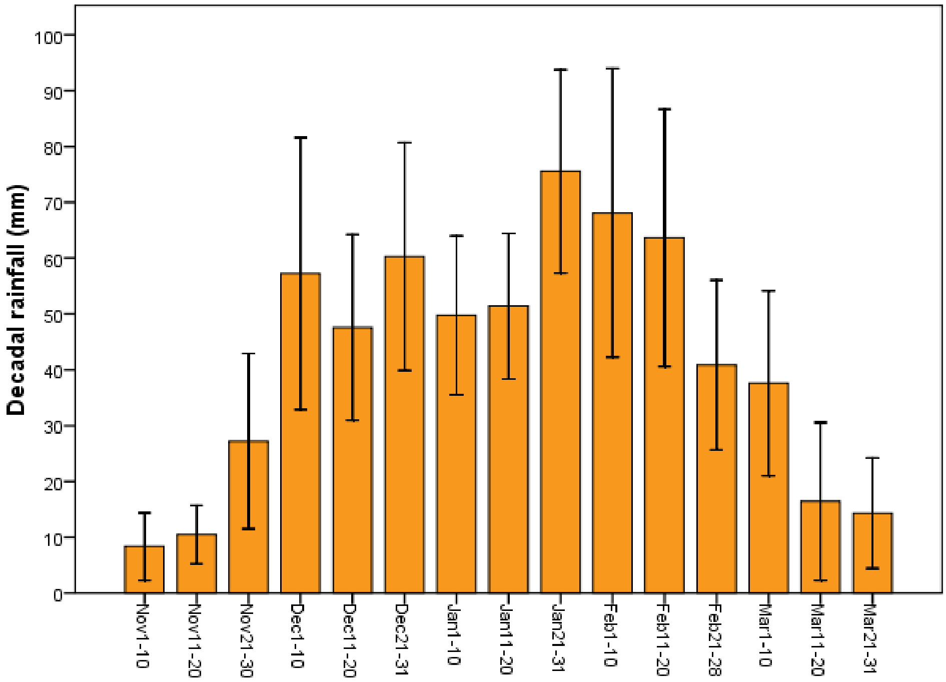


Figure 3.7: Mean decadal rainfall for Rushinga district. (Error bars: 95% Confidence Interval)

3.3.4 Dry spell analysis

Noticeable dry spells coincided persistently over the three normal years (1986/87, 2003/04 and 2008/09) years during the following periods: 320th to 330th Julian day (15-25 November); 37th to the 43rd Julian day (6-12 February) and 73rd to 76th Julian day (13-16 March).

The cumulative lengths of dry spells for the entire 25 year rainfall data stretched from 52 to 117 days during a period with 151 days during a normal year and 152 days during a leap year with a median of 82 days. The mean (SD) cumulative dry spell period is 84 (19) days. The normal years based on seasonal rainfall (1986/87, 2003/04 and 2008/09) had 95, 84 and 94 days cumulative dry spell periods. On average 56% of the entire rainy season duration was occupied by dry spells. There is a significant negative correlation (Pearson's correlation coefficient, -0.746; $P < 0.001$) between the cumulative length of seasonal dry spells and total seasonal rainfall. However, there were no significant changes ($P > 0.05$) of cumulative lengths of dry spells with time.

The most common intra-season dry spells are 6-10 days long, occurring during the major rainfall months with 26, 22 and 23% frequency of occurrence for December, January and February respectively (Table 3.2). On average the 6-10 days dry spells occurred three times per rainy season whilst the rest occurred once. The long-term data shows that longer dry spells started most frequently in November and March, i.e. 11-15 days (57%), 16-20 days (92%) and > 20 days (81%). Dry spells exceeding 20 days (Table 3.3) occurred in dry to above normal years but never in wet years (10% probability of exceedance).

Daily ET_0 during the cropping season ranges from 5.1 mm d^{-1} in February to 6.1 mm d^{-1} in November. A plot of mean decadal rainfall totals and ET_o shows that ET_o exceeded rainfall except during the period between the third decade of November to the first decade of March (Figure 3.8). Thus, during the major rainfall months rainfall exceeded ET_o. The estimated potential evapotranspiration of maize with a maximum rooting depth of 0.7 m that matures in 125 and 140 days was found to be 480 and 540 mm respectively.

Table 3.2: Number of dry spells of varying lengths in 25 years at Rushinga district

Month	Decade during which dry spell starts														
	Decade 1					Decade 2					Decade 3				
	5[a]	6-10[a]	11-15[a]	16-20[a]	> 20[a]	5[a]	6-10[a]	11-15[a]	16-20[a]	> 20[a]	5[a]	6-10[a]	11-15[a]	16-20[a]	> 20[a]
Nov	2	5	9	1	8	1	4	2	4	1	2	6	1	1	0
Dec	2	5	1	0	1	1	10	3	1	1	0	7	0	0	0
Jan	1	6	2	0	0	1	6	1	0	0	1	7	3	0	0
Feb	1	9	3	0	0	0	3	1	0	1	4	8	1	0	1
Mar	1	4	2	4	8	0	0	2	2	0	1	6	4	0	0
Total	**7**	**29**	**17**	**5**	**17**	**3**	**23**	**9**	**7**	**3**	**8**	**34**	**9**	**1**	**1**

[a]Length of dry spell (days)

Table 3.3: Occurrence of dry spells exceeding 20 days in Rushinga district November

Year	Seasonal rainfall (mm)	November		December-February		March	
		Days	Dates	Days	Dates	Days	Dates
1981/82	739	26	1-26	25; 30	1-25 December; 25 February-25 March		
1982/83	377			33	14 December-15 January	22	10-31
1987/88	692	27	1-27				
1988/89	783	27	1-27				
1989/90	447			38	22 February-31 March		
1991/92	427					28	4-31
1992/93	662	27	11November-7 December				
1993/94	442					29	3-31
1994/95	400	40	1 November-10 December			24	1-24
1995/96	680	29	1-29			25	7-31
2001/02	418			30	17 February-18 March		
2002/03	668	32	7 November-8 December				
2003/04	636	26	1-26				
2004/05	602	22	1-22			31	1-31

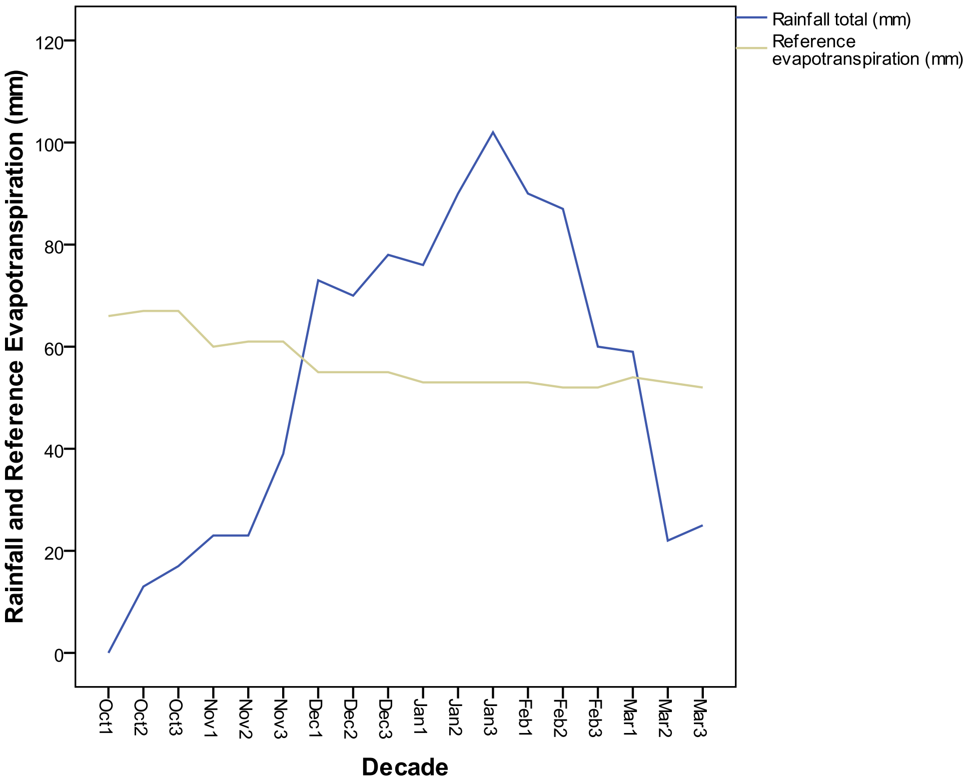


Figure 3.8: Decadal mean rainfall and reference evapotranspiration (ET_0) at Rushinga district (Note: Oct1, Oct2, and Oct3 refer to the first, second and third decades of October, etc.)

3. 4 Discussion

Our results depict high inter-annual variability in rainfall totals typical of semi-arid regions (Kahinda et al., 2007; Mbilinyi et al., 2005; Rockström and Falkenmark, 2000). Thus, rainfall data from Rushinga district, though lacking in spatial extent, confirms the candidacy of this location for the application of El Niño prediction to reduce the risk in agricultural production associated with rainfall variability as stated by Hulme and Sheard (1999). The yearly variation makes the planning of sowing and selection of crop types and varieties rather difficult. El Niño years were experienced in 1982/83, 1983/84, 1989/90, 1991/92, 1993/94, 1994/95 and 2001/02 representing almost 30% of the years. In such years, water is insufficient not only for rainfed crop production but also for livestock, gardening and other development needs. According to Tyson (1991) droughts are characterized by environmental stresses, deteriorating vegetation, agricultural losses, increased pressure on water resources, reduction in arable land areas, increased economic stresses, soil erosion and social pressures. All these effects were experienced in Zimbabwe during the historic 1991/92 drought including death of over one million head of cattle due to starvation (Maphosa, 1994).

On the other end La Niña years occurred in 1980/81, 1984/85, and 2000/01. Although the data for the year 1999/2000 was not available at the station this was also a wet year because of the occurrence of Cyclone Eline during that season. Thus a wet year is expected more than once in ten years. Wet years pose risks of floods, and reduced crop yields due to waterlogging and leaching of plant nutrients. However, in such years, upslope areas are less affected and gardening during the dry season provides an essential fall-back.

Seasonal rainfall (November to March) follows the same trend as annual rainfall, the only difference being an additional El Niño year 2006/07 to make a total of eight drought years from the available data implying that the frequency of occurrence of droughts is at least 3 out of every 10 years.

Since it is not possible to influence the timing and amount of rainfall (Shaxson and Barber, 2003; Stroosnijder and Slegers, 2008) the best way to produce crops in such an area is through irrigation. However, the high costs of irrigation development coupled with limited suitable hydrogeological conditions for irrigation development means that the role of irrigation will only be minimal in the foreseeable future. Under these conditions viable options include RWH, soil moisture retention or conservation, conservation farming and incorporating drought-tolerant crops in the farming systems. Rainwater harvesting mitigates the risks of intra-seasonal dry spells bridging the gap between rainfall events (Mbilinyi et al., 2005) whilst conservation tillage enables improved timing of operations, which is crucial in semi-arid farming and it has the advantage that it is applicable on most farmland (Rockström et al., 2002). Sadly, these farming systems do not help much in an absolute El Niño year when total rainfall is lower than the maize crop water requirements, estimated at 480 and 540 mm for a 125-day and 140-day cultivar, respectively. The figures compare favorably with a minimum of 500 mm cited by Wiyo et al. (2000) in Malawi. A more sustainable farming system is one that incorporates drought-tolerant crops such as pearl millet (*Pennisetum glaucum* (L.) R. Br.) and sorghum (*Sorghum bicolor* L. (Moench)) with minimum water requirements of 300 mm or less and 400 mm, respectively (Léder, 2004). Based on total seasonal rainfall data for Rushinga (Figure 3.2), all the 25 years had adequate rainfall for pearl millet and only two years had seasonal rainfall lower than sorghum crop water requirements. The other advantage of pearl millet is that it gives economic yields in soils that are too degraded to support other cereals. Bearing in mind that maize is the preferred cereal crop, a quota system should be adopted in semi-arid areas like Rushinga whereby a portion of land, enough to meet household requirements, is set aside for sorghum and pearl millet, and maize is allocated the remaining land for cereals.

Apart from the high inter-annual variability in both annual and seasonal rainfall, both annual and seasonal rainfall totals do not show evidence of time dependent trends in rainfall amounts. Variability in distribution among normal seasons (three seasons with rainfall totals that are closest to the seasonal mean of 631 mm, 1986/87, 2003/04 and 2008/09 with seasonal totals of 612 mm, 636 mm, and 654 mm, respectively (Figure 3.5) illustrates that normality based on rainfall amount does not imply a fair distribution.

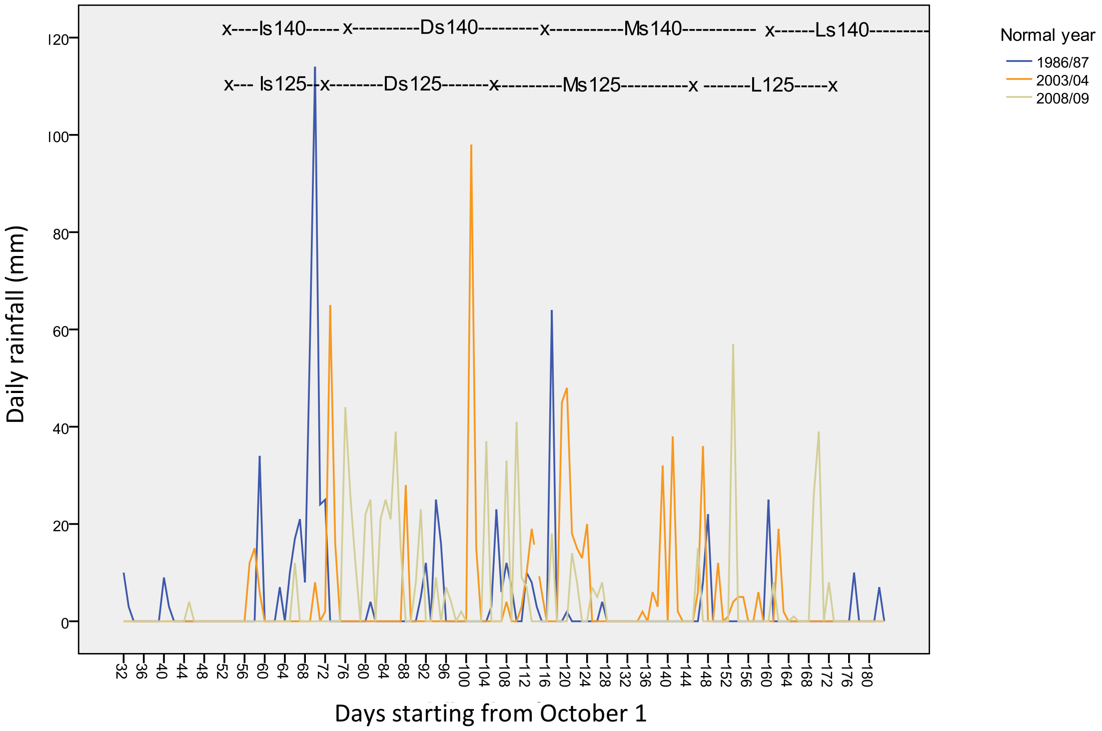
The high variability of wet days per season (19-60 days) conforms to the inter-annual variability in rainfall totals and distribution. The low probability of a wet day of 0.24 falls within the range of 0.17 long rains and 0.32 short rains obtained by Biamah (2005) in a semi-arid area in Kenya. The largest single day amounts ranging from 42.5 to 114 mm all fall in the heavy storms category (≥ 40 mm) confirming the convective nature of the rainfall. The fact that December has the largest share (36%) of the largest single day amounts and that the first decade of December is the modal recommended planting decade for both Zimbabwean planting criteria considered in this study, is a cause for concern as runoff losses are likely to be huge during the maize initial growth stage which on average lasts 25-30 days (Allen et al., 1998). The situation is exacerbated by the occurrence of the longest wet spells of which December accounts for 24%. Techniques like seed priming (soaking seeds in water before sowing, for 24 hours in the case of maize) which enhances crop water use efficiency by hastening germination and emergence (Shaxson and Barber, 2003) should be promoted. In order to improve crop water use efficiency during the initial growth stage of maize cassava (*Manihot esculenta*), a drought-tolerant perennial shrub that is cultivated primarily for its starch rich tuberous root system (Kelleher, 2003) may be incorporated in the cropping system. Since the cassava crop is already established during the initial growth stage of maize it will utilize the early rains. Although cassava is not widely used in Zimbabwe, people are familiar with it and it is grown extensively in the region. For example in Mtwara Region in Tanzania, farmers grow at least 15 varieties of cassava (de Waal et al., 1997). Due to its drought tolerance and ability to grow on marginal soils cassava is a potential food security crop for Zimbabwe (Kleih, 1995).

In-situ RWH techniques can be used to store water in the root zone for use by beneficial soil fauna and for later use as the plant roots deepen. Water stored in the root zone enables development of extensive root systems that are efficient in extracting soil moisture and essential plant nutrients. An extensive root system delays the onset, duration and severity of an agricultural drought (Shaxson and Barber, 2003). The capacity of a soil to store water and make it available to the crop is called the available water storage capacity (Anschütz et al., 2003). In order to maximize benefits from RWH the soil should have a high available water storage capacity. The available water storage capacity depends on soil texture and soil depth. Typical values of available water storage capacity (mm m^{-1}) are as follows: sand soil (55); sandy loam (120); clay loam (150) and clay (135) (Anschütz et al., 2003). Since available water storage capacity increases with an increase in soil depth shallow soils will not benefit much from RWH. Therefore RWH systems should be complemented by soil erosion control measures in order to maintain soil depth. Sorghum which develops an extensive root system which can extend up to 1.8 m in a friable soil (Rogers and Alan, 1998) has the ability to utilize the stored moisture. Inclusion of cassava further enhances water productivity. Excess water recharges groundwater and later becomes available for downstream use.

In soils that are prone to surface sealing and crusting a further limitation to successful crop establishment is poor seedling emergence. Use of mulch protects the soil from the raindrop impact and thus reduces soil surface crusting, encourages infiltration and reduces evaporation from the upper soil layers (Anschütz et al., 2003; Ofori, 1994; Shaxson and Barber, 2003) and moderates high temperatures in the upper root zone often experienced in low lying areas like Rushinga. Use of dead organic mulch in Rushinga district is recommended based on the assertion by Anschütz et al. (2003) that areas with marginal rainfall usually respond better to mulching with dead organic material than to cover crops because the former does not compete for water and nutrients. Raes et al. (2004) also note that although late plantings based on the depth criterion had potential to increase successful crop establishment, they shorten the cropping season and predisposes plant nutrients to leaching at the beginning of the season. Experiences from Zimbabwe show that delays in planting beyond threshold planting dates (usually around mid-November for the northern parts of the country) result in significant loss in yield. The yield decrease is largely due to loss of rainwater by deep percolation and evaporation, and loss of mineralized nutrients (Shaxson and Barber, 2003). Due to the large amounts of runoff generated during this period of low crop transpiration soil and water conservation structures located at field edges are critical for both crop and soil protection.

A common intra-season dry spell occurs from 6-12 February over the three normal years (Figure 3.9). This period coincides with the moisture sensitive reproductive stages of both a 125-day and 140-day maize cultivar assuming that planting is done in the third decade of November (Figure 3.9). These short season cultivars are better adapted to semi-arid areas than the long season cultivars. By selecting short season varieties of maize, the farmer compromises his yield but the yield losses due to dry spells, particularly those that shorten the growing season, are minimized. A drought-resilient cropping system that includes sorghum, pearl millet and cassava in addition to maize will ensure that the low yield obtained in wet years is compensated for by a relatively high stability of yield.

The common dry spell observed over the three normal years falls in the range of the most the common dry spell of length 6-10 days which has potential to damage a maize crop (Barron et al., 2003; Stroosnijder, 2007). Dry spells of this duration occur throughout the season with modal occurrence in December (26%). Thus, although the most frequent effects will be felt during the initial crop stage, all crop development stages are affected. If the land is degraded, agricultural dry spells will be longer than the observed meteorological dry spells. However, dry spells of this magnitude are in the range of time within which plants can survive on extracting plant available water from the soil under irrigation, hence they can be alleviated through enhancing infiltration of water at the soil surface and improving the capacity of the soil to store water. Extending the period in which soil moisture remains available to plants shortens the duration of potentially damaging water stress. Infiltration can be increased by in-situ RWH techniques.



Is_{140}, Ds_{140}, Ms_{140} and Ls_{140}, represent initial, development, mid-season, late-season stages for a 140-day cultivar.
Is_{125}, Ds_{125}, Ms_{125} and Ls_{125} represent initial, development, mid-season, late-season stages for a 125-day cultivar.

Figure 3.9: Fitting cultivars with growing periods of 140 and 125 days into the mean rainy season using Rushinga district rainfall data

The in-situ RWH techniques generally work best in soils of medium texture with good water holding capacity (Anschütz et al., 2003; Siegert, 1994). Improved soil organic matter content and reduced tillage can improve the soil water storage capacity to help bridge intra-seasonal dry spells (Barron and Okwach, 2005) particularly in light textured soils. This realization, that in-situ RWH and water conservation are viable options, is key in influencing policy shift in Zimbabwe where the often less feasible irrigation option is usually solely considered.

Generally yields may suffer significantly with either a late onset or early cessation of the growing season, as well as with high frequency of damaging dry spells within the growing season (Mugalavai et al., 2008). Our study revealed that dry spells occupy a considerable portion of the growing season (56%); therefore the maize crop is exposed to a range of mild to severe dry spells during its growing period. The cumulative lengths of dry spells are a good indicator of the seasonal rainfall total due to the strong correlation that exists between the two variables. This is also reflected in the similarity of lengths of cumulative dry spells among the normal years which are 95, 84 and 94 for 1986/87, 2003/04 and 2008/09 seasons respectively. The beginning of most dry spells more than 11 days long in November and March, have the effect of shortening the rainy season and hence the cropping season. The implication is that farmers should plant short season cultivars with a growth duration of ±130 days that fit in the major rainfall months. These so-called drought-escaping cultivars tolerate drought because they have short growing periods and mature quickly before all soil water has been depleted (Shaxson and Barber, 2003). A disadvantage of the drought escaping cultivars is that their short growing season restricts yields compared with long-season cultivars although in dry years they yield more. In the presence of reliable seasonal climate forecasts, farmers will benefit from allocating a greater proportion of their land to high yielding late maturing maize cultivars if a wet season is predicted. The fact that the wet years are free of debilitating dry spells exceeding 20 days increases the potential of obtaining high yields. According to Biamah (2005) an agricultural drought month occurring at the beginning of the rainy season has usually more serious effects on crop response than one occurring towards the end of the crop growth period. This is due to the negative effects on the critical crop establishment stage.

The low mean seasonal rainfall, high frequency of El Niño years, poor rainfall distribution, and relatively short period during which the rainfall exceeds ET_0 (about 110 days) confirms that Rushinga is a marginal area for maize production. However, with implementation of RWH, water conservation and appropriate agronomic practices (fertilization, weed control, early planting, adjusting plant population to expected rainfall, etc.) short-season cultivars maturing in 120-132 days can be grown in all but El Niño years. Management of soil as a storage medium for plant available water is key to successful maize production because of the short duration of the period in which rainfall exceeds ET_0 and the annual feature of dry spells. In order to achieve yield stability and avert the debilitating effects of droughts and dry spells a cropping system that incorporates more drought-tolerant cereals like sorghum and pearl millet and perennial crops like cassava should be adopted. The FEWS will continue to play a minimal role in influencing farmers' practices until massive farmer training and timely communication occurs. Patt et al. (2005.) established that the yield variance explained by forecasts was small, and the difference between a good and a bad year was far more important.

3.5 Conclusions

The rainfall recorded at Rushinga district did not show significant time dependent changes in rainfall amounts, number of wet days and recommended planting dates, i.e. there is no evidence of change in the rainfall pattern. The rainfall is extremely variable with a drought year occurring in 3 out of every 10 years and a wet year more than once in ten years. The cumulative lengths of dry spells exceed 56% of the rainy season and dry spells dominated by the 6-10 days dry spell duration occur throughout the rainy season. High frequency of the seasonal largest single day and the longest wet spell rainfall amounts in December during the initial crop development stage predispose the soil to degradation by rainfall and leads to high unproductive field water losses due to runoff, erosion and possible deep percolation because most plantings occur in the first decade of December based on the Zimbabwean planting criteria. High water losses occur because during the month of December the crop canopy cover has not developed enough to cover the soil and slow down surface runoff. Water losses are greater under the conventional system than under conservation farming because of the presence of more mulch in the latter. Furthermore deep percolation losses are high because, during the initial growth stages, the root system has not developed to utilize soil water significantly.

Except for the El Niño years it is possible to grow a successful maize crop with appropriate soil and water management techniques. Since irrigation is expensive, emphasis should be placed on RWH, water conservation and conservation farming practices that enhance the role of soil as a medium for water storage. Farmers should be advised to plant short season cultivars maturing in ±130 days and that fit in the rainy season. In order to provide a buffer against marginal years a quota system where the more drought tolerant sorghum and/or pearl millet crop is planted on a prescribed area in addition to the preferred maize crop should be encouraged. Incorporation of a perennial source of carbohydrate such as cassava will improve the water productivity particularly during the initial growth stage of maize. Cassava will also make better use of rains that fall after maturity of annual crops. Similarly, farmers with access to information on seasonal forecasts can allocate part of their land to high-yielding long season maize cultivars in wet years.

Chapter 4

Infiltration and planting pits for improved water management and maize yield in semi-arid Zimbabwe

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Agricultural Water Management (in press)

Infiltration and planting pits for improved water management and maize yield in semi-arid Zimbabwe

Abstract

Realising that rainwater harvesting (RWH) improves crop productivity smallholder farmers in semi-arid Zimbabwe modified contour ridges traditionally used for rainwater management by digging infiltration pits inside contour ridge channels in order to retain more water in crop fields. However, scientific studies on crop yield benefits of infiltration pits have not been conclusive. Combining field-edge RWH methods such as contour ridges with infiltration pits and in-field practices may enhance crop yield benefits. Thus, the objective of the study was to assess soil moisture and maize yield improvement of combining infiltration and planting pits. Field experiments were conducted in Rushinga, Zimbabwe for three seasons at three sites using a split-plot design: main-plot factor, field-edge rainwater management method (RWMM); and split-plot factor, tillage method. Soil moisture content was measured weekly using gravimetric and TDR methods. A household and field survey to establish farmers' perceptions, typology and availability of field-edge RWMM was conducted. In order to share experinces and enhance stakeholders' learning field days were held. Lateral movement of soil water was measured up to 2 m downslope from infiltration pits, hence infiltration pits did not improve maize yield and soil moisture content in the cropping area. Maize yield (kg ha^{-1}) was 45% higher under conventional tillage (2697) than planting pits (1852) but the yield gap decreased from 90 to 30% in the first and third year respectively. The value of infiltration pits is in reducing soil erosion by water and growing high value horticultural crops inside and close to pits, a view shared by host farmers and other stakeholders. Planting pits are an option for farmers without access to draught power and a fall-back method. Research is required to determine soil moisture, maize yield benefits and waterlogging risk in fields with underlying impermeable layers that enhance lateral flow of water.

Keywords: Maize yield, infiltration pits, soil moisture content, contour ridges; planting pits, field experiments.

4.1 Introduction

Rainwater harvesting (RWH) can contribute to rainfed crop productivity (Kauffman et al., 2003 ; Vohland and Barry, 2009); and it is recommended for combating land degradation (Siegert, 1994; Vohland and Barry, 2009); and meeting Millennium Development Goals in Africa (Ochola and Kerkides 2003; Kahinda et al., 2008). Rainwater harvesting practices are a range of technologies for collecting and storing water for productive uses (Kahinda et al., 2008; Siegert, 1994). Practices which store and use water on-site, i.e. within the field are called *in-situ* practices (Stroosnijder et al., 2008). In these techniques the water source is overland flow from microcatchment areas (Lövenstein, 1994; Siegert, 1994). *In-situ* RWH bridges the gap between rainfall events by increasing the amount of water stored in the soil for plant use through collecting runoff water and allowing it to infiltrate into the soil profile. In Eastern and Southern Africa the priority crops should include maize (*Zea mays* L.), the most important cereal crop in the region (Barron, 2004; Jamil et al., 2012; Magorokosho et al., 2003).

The need for co-management of soil fertility has been iterated (Giller et al., 2006a; Mupangwa et al., 2006; Rockström, 2000; Tittonell et al., 2007; Vanlauwe and Giller, 2006; Zingore et al., 2007). It is envisaged that RWH will lower the risk of crop failure and encourage investments in soil fertility (Rockström, 2000). However, the benefits have to be realised within a short period since poor people cannot afford long-term investments (Stroosnijder et al., 2008).

Semi-arid areas of Zimbabwe, agroecological regions (Natural Regions) IV and V, annual rainfall 450-650 mm and less than 450 mm respectively (Vincent and Thomas, 1960) cover 64% of total land area and 74% of the communal areas land (Whitlow, 1980). A trail of crop failures in these areas in the 1990s forced farmers to experiment with different RWH techniques in order to mitigate droughts and dry spells. The technologies have been promoted mainly by Non-Governmental Organisations (NGOs) since the early 1990s. However, the benefits of these technologies with regard to their effectiveness in increasing soil moisture and improving crop yields have not been adequately quantified (Motsi et al., 2004 ; Mugabe, 2004; Mupangwa et al., 2006).

Modifications to traditional rainwater management techniques such as contour ridges are among initiatives triggered by recurrent crop failure due to drought and dry spells in semi-arid Zimbabwe. Contour ridges were designed to control soil erosion by safely disposing runoff water and they have been in existence since the introduction of the plough in the 1920s (Whitlow, 1988; Wilson, 1995). A contour ridge consists of an upstream channel and downstream ridge (Critchley et al., 1992; Elwell, 1981) (Figures 1.1, 1.2 and 2.3). A standard contour ridge has the following dimensions: gradient (1:250); channel width (1.70 m); channel depth (0.23 m); embankment height (0.23 m) constructed downslope of the channel and embankment width (1.70 m) (Elwell, 1981).

Alterations to contour ridges in order to retain more rainwater in crop fields include digging of infiltration pits inside channels of contour ridges (Maseko, 1995; Motsi et al., 2004 ; Mugabe, 2004; Mupangwa et al., 2006; Mutekwa and Kusangaya, 2006); construction of dead level contours (Mupangwa et al., 2006; Mupangwa et al., 2012a); deepening the contour ridge channel and constructing ties in the contour ridge channel forming check dams.

This study focused on infiltration pits (Figures 1.2 and 2.3) and planting pits (planting basins). Infiltration pits are rectangular trenches of varying dimensions excavated at intervals in the channels of contour ridges for collecting runoff water, storing it and allowing it to infiltrate and presumably flow through the soil layers. There is wide variability in both recommended and observed infiltration pits dimensions. Infiltration pits were adopted by most farmers in southern Zimbabwe (Hagmann et al., 1999; Hughes and Venema, 2005 ; Mutekwa and Kusangaya, 2006). In a study covering southern and northern Zimbabwe, Motsi et al. (2004) reported that infiltration pits were preferred to retention trenches (*fanya juus*) by farmers. *Fanya juus* are ridges within cultivated land where trenches are dug and the excavated soil is placed upslope (Makurira et al., 2009; Motsi et al., 2004). The channel depth is usually 0.5-0.6 m with ties at 10-m intervals.

Experimental research on infiltration pits in Zimbabwe has produced mixed results, and available information is inadequate to explain the causes of the differences in results. Further research is therefore needed in order to avail accurate and consistent information to farmers and policy makers. Motsi et al. (2004) reported soil moisture and maize yield benefits averaging 2.4 t ha^{-1} under infiltration pits compared to 1.5 t ha^{-1} under conventional tillage on sandy loam to sandy soils in Mudzi district in northern Zimbabwe, and Gutu and Chivi districts in southern Zimbabwe. Mugabe (2004) observed soil moisture benefits up to 11.8 m downstream of the pits with most benefits being experienced within 3.4 m of the infiltration pits on sandy loam soil in fields with less than 2% slope in southern Zimbabwe. Mupangwa et al. (2012a) reported soil moisture benefits at 2 m upslope and 3 m downslope from the centre of the infiltration pits in dead level contours on sand to loamy sand soils in fields with 1% slope in southern Zimbabwe.

It is difficult to conceive how infiltration pits benefit crops given their location at edges of fields which are on average 20 to 25 m wide. Knowledge from soil physics and hydrology suggests that in a homogenous soil profile most of the water infiltrates downwards below the pit to recharge the water table without significant lateral movement into the rootzone of the cropping area. However, subsurface lateral flow may dominate when the lateral hydraulic conductivity of the surface soil horizons exceeds the vertical hydraulic conductivity through the soil profile (Boonstra, 1994; Ward and Robinson, 2000). In our view the value of infiltration pits is more in sustainable land management through combating land degradation caused by soil water erosion, and improving farm water use efficiency by cropping close to or inside the infiltration pits than soil water and field crops yield benefits.

Planting pits are planting holes dug using the hand hoe as part of the conservation farming system. The soil from the pit is placed at the downstream side of the pit creating a 'damming effect' for retaining the water collected in the pit. Planting pits resemble zaï pits used in West Africa (Anschütz et al., 2003; Shaxson and Barber, 2003; Twomlow et al., 2008). Mupangwa et al. (2012b) used a spacing of 0.9 m × 0.6 m with each planting pit measuring 0.15 m (length) × 0.15 m (width) × 0.15 m (depth). FACHIG, an NGO that has been operating in northern Zimbabwe for more than ten years recommends planting pits measuring 0.20-0.25 m (diameter) and 0.15 m (depth). From 2010/11 through 2012/13 season planting pits were being promoted in Zimbabwe countrywide by the Zimbabwean Conservation Agriculture Task Force (ZCATF) coordinated by the Food and Agriculture Organisation of the United Nations (FAO) Emergency Office in Zimbabwe with various NGOs as implementing partners. This was part of a campaign that started during the 2004/05 season (Twomlow et al., 2008). Planting pits were selected for this study because they are an option for farmers without access to adequate draught power and are a fall-back tillage method in the event of disasters that wipe out livestock as for example the 1991/92 drought and cyclone Eline in 2000.

The rationale for considering planting pits only is that most farmers in Rushinga district only practised conservation agriculture as far as digging planting pits. Therefore, in line with the argument by Giller et al. (2009) that constraints for farmers to adopt all principles of conservation agriculture make it necessary to evaluate the benefits of each principle we decided to study planting pits to mimic farmers' practice.

We combined infiltration pits and planting pits because the techniques complement each other by virtue of their different dimensions and locations (Nyagumbo, 1999). The larger field-edge structures regulate runoff water particularly from heavy storms by slowing it down, partially redirecting it for safe disposal and allowing it to filter into the cropping area in less erosive quantities. Planting pits are located inside the cropping area whilst infiltration pits are constructed along field edges. In West Africa, zaï pits are often combined with stone bunds or grass strips for the same reasons (Anschütz et al., 2003).

The objective of the study was to assess the benefits in terms of, soil moisture and maize yield improvement of combining infiltration pits and planting pits.

4.2 Materials and Methods

4.2.1 Study area

Location and general description

The study was conducted in Rushinga District (16° 40'.000'S; 32° 15'.000E, altitude, 730 m a.s.l.) in Mazowe River valley, Zimbabwe. The area is in Natural Region IV, characterised by rainfall between 450 mm and 650 mm and mean annual temperatures 14.1 ^{0}C minimum and maximum of 28.6 ^{0}C. Rainfall analysis for the period 1980 to 2009 by Nyakudya and Stroosnijder (2011) shows a mean annual rainfall of 631 mm. Rain usually falls between mid-November and end of March. The most cultivated crops are maize, cotton (*Gossypium hirsutum* L.) and groundnuts (*Arachis hypogaea* L.). Other cultivated crops include sorghum (*Sorghum bicolor* L. (Moench)), sunflower (*Helianthus annuus* L.), pearl millet (*Pennisetum glaucum* (L.) R. Br.), and cowpeas (*Vigna unguiculata* (Walp) L.). The soil parent materials in this area are associated with the Zambezi mobile belt and include gneisses, paragneisses and mafic granulites (Anderson et al., 1993). Dolomitic limestone is also prevalent particularly near Rushinga District offices.

Experiments were conducted at three farmers' fields in three villages namely Chongoma in Ward 11 (Mr. Gwaka's field) (16^{0}35'.311S, 31^{0}59'.512E, altitude 912 m a.s.l.), Magaranhewe in Ward 12 (Mrs. Chiropa's field) (16^{0}36'.888S, 32^{0}02'.512E, 1014 m a.s.l.) and Kapitawo in Ward 12 (Mr. Karwizi's field) (16^{0}38'.905, 31^{0}59'.769, altitude 940 m a.s.l.) for three cropping seasons (2010/11, 2011/12 and 2012/13) with the third farmer being added during the second season (Figure 4.1).

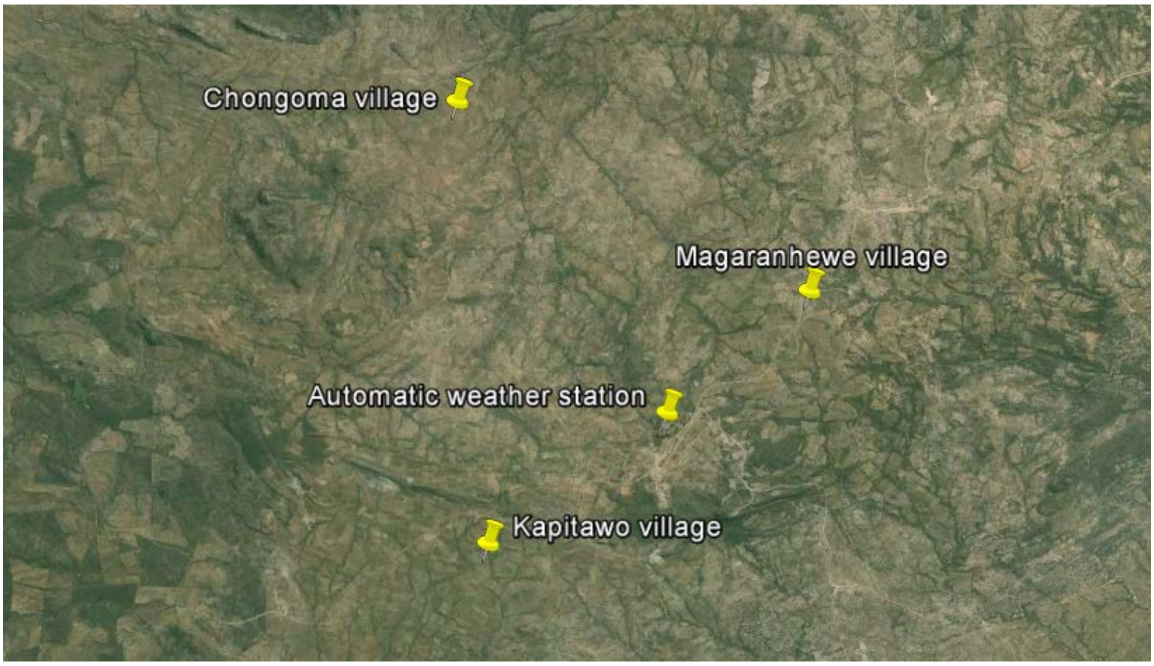


Figure 4.1: Satellite map showing location of experiment sites in Wards 11 and 12 of Rushinga district, Zimbabwe

Selection of experimental sites

Fields with contour ridges on slopes > 4% with potential to generate large quantities of runoff were selected. We hypothesized the need for an impermeable layer below the rootzone for infiltration pits to increase soil water in the maize crop growing area (section 4.1); such hydrogeological conditions are unique, therefore, we opted to study infiltration pits in fields that are not endowed with such physical properties. This makes our results applicable to the majority of farmers and we also complement previous research which we found inconclusive. Sites were chosen from wards within a 10 km radius from Rushinga District Offices ($16^0$37'.899S, $32^0$1'.288, 1045 m a.s.l.) where an automatic meteo-station had been installed (Figure 4.1). At selection obligations of researchers and farmers participating in the field experiments were discussed and agreed upon. We provided inputs for the experiments and assisted the farmers with carrying out field operations particularly reconstruction of contour ridges, and digging of infiltration and planting pits. Farmers contributed labour for the other operations and hosted field days in

February 2011. The field days were meant to provide a platform for evaluating benefits of infiltration and planting pits by farmers, NGOs and policy makers.

Characterisation of experimental sites

Soil samples for determination of soil physical and chemical characteristics were taken at each site at the end of the first season due to time constraints in the first year. Samples for determining texture and bulk density were collected at one representative site in each block at 0.2-m depth intervals up to 1.0 m (Panigrahi and Panda, 2003). Soil depth was determined using soil profile pits and soil colour was determined using the Munsell soil colour chart. Soil physical and chemical analyses were performed using the following standard methods: hydrometer method for particle size distribution, ammonium chloride for exchangeable bases, 0.01 M calcium chloride for pH. Soil bulk density was determined using the core method. Soil saturation capacity, field capacity and wilting poing point were determined using a combination of the sand box method and ceramic pressure plates apparatus.

Field and soil characteristics

All fields were located on the midslope position with 6.0% slope for Chongoma, 6.2% for Magaranhewe and 4.6% for Kapitawo.

Chongoma had medium sandy clay loam soils (mSaCL) (20.1% clay, 6.9% silt, 27.1.% fine sand, 44.1% medium sand and 1.6% coarse sand) underlying medium sandy loam (mSaL) soils (14.0% clay, 6.5% silt, 30.5% fine sand, 47.5% medium sand, 1.5% coarse sand). Magaranhewe had a mSaL topsoil and textural gradient in the crosslope direction from mSaL to mSaCL soil at depth 0.3 to 0.5 m below which uniform mSaCL soil existed but the mean particle size distribution for the site was 16.2% clay, 9.0% silt, 27.8% fine sand, 45.5% medium sand and 1.4% coarse sand. Kapitawo had uniform soil throughout the profile in the fine sandy loam category (15.0% clay, 10.0% silt, 53.2% fine sand, 20.6% medium sand and 1.2% coarse sand). Percentage gravel was 5.2 for Chongoma, 8.0 for Magaranhewe and 5.8 for Kapitawo. Soil profile bulk density ranges (g cm^{-3}) were 1.50 to 1.60 for Chongoma, 1.41 to 1.53 for Magaranhewe, and 1.47 to 1.52 for Kapitawo. Soil available water capacity in the top 0.6 m was 61 mm for Chongoma, 71 mm for Maranhewe and 74 mm for Kapitawo.

Beyond 0.80 m the soil was compacted and more gravelly at Chongoma and Magaranhewe but there was no restrictive layer at this depth at Kapitawo. The mean soil pH was 5.6 for Chongoma, 6.3 for Magaranhewe and 6.1 for Kapitawo. The Ca to Mg ratios were 2:1 for Chongoma, 4:1 for Magaranhewe and 3:1 for Kapitawo.

The soils are classified as chromic luvisols according to Soil Taxonomy and Haplic lixisols (FAO/UNESCO/ISRIC) (Anderson et al., 1993).

4.2.2 Research design and description of treatments

The experiments were laid out in a split-plot design with two factors both at two levels. The main plot factor was the field-edge rainwater management method (RWMM) i.e. contour ridges only (CR) and contour ridges with infiltration pits (IP). The split-plot factor was tillage method which was either conventional tillage (CT) or planting pits (PP). Thus, four treatment combinations were tested: (1) contours ridges with infiltration pits plus conventional tillage (IP+CT); (2) contour ridges with infiltration pits plus planting pits (IP+PP); (3) contour ridges only plus planting pits (CR+PP) and (4) contour ridges only plus conventional tillage (CR+CT).

The experiment was laid out in three blocks giving three replications per treatment. The blocks were 60 m long and approximately 20 m wide. Thus 12 plots, 15 m long and approximately 20 m wide were marked at each experimental site. Blocking was done on the basis of position in the cross slope or down slope direction. In order to create experimental conditions for measurement, treatments were replicated in an upper field at each site (Figure 4.2). No measurements were taken in the upper field. Fields are hydrologically connected (Bouman, 2007), therefore, the same major treatment was applied downslope to minimize interaction between treatments. The novelty of our experimental design is twofold. Firstly by replicating treatments in an upper field where no measurements are taken we were able to clearly define the runoff area (catchment area) for the field-edge RWMM; the runoff area type and size determines the amount of runoff that is generated. Secondly, by combining field-edge RWMM and in-field tillage methods it is possible to study synergy between the methods.

Infiltration pits measuring 1 m wide, 2 m long and 0.75 m deep spaced at 10-m intervals were dug in 2010 in the channels of a contour ridges based on recommendations from a Zaka farmer (Hughes and Venema, 2005). Two farmers had unmaintained standard contour ridges, whilst the other farmer maintained his contour ridges but used smaller dimensions. We therefore used a smaller channel width between 1.20 to 1.30 m relative to 1.70 m for standard contour ridges. Mhizha and Ndiritu (2013) used contour ridges graded at 5%, but we used about 0.4% slope to mimic existing conditions in farmers' fields that are based on standard contour ridges. We designed our experiment to mimic optimum conditions for achieving the attainable yield. Attainable yield is the yield achieved in farmers' fields under best management practices including optimum supply of plant nutrients, timely and effective weed, pests and disease control. Farmers were discouraged from burning crop residues on both treatments by explaining to them benefits of retaining residues. However, crop residue cover was not quantified. Farmers bulked most of the stover in structures close to their homesteads for feeding livestock during the dry season.

Conventional tillage ploughing was done to a depth of 0.20 to 0.23 m and planting furrows were opened at 0.90 m spacing using the mouldboard plough. An in-row spacing of approximately 0.45 m was used. The planting pits were 0.15 m deep and 0.20 m diameter (FACHIG, 2009) spaced at 0.9 m × 0.5 m. A ridge was formed by placing excavated soil from the planting pit immediately downslope of the pit in order to maximise volume of water harvested. For both treatments two seeds were planted per station on planting dates based on the Depth criterion i.e. after receiving at least 40 mm in four days (Raes et al., 2004). The respective target plants ha^{-1} were 49383 for conventional tillage and 44444 for planting pits.

4.2.3 Crop management and measurements

An early maturing (< 125 days from sowing to maturity at 1000 m a.s.l.) white kernel type maize cultivar, SC513 with a yield potential of 2-8 t ha^{-1} (Seed Co, 2004) and recommended for this agroecological region was chosen for the experiments. Maize was selected because it is the staple and an important cash crop.

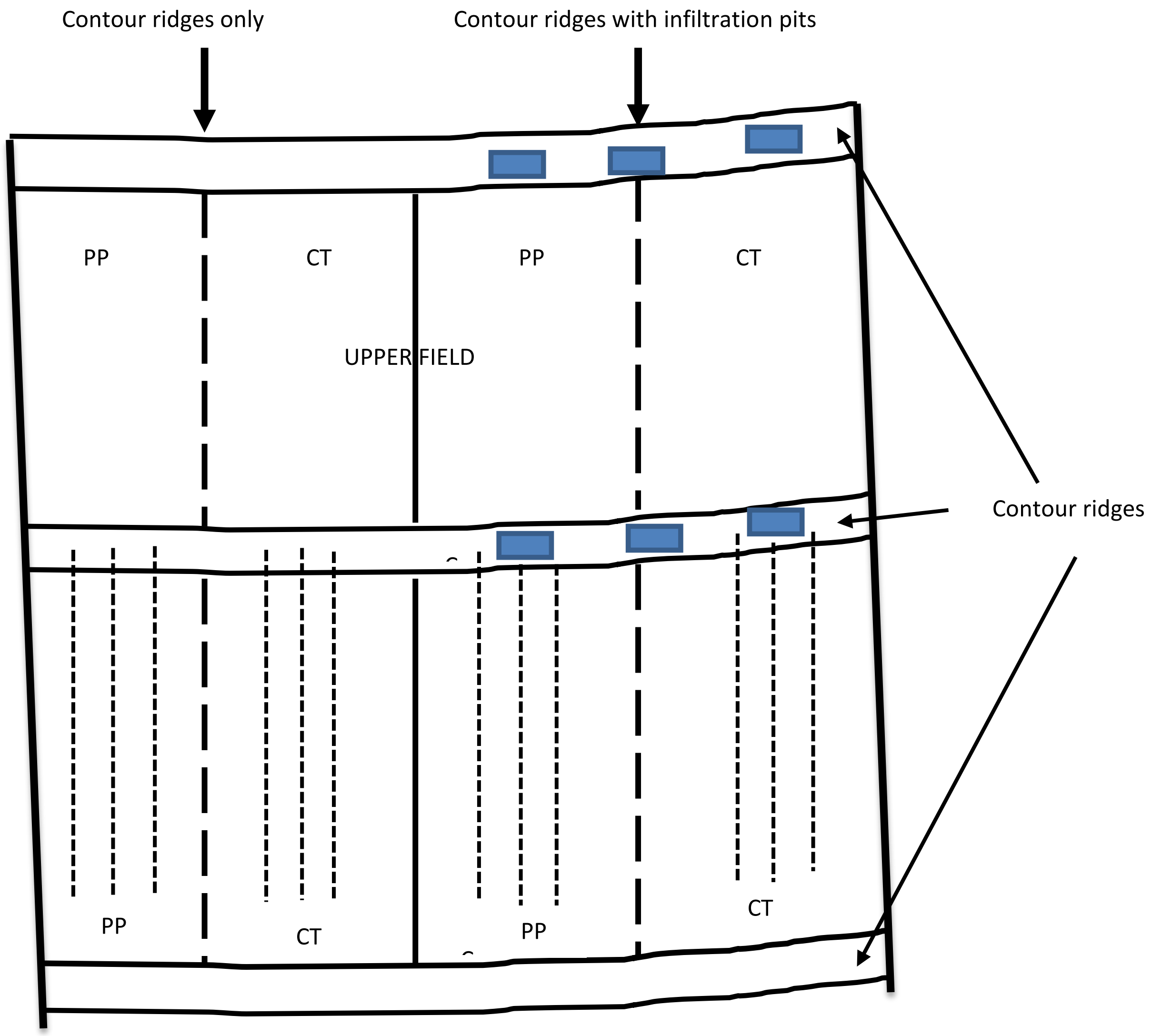


Figure 4.2: Schematic presentation of typical experimental design in a single block at Magaranhewe. Solid vertical lines show main-plot borders, dashed thick vertical lines show split-plot borders within the main- plots; dashed thin lines show transects on which eight access tubes per transect were installed during the 2011/12 and 2012/13 seasons in one block; Filled rectangles represent infiltration pits. (PP stands for planting pit, and CT stand for conventional tillage)

Basal fertilizer was banded below the seed at a rate of 250 kg ha^{-1} Compound D (7% N: 14% P_2O_5:7% K_2O) equivalent to 17.5 kg N ha^{-1}, 15.3 kg P ha^{-1} and 14.5 kg K ha^{-1}. Split application of ammonium nitrate fertilizer (NH_4NO_3) was done at a rate of 77 kg N ha^{-1} in two applications of 33.5 kg N ha^{-1} in order to minimize leaching losses during the wet December to January period. The top dressing fertilizer was spot applied. These application rates were based on recommendations by the Department of Agricultural Technical and Extension Services (Agritex) and they correspond to a yield potential of 3 to 5 t ha^{-1} (Seed Co, 2004). The rates described here are for conventional tillage, planting pits received approximately 25 kg ha^{-1} Compound D and 22 kg ha^{-1}ammonium nitrate less due to the lower plant density because we used the same rate per planting station (section 4.2.2). In the research area mineral and organic fertilizer application rates in farmers' fields varied among farmers and among fields of individual farmers in line with observations by Giller et al. (2006b; Mutambanengwe and Mapfumo, 2005). Two weedings were done, the first within two weeks after emergence and the second within seven weeks after emergence. Plant emergence percentage was determined for the 2012/13 season on 22 December 2012, ten days after the latest plantings when crop emergence was assumed to be complete. This was after realising that germination was a yield limiting factor after poor crop emergence during the second season. Unfortunately for the second season measurements were inadequate for proper statistical analysis, which was an oversight on our part.

Maize was harvested from sub-plots of 10 m × 10 m in the centre of the plot in order to avoid border effects. The mass of grain was measured using a digital balance. Moisture content was measured soon after weighing and the grain weight was adjusted to 12.5% moisture content which is the maximum moisture content recommended for storage by the Grain Marketing Board.

4.2.4 Measurement of climatic data

A compact all-in-one meteo-station for measurement of precipitation, solar radiation, air humidity, temperature, wind speed and direction was set-up at Rushinga district offices for determination of potential evapotranspiration. Additional non-recording rain gauges (pluviometers) were installed at each experimental site in order to have site specific rainfall data.

4.2.5 Installation of access tubes and measurement of soil moisture content

Soil moisture content measurements were done at two sites, Magaranhewe and Chongoma for three seasons 2010/11 through 2012/13. During the 2010/11 season preliminary measurements were done and these were then used to design more detailed measurements in the last two seasons. For Magaranhewe during the 2011/12 season incompatibility between parts of the soil measuring system led to a delay in starting measurements. However, since our focus was on comparing trends in differences in soil moisture storage rather than absolute soil moisture contents the results were considered sufficient.

Thin-wall access tubes for the TRIME-PICO IPH tube probe were installed using the Dutch Edelman soil auger to a depth of 1.4 m where soil depth allowed inside and close to the contour ridge and up to a depth of 0.8 m in the maize crop growing area. Access tubes were only installed in one block at Magaranhewe. During the first season three lines of five tubes each were installed, one line in a section with contour ridges only and two in a section with contour ridges plus infiltration pits. The access tubes were located 0 m, 1 m, 2 m, 11 m and 15.7 m from the centre of the infiltration pit or contour ridge channel. The measuring sections were under conventional tillage. In the second and third seasons, tubes were installed in 12 lines (i.e. three lines per treatment) (Figure 4.2). Eight tubes were installed per line at the following distances (m) downstream from the centre of the contour ridge channel or infiltration pit: 0, 1, 2, 3, 5, 8, 12, and 17. At the first three access tube positions 2 m long tubes were installed and further downstream 0.8 m long access tubes were installed. The first three access tubes were meant to capture moisture content changes at deeper levels close to the RWMM treatment factor whilst tubes further downslope would capture moisture changes within the rootzone of the crop growing area.

Access tubes were numbered using an alphabetical and numerical code based on their distance downstream of the centre of the contour ridge channel or infiltration pit with tubes equidistant from the centre of the contour ridge channel or infiltration pit having the same code. The alphabetical prefix "A" stands for access tube. For example A0 refers to the access tube at the centre of the infiltration pit or contour ridge channel and A12 refers to access tube 12 m downstream from the centre of the infiltration pit or contour ridge channel.

Soil moisture content was measured weekly during the rainy-season using the TRIME-PICO IPH intelligent soil moisture/temperature probe with integrated Time Domain Reflectometry (TDR) electronics at 0.2 m depth intervals up to 1.4 m. During the 2010/11season the TRIME-PICO IPH was used together with a Personal Digital Assistant (PDA) with the software PICO-Talk in combination with the PICO Bluetooth Module. During the final two years the TRIME-PICO IPH was used together with the mobile moisture meter (HD2).

The TRIME-PICO IPH was calibrated using the gravimetric moisture content data for samples taken from within 0.5 m of the access tubes on the same dates (Wiyo et al., 2000). Initially, the gravimetric moisture content data were converted to volumetric moisture content using respective bulk densities for the soil depths. Thereafter TRIME-PICO IPH soil moisture values in the crop growing area (TDR_{field}) were converted to oven-dry calibrated moisture content on a volume basis $\theta v_{\text{(oven dry calibrated)}}$ prior to data analyses using regression equation: $\theta v_{\text{(oven dry calibrated)}} = 1.287 \times TDR_{field} - 3.869$ ($R^2 = 0.724$; $P < 0.001$). TRIME-PICO IPH consistently underestimated soil moisture values although at lower values the model depicts some overestimation. The R^2 of 0.724 is acceptable, Wiyo et al. (2000) obtained $R^2 = 0.69$. Calibration was only done for measuring points within the cropping area where corresponding bulk densities were available. The contour ridge areas are often relatively undisturbed compared to the cropping area, therefore bulk densities for the two areas differ.

Within the cropping area, a few very low TDR soil moisture content values ≤ 6% were discarded as they fell outside the range of data used for calibration. In addition at low moisture content values the calibration regression model showed that TDR overestimated soil moisture content and yet in practice presence of stones in the soil profile may actually lead to lower TDR values.

At Chongoma the gravimetric method for determining soil moisture content was used. Although access tubes were not used at this site we maintained the nomenclature of the measuring positions for consistency. During the 2010/11 season soil moisture measurements were conducted at similar positions to Magaranhewe village but for a uniform depth of 0.0-0.8 m. Soil moisture measurements were conducted in the cropping area of all plots for the top 0.2 m during the 2011/12 season and from 0.0 to 0.4 m in all plots of a single block during the 2012/13 season. The 0.4 m depth covers the effective rooting zone for maize under local conditions. Vogel (1993) observed good maize growth in places where the bulk roots grew to 0.3 m with a few roots penetrating to 0.4 m depth. Soil moisture content was determined at 4.5 and 9 m downslope from the centre of the infiltration pit or contour ridge channel at an interval of 7 to 10 days throughout the cropping season. The first measuring position A4.5 is in the first quarter of the field and A9 is at the centre of the field.

4.2.6 Household survey and observation of existing rainwater management structures

In order to gain insight into famers' perceptions about rainwater management and to establish typology and availability of field-edge rainwater management structures, a household questionnaire survey coupled with field observations of existing field-edge rainwater management methods was conducted within a 20-km radius of the experimental sites. Eighty-four (84) respondents were randomly selected from a sampling frame of crop growing households. Field observations were done concurrently with face-to face interviews with the selected farmers. Dimensions of rainwater management structures were measured using a measuring tape. In addition farmers hosted field days in February 2011.

4.2.7 Statistical analysis

All statistical analyses were done using SPSS for Windows Version 19.0 after preliminary data processing using Microsoft Excel 2010.

Graphic trends analysis was done for soil moisture data. For Magaranhewe at A0 to A3 (outside the cropping area) the independent samples t-test was used to compare means of the two RWMM. Inside the cropping area (A5 to A17) analysis of variance was applied. For Chongoma the General Linear Models two-factor split-plot anova was used for the second year data that was collected from all plots in the field. The design of the two-factor split-plot anova model was: intercept + main plot factor + block(main plot factor) + split-plot factor + main plot factor × plit-plot factor. For the other years the independent samples t-test and analysis of variance were used.

Germination percentage, maize grain and stover yield were analysed using the General Linear Models two-factor split-plot anova. Percentage germination values were log-transformed in order to convert the percentages into interval data prior to analysis.

Levene's test of homogeineity of error variances across sites and years was used to determine if results from individual sites and years could be pooled into combined analyses.

Reference evapotranspiration was calculated from the climate data using the ET_o Calculator (Raes, 2009).

Data from household surveys and field observations were analyzed using descriptive statistics.

4.3 Results

4.3.1 Seasonal rainfall and reference evapotranspiration (ET_o)

Seasonal (November to March) rainfall totals (mm) in the order 2010/11, 2011/12 and 2012/13 were: meteo-station (Rushinga district offices) (615, 634, and 745); Chongoma (545, 778 and 516); Magaranhewe (861, 916, and 767); and Kapitawo (..., 670, 621). The November to March cumulative ET_o was 600 mm for 2011/12 and 544 mm for 2012/13. Cumulative ET_o for 2010/11 is not presented because measurements only started on 20 November 2010. Despite the short distances between sites there are differences in elevation (Figure 4.2) that results in differences in rainfall (Figure 4.2). Magaranhewe and Rushinga district offices are only 2.8 km apart but they have an elevation difference of 31 m. The largest difference in elevation between field experimental sites is 102 m between Magaranhewe and Chongoma within a distance of 6.0 km. Rainfall in the area normally comes from the north east; therefore lower sites are in a rain shadow area. Although the weather station was located on a ridge it was on the south-west facing side of the ridge which is part of the rain shadow area. There was no rainfall in April at all sites throughout the study period and only a few mm in October 2010. The 10% probability of exceedance (wet year) and the 90% probability of exceedance seasonal rainfall totals are 858 mm and 402 mm respectively (Nyakudya and Stroosnijder, 2011). Therefore, Chongoma and Kapitawo had normal rainfall (456-857 mm) during the duration of the experiments but Magaranhewe had wet seasons in 2010/11 and 2011/12.

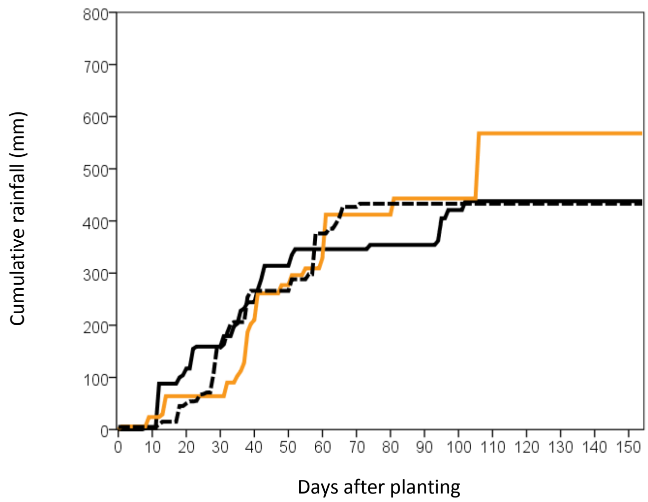
A common feature during the duration of field experiments was the occurrence of large single-day rainfall events that make it imperative to construct large structures for storm water control at field edges. In most cases these large rainfall events occur early in the season and coincide with the initial development stages of the maize crop and hence they do not benefit the crop much and generate a lot of surface runoff or they occur at the end of the season when the crop has either matured or dried prematurely. The largest single-day rainfall events were:

(1) 2010/11 season: 86 mm, 85 mm and 138 mm on the 24th of November, 19th and 21st of December 2010 for Rushinga district offices, Chongoma, and Magaranhewe respectively;

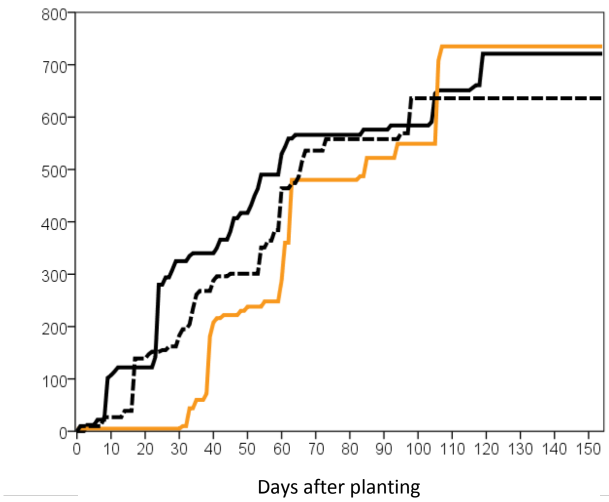
(2) 2011/12 season: 136 mm on 14 December 2011 for Chongoma, 78 mm on 15 February 2012 for Kapitawo and 83 mm and 136 mm at Rushinga district offices, and Magaranhewe respectively on 30 March 2012; and

(3) 2012/13 season: 100 mm (twice) on 10 and 28 December 2012 for Magaranhewe, 87 mm for Rushinga district offices and Kapitawo on 10 December 2012, and 78 mm on 10 February 2013 at Chongoma.

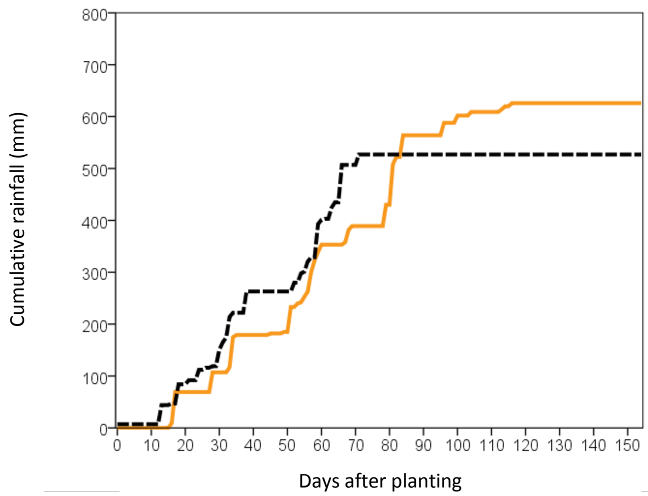
The highest rainfall intensity recorded at the meteo-station was 46 mm h^{-1} with four other storms recording intensities > 40 mm h^{-1} during the duration of the experiments.



(a) Chongoma village



(b) Magaranhewe village



(c) Kapitawo village

Figure 4.3: Seasonal rainfall distribution at experimental sites in Rushinga district, Zimbabwe for 2010/11 (solid black line), 2011/12 (solid light line) and 2012/13 (black dotted line). Planting dates : 2010/11 season: Chongoma, 7 Dec 2010, Magaranhewe, 27 Nov 2010; 2011/12 season: Chongoma and Magaranhewe, 15 Dec 2011, Kapitawo, 26 Nov 2011; 2012/13 season: Chongoma and Kapitawo 12 Dec 2012, Magaranhewe 11 Dec 2012

4.3.2 Soil moisture content

In this section soil moisture results are presented as seasonal averages in Tables 4.1 through 4.3, and means of measured values at specific points in time in Figures 4.4 through 4.6.

Soil moisture content close to the contour ridge channel

At Chongoma, during the 2010/11 season for A1 and A2 contour ridges with infiltration pits had higher ($P < 0.05$) soil moisture content than contour ridges only (Table 4.1). Similarly at Magaranhewe during the 2010/11 season for A0 to A2 contour ridges with infiltration pits consistently had higher ($P < 0.001$) soil moisture content than contour ridges only (Table 4.1). However, at A2 we noted influence of stones in the soil profile that reduced soil moisture content values from 0.4 m downwards for both treatments but the effect was more pronounced in the section with contour ridges only. We also noted that that roots of an annual herbaceous plant that grew close to A1 reduced soil moisture content from 63 to 92 days after planting.

At Magaranhewe contour ridges only had higher ($P < 0.001$) soil moisture content than contour ridges with infiltration pits from A0 to A3 (Table 4.1) for the 2011/12 season. For 2012/13 season the contour ridges with infiltration pits had higher ($P = 0.001$) soil moisture content than contour ridges only from A0 to A2 (Table 4.1, Figure 4.4). Further away from the RWMM structures (at A3) treatments did not differ ($P = 0.914$) in performance.

Soil moisture content inside the crop growing area

At Chongoma for the 2010/11 season, at A11 and A15.7 there were no differences ($P > 0.05$) in soil moisture content between contour ridges only and contour ridges with infiltration pits (Table 2).

During the 2011/12 and the 2012/13 season there were no differences ($P > 0.05$) between both RWMM treatments and tillage methods treatments (Table 4.2; Figure 4.5). There were also no interactions ($P < 0.05$) between RWMM and tillage treatments.

At Magaranhewe for the 2010/11 season, contour ridges only had higher ($P < 0.05$) soil moisture content than contour ridges with infiltration pits (Table 4.3). However, during this season the section with contour ridges only was not replicated laterally, therefore, we attributed the unexpected results to experimental error.

During the 2011/12 season contour ridges only had higher ($P < 0.001$) soil moisture content than contour ridges with infiltration pits (Table 4.3). Tillage treatments performances were different ($P \leq 0.001$) at A8 through to A17 but there was no consistent trend (Table 4.3, Figure 4.6). Interactions between RWMM and the tillage treatments occurred at the furthest positions from the centre of infiltration pit or contour ridge channel ($P = 0.054$) at A12 and ($P < 0.001$) at A17.

During the 2012/13 season there were no differences ($P > 0.05$) between RWMM except for A5 where contour ridges only had higher ($P < 0.001$) soil moisture content than contour ridges with infiltration pits (Table 4.3). For the tillage methods there was no consistent trend in soil moisture content (Table 4.3). However, planting pits had higher ($P < 0.001$) soil moisture content than conventional tillage at A5 and A17 sandwiching A8 and A12 where there were no differences ($P > 0.05$) in soil moisture content. Except for position A12 there were interactions ($P < 0.05$) between RWMM and tillage treatments.

Table 4.1: Mean (SD) soil profile volumetric moisture content (%) close to the infiltration pit or contour ridge channel for contour ridges with infiltration pits (IP) and contour ridges only (CR) from the 2010/11 through 2012/13 season, at Chongoma and Magaranhewe, Rushinga district Zimbabwe

[a]Site	[b]A	Depth (m)	2010/11 season					2011/12 season					2012/13 season				
			Soil moisture content		df	t-statistic	p-value	Soil moisture content		df	t-statistic	p-value	Soil moisture content		df	t-statistic	p-value
			IP	CR				IP	CR				IP	CR			
Chongo	A1	0.0-0.8	25.10 (7.09)	19.28 (5.56)	30	2.57	0.016	n/m	n/m				n/m	n/m			
	A2	0.0-0.8	18.48 (6.00)	13.20 (5.08)	25	2.430	0.023	n/m	n/m				n/m	n/m			
Maga	A0	0.0-1.4	22.23 (10.87)	12.18 (3.30)	151	9.03	0.000	12.42 (5.51)	18. 65 (5.81)	598	-13.49	0.000	25.20 (6.228)	21.21 (3.95)	506	8.79	0.000
	A1	0.0-1.4	16.64 (4.67)	14.75 (5.39)	270	3.71	0.000	11.94 (5.43)	13.72 (7.21)	621	-3.63	0.000	20.93 (5.57)	18.42 (5.46)	636	5.73	0.000
	A2	0.0-1.4	13.54 (5.32)	9.14 (5.23)	464	8.42	0.000	10.63 (4.01)	14.45 (6.40)	490	-8.67	0.000	20.04 (5.34)	18.34 (4.74)	527	3.89	0.000
	A3	0.0-0.8	n/m	n/m				13.71 (3.48)	17.68 (5.52)	322	-8.34	0.000	20.56 (3.74)	20.51 (4.58)	393	0.11	0.914

[a]Chongo stands for Chongoma, Maga stands for Magaranhewe

[b] A1, A2 ... refer to measuring positions and the numerical code gives the distance (m) from the centre of the infiltration pit or contour ridge channel.

n/m stands for “not measured”

At Chongoma measurements were not taken at A0 because it was not possible to auger when there was in the pit.

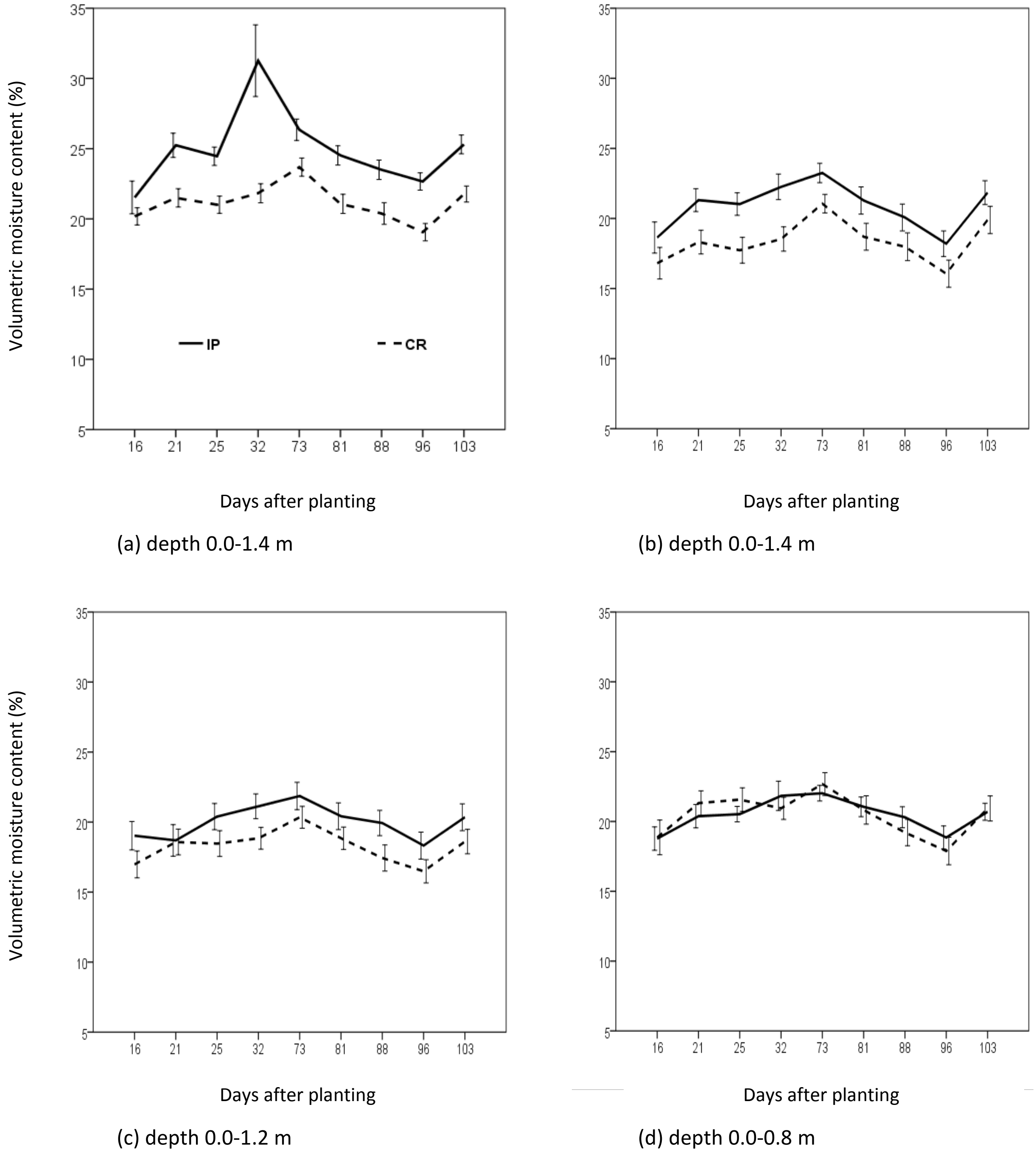


Figure 4.4.: Mean soil moisture content under contour ridges with infiltration pits (IP) and contour ridges only (CR) at (a) 0 m, (b) 1 m, (c) 2 m and (d) 3 m from the centre of the infiltration pit or contour ridge channel during the 2012/13 season at Magaranhewe in Rushinga district, Zimbabwe. (Error bars represent standard deviation)

Table 4.2: Mean (SD) soil profile volumetric moisture content (%) in the crop growing area under rainwater management methods (RWMM) namely contour ridges with infiltration pits (IP) and contour ridges only (CR)) and tillage methods (conventional tillage (CT) and planting pits (PP)) for the 2010/11 season (depth 0.0-0.8 m), 2011/12 (depth 0.0–0.2 m) and 2012/13 season (depth 0.0 – 0.40 m) at Chongoma in Rushinga district, Zimbabwe

Season	**[a]Measuring position**	**Soil moisture content**				**RWMM**			**Tillage method**			**RWMM x Tillage method**		
		IP	CR	CT	PP	df	F-/t-statistic	P-value	df	F-statistic	P-value	df	F-statistic	P-value
2010/11	A11	20.04 (5.93)	20.13 (5.28)			33	-0.48	0.962						
	A15.7	21.79 (4.08)	21.07 (5.00)			34	0.48	0.635						
2011/12	A4.5	17.77 (7.63)	17.70 (7.44)	18.61 (7.71)	16.85 (7.26)	1	0.01	0.946	1	1.66	0.201	1	0.70	0.405
	A9	13.67 (6.36)	14.20 (6.17)	14.32 (6.36)	13.55 (6.17)	1	0.31	0.610	1	0.45	0.505	1	0.580	0.448
2012/13	A4.5	18.59 (4.70)	18.41 (4.49)	19.16 (4.72)	17.30 (4.09)	1	0.07	0.798	1	3.38	0.068	1	1.547	0.215
	A9	17.07 (6.14)	16.92 (4.53)	16.21 (4.95)	17.78 (5.71)	1	0.03	0.864	1	3.46	0.065	1	0.52	0.474

[a]A11, A15.7, A4.5 and A9 m refer to 11 m, 15.7 m, 4.5 m and 9 m from the centre of the infiltration pit or contour ridge channel respectively.

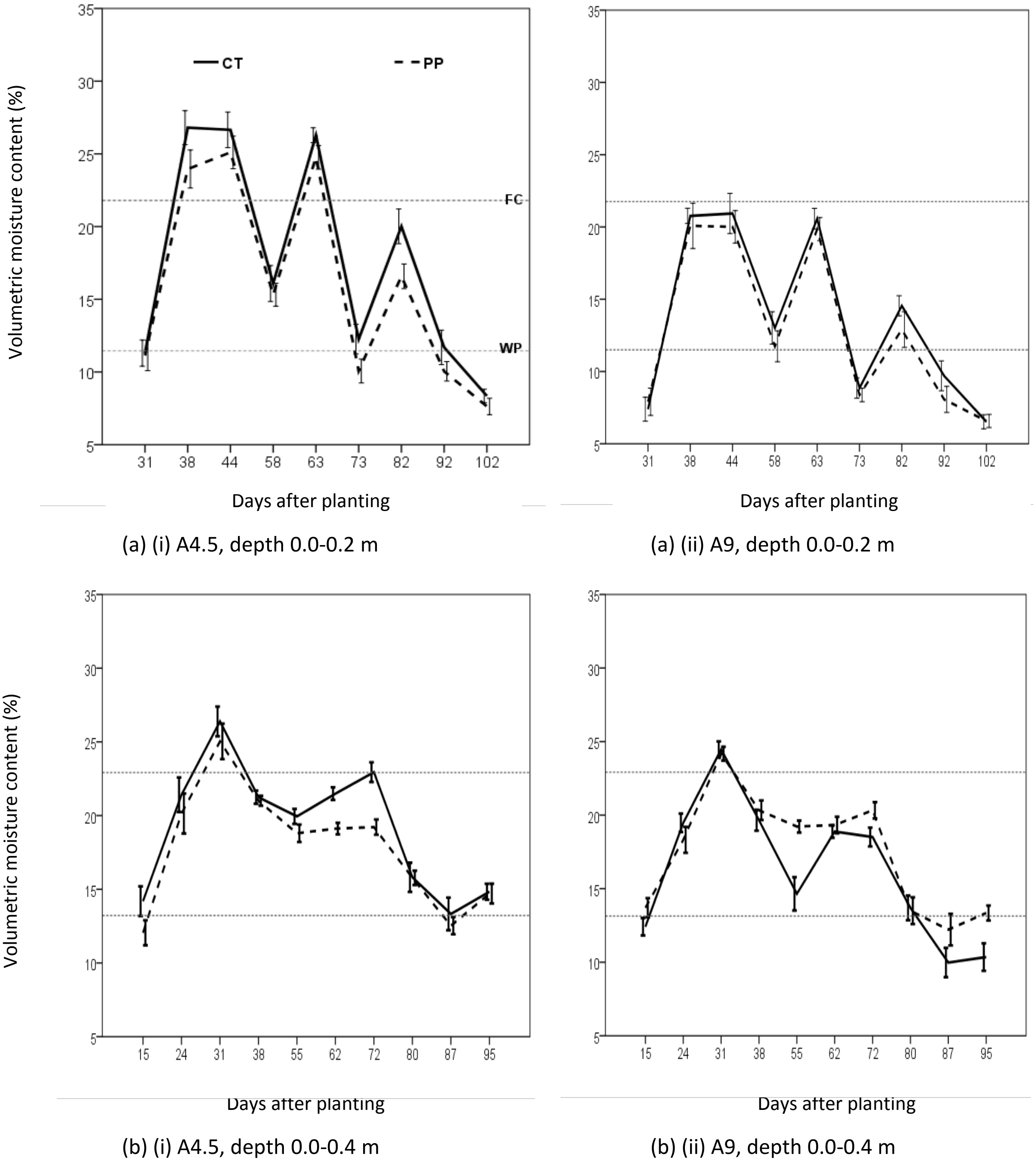


Figure 4.5: Mean soil moisture content under conventional tillage (CT) and planting pits (PP) at 4.5 m (A4.5) and 9 m (A9) from the centre of the infiltration pit or contour ridge channel (a) 2011/12 season and (b) 2012/13 season at Chongoma in Rushinga district, Zimbabwe. (FC, moisture content at field capacity, WP, moisture content at permanent wilting point). (Error bars represent standard deviations)

Table 4.3: Mean (SD) soil profile moisture content (%) within the crop growing area under rainwater management methods (RWMMM) namely, contour ridges with infiltration pits (IP) and contour ridges only (CR) and tillage methods (conventional tillage (CT) and planting pits (PP)) from the 2010/11 through 2012/13 season for A5 to A17 at depths 0.0 to 0.8 m at Magaranhewe in Rushinga district, Zimbabwe

Season	Measuring position[a]	Soil moisture content				RWMM			Tillage method			RWMM x Tillage method		
		IP	CR	CT	PP	df	F-/t-statistic	P-value	df	F-statistic	P-value	df	F-statistic	P-value
2010/11	A11	18.37 (6.13)	21.04 (6.97)			159	-3.02	0.003						
	A15.7	20.18 (7.13)	23.72 (5.75)			210	-4.37	0.000						
2011/12	A5	11.33 (3.59)	20.34 (4.69)	16.37 (6.13)	15.58 (6.17)	1	430.97	0.000	1	1.76	0.186	1	3.48	0.063
	A8	11.66 (3.39)	19.76 (4.99)	16.01 (6.13)	15.13 (5.58)	1	377.91	0.000	1	11.16	0.001	1	0.057	0.811
	A12	14.39 (4.60)	19.07 (4.96)	17.32 (5.40)	16.08 (5.18)	1	100.49	0.000	1	11.71	0.001	1	3.74	0.054
	A17	15.43 (6.48)	20.47 (6.75)	16.42 (5.62)	19.26 (7.73)	1	44.36	0.000	1	17.37	0.000	1	17.53	0.000
2012/13	A5	20.12 (6.07)	22.58 (5.29)	19.75 (6.35)	22.97 (4.71)	1	23.28	0.000	1	40.82	0.000	1	62.79	0.000
	A8	21.62 (4.88)	21.57 (5.66)	21.98 (5.76)	21.22 (4.73)	1	0.01	0.926	1	2.28	0.132	1	11.82	0.001
	A12	20.47 (5.51)	19.76 (4.31)	20.04 (5.10)	20.20 (4.81)	1	2.14	0.144	1	0.11	0.740	1	0.00	0.997
	A17	21.70 (4.94)	21.48 (5.62)	19.83 (4.88)	23.43 (5.05)	1	0.039	0.843	1	55.46	0.000	1	9.69	0.002

[a]A11, A15.7,... refer to measuring positions and the numerical code gives the distance (m) from the centre of the infiltration pit or contour ridge channel.

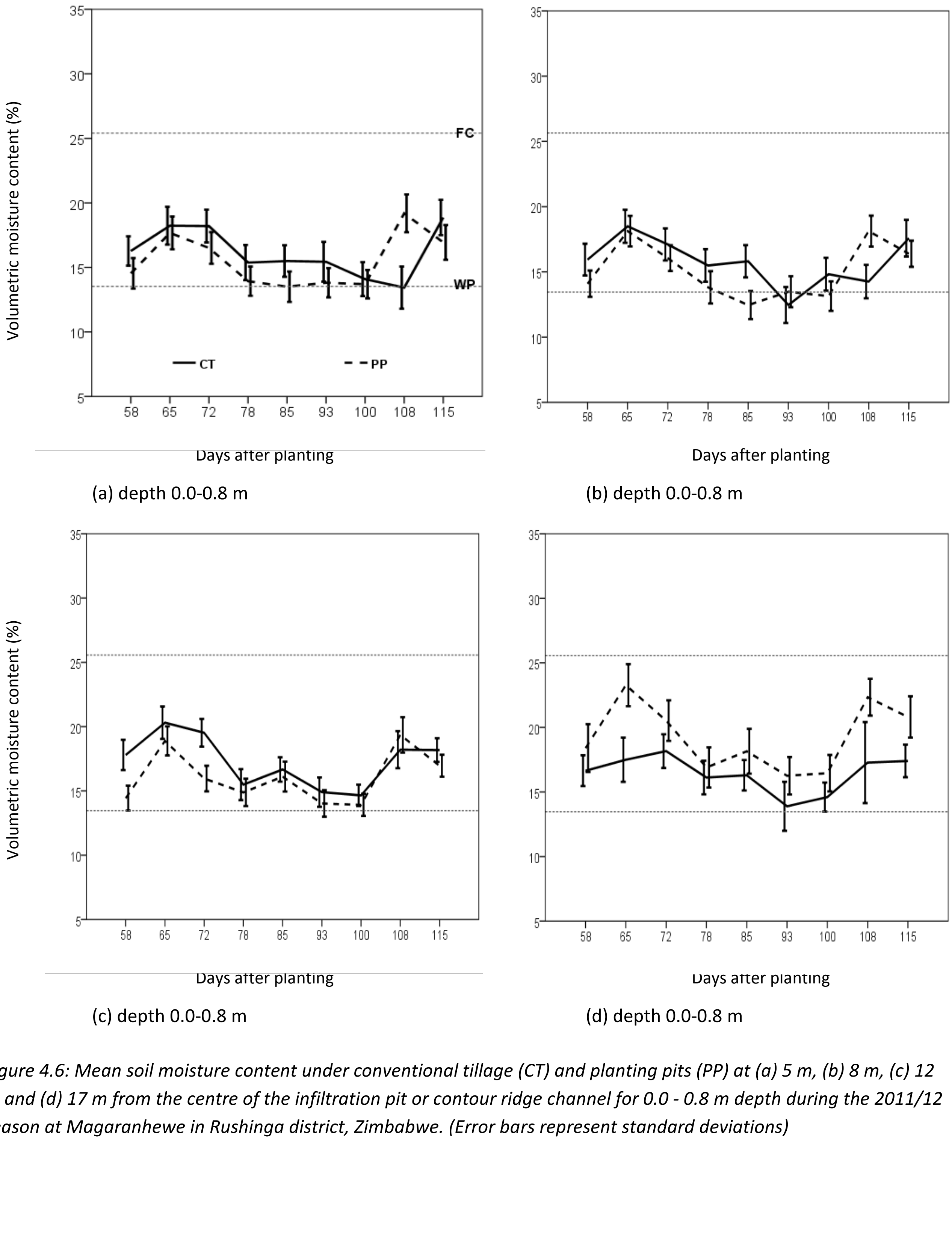


Figure 4.6: Mean soil moisture content under conventional tillage (CT) and planting pits (PP) at (a) 5 m, (b) 8 m, (c) 12 m and (d) 17 m from the centre of the infiltration pit or contour ridge channel for 0.0 - 0.8 m depth during the 2011/12 season at Magaranhewe in Rushinga district, Zimbabwe. (Error bars represent standard deviations)

4.3.3 *Maize yield response to infiltration pits and planting pits*

There was heterogeneity (P < 0.05) of error variances across years and sites hence the data from individual years and sites were not pooled into combined statistical analyses.

Infiltration pits

There was no difference (P > 0.05) in germination percentage between plots with contour ridges with infiltration pits and those with contour ridges only at all sites for the 2012/13 season (Table 4.4). Similarly for the entire duration of the field experiments 2010/11 through to 2012/13 season RWMM produced similar (P > 0.05) grain yields and stover yields (Table 4.5) at all sites. There was no interaction (P > 0.05) between the treatment factors.

Planting pits

During the 2012/13 season, planting pits had higher emergence percentage than conventional tillage at Magaranhewe (P = 0.01) and Kapitawo (P = 0.005). For Chongoma CT = PP, P = 0.070. Plant densities (plants ha^{-1}) based on emergence percentage starting with conventional tillage in each case were: Chongoma (27753; 22400); Magaranhewe (32593; 33911) and Kapitawo (31556; 32133) (refer to section 4.2.3 for target population).

At Chongoma for the entire duration of the field experiments 2010/11 through to 2012/13 season conventional tillage (P < 0.05) outyielded planting pits (Table 4.5). At Magaranhewe conventional tillage produced more (P = 0.021) grain than planting pits in one (2011/12) of the three seasons. For stover yields, conventional tillage outyielded planting pits during the 2010/11 (P = 0.009) and 2012/13 (P = 0.016) seasons. For Kapitawo tillage treatment yields did not differ (P = 0.330 for grain yield and P = 0.260 for stover yield) during the 2011/12 season. During the 2012/13 season conventional tillage produced more grain (P = 0.037) and more stover (P = 0.021) than planting pits. For all sites and cropping seasons grain yield was 45% higher for conventional tillage (mean 2697 kg ha^{-1}) than planting pits (mean 1852 kg ha^{-1}) (Table 4.5). However, conventional tillage/planting pits grain yield ratio decreased in the order 1.9 for 2010/11 > 1.7 for 2011/12 > 1.3 for 2012/13.

Table 4.4: Maize emergence percentage for the 2012/13 season and rainfall ≤ 3 days prior to planting at Chongoma, Magaranhewe and Kapitawo in Rushinga district, Zimbabwe

Tillage method	**Field-edge rainwater management method (RWMM)**								
	Chongoma (66 mm)			Magaranhewe (80 mm)			Kapitawo (92 mm)		
	IP	CR	Mean (SE)	IP	CR	Mean (SE)	IP	CR	Mean (SE)
CT	63.9	58.3	60.2 (3.0)	66.9	65.2	66.0 (2.5)	62.6	65.2	63.9 (2.0)
PP	48.3	52.6	50.4 (2.5)	78.7	73.9	76.3 (2.5)	71.3	73.3	72.3 (2.0)
Mean (SE)	54.5 (3.0)	55.8 (2.4)	55.3 (2.0)	72.8 (1.9)	69.6 (1.8)	71.2 (1.3)	67.0 (2.0)	69.3 (2.0)	68.1 (1.4)

Where IP, CR, CT and PP stands for contour ridges with infiltration pits, contour ridges only, conventional tillage and planting pits.

Table 4.5: [c]Mean (SE) maize grain and stover yields (kg ha^{-1}) under conventional tillage and planting pits, planting dates, and total rainfall for 2010/11, 2011/12 and 2012/13 seasons at Chongoma, Magaranhewe and Kapitawo in Rushinga district, Zimbabwe

Site	Season/Planting date	Rainfall (mm)	Tillage method	Grain	Stover
Chongoma	2010/11	545	Conventional	1438(68)^{a}	4933 (117)^{a}
	7 Dec 2010		Planting pits	873(68)^{b}	3567 (117)^{b}
			Mean (SE)	1156 (48)	4250 (82)
			SE (RWMM x Tillage)	97	165
	2011/12	778	Conventional	2581(172)^{a}	5867 (168)^{a}
	15 Dec 2011		Planting pits	723(172)^{b}	2617 (168)^{b}
			Mean (SE)	1652(122)	4242 (118)
			SE (RWMM x Tillage)	243	238
	2012/2013	516	Conventional	3292 (274)^{a}	5998 (221)^{a}
	12 Dec 2012		Planting pits	1729 (274)^{b}	4041 (221)^{b}
			Mean (SE)	2511 (194)	5019 (156)
			SE (RWMM x Tillage)	388	312
Magaranhewe	2010/11	861	Conventional	2148 (304)^{a}	4733 (313)^{a}
	27 Nov 2010		Planting pits	1024 (304)^{a}	2633 (313)^{b}
			Mean (SE)	1586 (213)	3683 (221)
			SE (RWMM x Tillage)	429	442
	2011/12	916	Conventional	2174(131)^{a}	4275 (626)^{a}
	15 Dec 2011		Planting pits	1484 (131)^{b}	2917 (626)^{a}
			Mean (SE)	1829(92)	3596 (442)
			SE (RWMM x Tillage)	185	886
	2012/2013	767	Conventional	4747 (212)^{a}	6363(150)^{a}
	11 Dec 2012		Planting pits	4531 (212)^{a}	5515 (150)^{b}
			Mean (SE)	4639 (150)	5939 (106)
			SE (RWMM x Tillage)	300	212
Kapitawo	2011/12	670	Conventional	2237(171)^{a}	4867 (270)^{a}
	26 Nov 2011		Planting pits	1969(121)^{a}	4367 (270)^{a}
			Mean (SE)	2103(121)	4617 (191)
			SE (RWMM x Tillage)	241	382
	2012/13	621	Conventional	2960 (109)^{a}	4882 (160)^{a}
	12 Dec 2012		Planting pits	2485 (109)^{b}	4042 (160)^{b}
			Mean (SE)	2723 (77)	4462 (113)
			SE (RWMM x Tillage)	154	226

[c]Treatments with common superscripts within a single site and season have similar mean yields ($P < 0.05$). Treatments with different superscripts within a single site and season have different mean yields ($P < 0.05$).

4.3.4 Effect of rainfall distribution on maize yields

There was poor rainfall distribution particularly from February to the end of season and early cessation of rains. This period coincided with the critical reproductive and grain filling period for the maize crop. For example for Chongoma and Magaranhewe during the 2010/11 season there was inadequate rainfall in February (Figure 4.3).

In the 2011/12 season similar patterns were observed for Chongoma and Kapitawo where at Chongoma a 21-day dry spell from 15 February to 5 March occurred during the maize grain filling period. This was interrupted by 31 mm on 5 March and followed by a 24-day dry spell. Consequently the maize crop dried prematurely and 125 mm that fell on 30 March did not benefit the crop (Figures 4.3 and 4.5). At

Kapitawo there was a 13-day dry spell from 19 to 31 February and only 62 mm of rainfall against ET_o of 107 mm during March (Figure 4.2) when the maize crop was at the grain filling stage.

The 2012/13 season had short crop growth periods with rainfall, 92 days for Chongoma and 72 days for Kapitawo. The maize cultivar SC513 requires at least 115 days to mature in this agroecological region. As depicted in the soil moisture trends graphs (Figure 4.5) a period of inadequate soil moisture ensued at Chongoma. Soil moisture content fell below wilting point 92 days after planting and the crop dried prematurely.

4.3.5 Effect of weeds

Witch weed (*Striga* spp.) was observed at all sites but its effects were most severe at Magaranhewe. The weed affected both conventional tillage and planting pits plots. After the first season the block that was mainly affected by the *Striga* spp. was abandoned and a new block was created at Magaranhewe.

At all sites planting pits coped less well with high weed infestation and this reduced yield in the planting pits plots. The weed pressure was particularly high during the first two seasons.

4.3.6 Farmers' perceptions, availability and typology of field-edge rainwater management methods (RWMM)

Most farmers (67.9%) were of the opinion that contour ridges are beneficial for erosion control and water retention (36.9%). A few farmers complained that contour ridges create water logging conditions (1.2%), increase gulley erosion (1.2%), and they take up productive land (2.4%). Although farmers generally revealed the usefulness of contour ridges, some reported that the contour ridges were not pegged by specialists hence the need for re-pegging (27.4%).

Most households (92.9%) had contour ridges or their modifications in their fields. A few new constructions of contour ridges (5.1%) were observed. There was no maintenance of contour ridges but repair efforts were observed.

Different types of conservation structures were observed ranging from non-tillage structures including stone lines (23%) and grass terraces strips (18%), to contour ridges with different dimensions (62%). Only 20 structures had the standard width of contour ridges (3.4 m), the mean width of non-standard structures was 1.70 m and the mean depth was 0.20 m. The most commonly occurring structures were ridges with channel followed by stone lines. The different structures also existed as combinations on farmers' fields.

4.3.7 Infiltration pits for storm water control

Host farmers of field experiments reported that they observed reduced runoff losses and as a result reduced soil erosion at the points of discharge to the water ways. We also observed zero contour ridge breakages in our experimental fields compared to the multiple breakages in neighboring farmers' fields and in untreated fields of the host farmers especially during the heavy storms.

4.4 Discussion

4.4.1 Effect of land slope, soil properties, plants, and human activities on soil moisture

Observed field slopes between 4.6 and 6.2% are in the order of magnitude of the recommended 5% for RWH techniques by Siegert (1994). Fu and Gulinck (1994) classified these slopes under low erosion risk, but soil erosion can be severe and limit crop yields especially in semi-arid areas where rainfall often comes as high intensity storms. For our sites over the study period the largest single-day rainfall events ranged from 78 mm to 138 mm and the highest intensity was 46 mm h^{-1}. On sloping land, water and eroded sediments collect at the furthest distances downstream of infiltration pits creating a soil moisture and fertility gradient. Similar gradients exist in the cross slope direction. Depressions in the lower parts are filled with sediment, thus creating local differences that affect soil moisture content results.

Typical effects of textural differences were observed at Magaranhewe village during the 2010/11 season where a section with contour ridges only had higher soil moisture content than a section with contour ridges with infiltration pits. The soil texture in the subsoil was heavier in the section with contour ridges only. Whilst this may be viewed as an error in the design, it is also important in that it indicates the importance of linking soil moisture content measurements with soil physical properties. From this study the fallacy of making wrong conclusions from soil moisture content measurements is made apparent. If this section had coincided with the section with contour ridges with infiltration pits there is a possibility that an unassuming researcher would attribute the moisture content increase to infiltration pits. In order to minimize the influence of soil texture during the third season we randomised treatments in the last two plots thus reducing the experimental area from a 60 m long block to 30 m.

An annual herbaceous plant that grew close to A1 in the section with contour ridges only reduced soil moisture content from 63 to 92 days after planting during the 2010/11 season. This position was on the ridge where the effect of the infiltration pit in the top 0.4 m may be negligible. If the effect of the herbaceous plant is removed the difference in moisture content between the two RWMM is reduced. Previous soil manipulations may also influence soil moisture content results.

In addition there are also instrument limitations to consider. The TRIME-PICO IPH access probe measures soil moisture content within a radius of ± 6 cm (IMKO, 2010) compared to the neutron probe with a measuring radius of 15 to 18 cm (Shiraz and Isobe, 1976). The relatively low measuring volume of the TRIME-PICO IPH access probe renders measurements prone to interference with gravel and stones in the soil profile resulting in lower moisture values. The effect of gravel and stones in reducing TDR moisture content values is twofold. Firstly stones and gravel do not absorb water and secondly stones and gravel create air gaps between the access tube and soil. For example at 15% water content an air gap of 1 mm around the whole length of the tube would result in an underestimation of 1-2% and this increases to an error of 5% at 25% moisture content (IMKO, 2010). Predictably, the TRIME-PICO IPH also underestimated soil moisture values in this study. In order to correct for instrument-related errors we calibrated in-field measurements using soil moisture data obtained using the gravimetric method.

Due to many possible sources of error, soil moisture studies need to be adequately replicated in order to minimize erroneous conclusions.

4.4.2 Infiltration pits

Results from this study indicate that the effect of infiltration pits on soil moisture content is minimal being experienced up to only 2 m downstream from the centre of the infiltration pit or contour ridge channel. Mugabe (2004) reported a distance of 11.9 m both upstream and downstream with most benefits being experienced at 3.4 m on sandy loam soils in fields with 2% slope during a season with 625 mm rainfall. Our findings are closer to observations by Mupangwa et al. (2012a) who reported increase in soil moisture due to infiltration pits in dead level contours 2 m upstream and 3 m downstream from the centre of infiltration pits on sandy to loamy sand soils in fields with 1% slope for seasonal rainfall < 300 mm. Probably Mugabe (2004) worked a site with an impermeable layer that restricted downward and enhanced lateral flow of water as explained in section 4.1.

At the bottom of the infiltration pits layers of fine sediment up to 0.1 m deposited during the season were observed. These layers reduce infiltration rate at the bottom of the pit but only enhanced minimal lateral movement of water. Makurira et al., (2009) also noted sediment deposition on *fanya juus*. In our study the 2-m distance was outside the cropping area at Magaranhewe and Chongoma where moisture measurements were done therefore, the maize crop did not benefit from the harvested rainwater.

In view of our findings obtained under conditions of large 24-h rainfall events (section 4.3.1), and results reported by Mupangwa et al. (2012) we uphold our hypothesis that for infiltration pits to have a direct effect on soil moisture in the cropping area, they require specific hydrogeological conditions (section 4.1).

In Zimbabwe such conditions are available in the form of 'rock outcrops or dwalas (*ruware*). The rock outcrops are usually associated with steep slopes and shallow soils and occupy 20 to 35% of the land area and in some cases over 50% (Whitlow, 1980). Two thirds of the rock outcrops occur in the semi-arid Natural Regions IV and V (Whitlow, 1980). They provide an opportunity for harvesting surface runoff from steep slopes. Indeed Zimbabwe's RWH icon (Mr. Zephania Maseko Phiri) derived his fame from harvesting water from a rock outcrop upstream of his field. His field is located in an area with sandy soils and a closer look shows that soil moisture content benefits are experienced more than 150 m (at the foot of the slope) from where the rock outcrop is covered by the soil although the series of infiltration pits were dug as close as 50 m from this point. Thus, even in areas where a rock outcrop exists the direction of the rock should be more or less parallel to the ground surface but it is important that soils are sufficiently deep (≥ 1.0 m).

Typical land slopes consist of top, shoulder, midslope, foot and bottom. Usually, the top and the shoulder are drier, and the foot and the bottom of a slope are moister (Miyazaki, 2006). When reporting soil moisture measurements or benefits as claimed by farmers it is, therefore, critical to specify the position of measurements on the slope.

As expected the RWMM did not have an effect on germination percentage because they did not have significant effect on soil moisture content in the cropping area.

In line with soil moisture content results there were no significant differences in maize grain and stover yield between contour ridges only and contour ridges with infiltration pits. Thus, from our study there is no evidence of maize yield increase due to infiltration pits. Our results contradict those obtained by Motsi et al. (2004) and reports from Mutekwa and Kusangaya (2006). Motsi et al. (2004) present averages from Mudzi district in northern Zimbabwe and Gutu and Chivi districts in southern Zimbabwe on sandy to sandy loam soils, therefore, it was not possible to infer reasons why their results are markedly different from ours.

4.4.3 Planting pits

At the drier Chongoma site conventional tillage and planting pits had similar soil moisture content but surprisingly conventional tillage consistently outyielded planting pits both for grain (119.9% more grain under conventional tillage) and stover. Superior performance of conventional tillage can be attributed to lower weed infestation in conventional tillage plots than planting pits plots.

Soil moisture content did not show a consistent trend at the wetter Magaranhewe site. Similarly, tillage methods did not show consistency in performance for maize yield at this site (Table 4.5), but on average conventional tillage performed better than planting pits.

Conventional tillage/planting pits grain yield ratio decreased from 1.9 in the 2010/11 season to 1.3 in the 2012/13 season; this progressive reduction in yield gap underlines positive effects of residual fertilizers in precision farming. In a tillage experiment with conventional tillage, ripping and planting pits (basins) Mupangwa et al. (2007) observed that treatment effects on soil moisture content and maize yield were not significant.

Emergence percentages at Chongoma were lower than those for the other sites. We attribute this to the low soil available water capacity, which was 39 mm for the top 0.4 m at Chongoma compared to 45 mm and 53 mm for Magaranhewe and Kapitawo respectively. Better plant establishment in planting pits than conventional tillage at Magaranhewe and Chongoma is probably due to early season RWH by planting pits complemented by the larger available water capacity at these sites. Mupangwa et al. (2012b; 2007) also observed that planting pits had higher plant stand than conventional tillage and attributed this to early season RWH by planting pits. The synergistic effects between RWH and the soil's available water capacity reinforces the need conserve soil and improve soil available water capacity through building organic matter content of soils.

During the 2011/12 and 2012/13 seasons plots with planting pits had higher ($P < 0.001$) soil moisture content than conventional tillage in the last quarter of the field downstream from the contour ridge channel at Magaranhewe (Figure 4.6, Table 4.3). At this part of the field runoff water from the upslope collects, therefore, planting pits harvested this water. Therefore, under wet conditions there is a potential risk for water logging in this part of the field

We observed that it is easy for rodents to spot the place where seed is placed in planting pits than under conventional tillage because planting stations are more conspicuous under planting pits than conventional tillage. First plantings also suffer most as they are the only field crop targets and this renders early planting risky yet delays in planting often lead to yield loss.

Rainfall distribution exerted its influence on maize yields underlying the fact that both tillage treatments are vulnerable to poor rainfall distribution. For example at Magaranhewe, despite the 2010/11 season being a wet year, poor rainfall distribution and the resultant inadequate rainfall in February 2011 (Figure 4.3) adversely affected maize grain filling and this led to low crop yields. Witch weed was favoured by the dry spell and further reduced maize yield. Mulching with crop residues where available and improving the soil available water capacity through addition of organic fertilizers may help to mitigate the dry spells.

4.4.4 Effect of soil fertility

Magaranhewe site typifies the limitations posed by soil fertility in semi-arid communal area crop production systems. Firstly there was high incidence of *Striga* spp. Jamil et al.(2012) state that nutrient deficiency aggravates *Striga hermonthica* infestation may be due to secretion of *Striga* germination stimulants into the soil by host plants. Secondly the relatively high Ca to Mg ratio of 4:1 implies that Mg deficiencies may occur. It is best to have a Ca to Mg ratio of 2:1 (Hussein, 1997). For our experimental sites, soil pH ranging from 5.6 to 6.3 is suitable for most crops although maize also grows well at pH less than 5.0 in Zimbabwe (Nyamangara et al., 2000). Nutritional problems are often encountered for P, Zn and Fe at high pH levels (Olson and Sander, 1988). Therefore, soil fertility management needs to be prioritised and implemented concurrently with RWH interventions. Intercropping maize with grain legumes such as pigeonpea is a viable option for reducing the effect of witch weed. Rusinamhodzi et al. (2012) observed that sole maize yield was reduced by *Striga asiatica* (L.) Kuntze but no such effect was observed in the intercrops and sole pigeonpea in the third season.

The maize grain yields at all sites (Table 4.5) were below the yield potential of 3 to 5 t ha^{-1} at fertilizer application rates of 250 kg ha^{-1} Compound D (7% N: 14% P_2O_5: 7% K_2O) and NH_4NO_3 at 77 kg N per ha (Seed Co, 2004) for the 2010/11 and 2011/12 seasons. We attribute this partly to yield suppression by *Striga* spp. and probably a deficient soil fertility management regime. Although, we attempted to achieve attainable yield in this study, in reality observed yields are lower because of non-application of organic fertilizers. Rusinamhodzi et al. (2013) observed that a combination of mineral and organic fertilizers gave the largest maize grain yield increase.

4.4.5 Implications of results

It is evident from this study that infiltration pits are not an option for improving soil moisture content for improved maize yields in semi-arid areas for landscapes with homogenous soils where there is no underlying impermeable layer that impedes deep drainage. However, infiltration pits retain more rainwater in the crop fields and help to reduce land degradation. As Makurira et al. (2009) proposed with respect to *fanya juus*, the wetter pits can support horticultural crops. In fields that are protected against free grazing livestock smallholder farmers can plant fruit trees that utilise the water close to the infiltration pits. Xiao-Yan et al. (2006) recommended production of apples, grape and Jujube in China. Makurira et al. (2009) report that in Tanzania farmers grow bananas, cassava, paw paws and other perennial crops around the *fanya juu* structure. In Rushinga we observed two farmers within a 5-km radius of the Magaranhewe site who grew bananas in infiltration pits using runoff water from roads. These farmers were already using infiltration pits before we started the experiments and they believed that infiltration pits increased water supply to in-field crops though they were not sure to what extent. Mutekwa and Kusangaya (2006) report that farmers in Chivi District in southern Zimbabwe grow bananas and fruit trees as a result of adopting RWH technologies.

In order to improve household food security Nyakudya and Stroosnijder (2011) suggest planting of cassava (*Manihot esculenta*) hedges close to the infiltration pits along the contour ridges. The cassava will be able to utilise the soil water throughout the rainy season including the heavy showers that fall at the beginning of the season when maize is still at the initial crop growth stage and at the end of the season when the field crop has reached physiological maturity or has dried prematurely. However, extension efforts will be required in order to popularise cassava in Zimbabwe.

Rusinamhodzi et al. (2013) assert that crop production systems need to go beyond productivity to provide ecosystem services. There is no doubt that inclusion of infiltration pits in contour ridges improves the land's resilience to natural and human-induced degradation for example soil erosion. Farmers and stakeholders who attended field days at Magaranhewe and Chongoma in February 2011 echoed the same sentiments. Host farmers for our experiments noted reduced rill and gully erosion at the experimental sites due to the infiltration pits. From this perspective smallholder farmers should be encouraged to adopt infiltration pits as a sustainable management practice especially in areas which experience high intensity storms.

Planting pits yielded less than conventional tillage in our experiments; therefore they are only useful as a coping strategy in event of livestock loss due to disasters. Mixed crop-livestock farming systems that are heavily reliant on animal draught power as is the case in semi-arid Zimbabwe are prone to livestock loss to disasters such as droughts, cyclones, and diseases and fire-outbreaks. When livestock loss occurs smallholder farmers become desperate and resort to tilling the land with the hoe. Hagmann (1996) reported that after the severe drought in 1991/92 many draught animals died and many farmers were tilling the land using hoes. Furthermore in drought years smallholder farmers sell cattle to raise cash to buy food (Kinsey et al., 1998). In Rushinga district droughts occur with a frequency of at least 3 in 10 years thus necessitating availability of a non-animal draught power dependent fall-back tillage method. In drier areas of southern Africa (Twomlow et al., 2008) highlights that the frequency of drought is once every two or three years, thus making the need for a fall-back method even greater.

Experiences, from our experiments and observations from other farmers in the research area show that planting pits face labour constraints for digging pits and weed control. Farmers expressed concern about the high labour demand for planting pits. With reference to planting pits a farmer in the study area, Mr. Leo Chiropa said "...you want us to die early." By this the farmer implied that the practice of digging planting pits is so strenuous that it reduces someone's life span. Herbicides which made no-till farming a practical reality (Lal, 2013) are not affordable to the resource-poor smallholder farmers whilst those who afford require adequate training in herbicide technology. The use of residue mulch to control weeds is constrained by competition between crops and livestock and other uses for example fuel. In practice very few farmers practised conservation tillage principles beyond the principle of minimum soil disturbance. In Rushinga NGOs and Agritex were concerned that farmers adopted conservation agriculture only as far as digging planting pits. Towards the end of the field experiments there were reports that FAO had introduced a 'mechanized' hoe. It remains to be seen how the mechanized hoe will perform, but mechanization of conservation agriculture through promoting use of equipment such as ripper tines and direct planting seeders should be accelerated for the benefit of smallholder farmers with draught animal power.

4.5 Conclusions

Infiltration pits did not improve maize yield and soil moisture content in the cropping area. Soil moisture benefits were experienced only up to 2 m downstream from the centre of the infiltration pits. However, infiltration pits have potential to improve maize yield in areas with rock outcrops (dwalas). For fields with deep homogenous soil profiles the value of infiltration pits is in combating land degradation caused by soil erosion by water and growing of high value horticultural crops.

On average maize grain yield was 45% higher for conventional tillage (2697 kg ha^{-1}) than planting pits (1852 kg ha^{-1}). However, progressive decline in yield gap from 90% in the first year to 30% in the third year due to precision farming was observed. Planting pits face constraints with respect to labour for digging and weed control. We, therefore, recommend them only for the poor farmers without access to adequate draught animal power and as a coping tillage method in the event of livestock loss to disasters.

Soil fertility limitations reduce anticipated benefits from soil and water conservation methods. Corrective measures to improve soil fertility that include fertilisation with both mineral and organic fertilizers should be implemented in conjunction with soil and water conservation initiatives.

Future studies are required to determine soil moisture and maize yield benefits, and the waterlogging risk in fields with an underlying impermeable layer just below the rootzone.

Chapter 5

Effect of rooting depth, plant density, and planting date on maize (*Zea mays* L.) yield and water use efficiency in semi-arid Zimbabwe: modelling with AquaCrop

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Effect of rooting depth, plant density, and planting date on maize (*Zea mays* L.) yield, and water use efficiency in semi-arid Zimbabwe: modelling with AquaCrop

Abstract

Under low and poorly distributed rainfall higher food production can be achieved by increasing crop water use efficiency (WUE) through optimum soil fertility management and selection of deep-rooting cultivars, appropriate plant density and planting dates. We explored AquaCrop's applicability in selecting adaptive practices for improving maize yield and WUE under rainfed smallholder farming in semi-arid Zimbabwe. AquaCrop was first tested without calibration using field measurements. The model was subsequently applied to estimate effect of effective rooting depth, plant density and planting date on maize yield. Simulations were done with rainfall data for 25 seasons. AquaCrop simulated canopy cover development fairly well and simulated biomass accumulation showed good agreement with measured values. The model overestimated soil water, and observed final biomass and grain yield were 96 and 92% of simulated values respectively at 0.40 m effective rooting depth. Effects of effective rooting depth and plant density were mostly observed in normal seasons. Increasing effective rooting depth (m) from 0.40 to 0.60 increased grain yield from 6.0 to 7.0 t ha^{-1}. Increasing effective rooting depth (m) from 0.60 to 0.80 at 32500 plants ha^{-1} resulted in 0.3 t ha^{-1} yield gain. Increasing plant density (plants ha^{-1}) from 32500 to 44400 at 0.40 m effective rooting depth increased grain yield to 6.6 t ha^{-1}. Grain yield increased to 7.8 t ha^{-1} when the model was run at 0.60 m effective rooting depth and 44400 plants ha^{-1}. Grain water use efficiency and green water use efficiency (GWUE) at 0.60 m effective rooting depth and 44400 plants ha^{-1}, 26.0-28.0 kg ha^{-1} mm^{-1}, and 24.8-27.2% compare favourably with 27.5 -29.4 kg ha^{-1} mm^{-1} grain water use efficiency and 26.8-28.0% GWUE at 0.80 m effective rooting depth. Drainage below the rootzone was ≥ 40% of non-productive water losses in normal and wet seasons whilst soil evaporation contributed 47% in dry seasons at 0.80 m effective rooting depth. To improve yield and WUE, we recommend: incorporation of deep-rooting legumes, deeper-rooting cultivars (≥ 0.60 m effective rooting depth) and practices that improve effective rooting depth, a plant density of 44400 plants ha^{-1}; and practices that reduce soil evaporation e.g. mulching and addition of organic fertilizers to improve soils' available water capacity and enhance response to mineral fertilizers. Further research should include participatory field testing of results from this study with farmers.

Keywords: Maize yield, AquaCrop modelling, water use efficiency, plant density, efective rooting depth, smallholder farming.

5.1 Introduction

The challenge in semi-arid areas is to increase food production under low and poorly distributed rainfall. Higher food production can be achieved by increasing crop water use efficiency (WUE) through appropriate management practices. There is general agreement that crop yields and WUE in smallholder farming systems can be improved through proper agronomic management including selection of deep rooting cultivars, appropriate planting dates and plant density, and soil fertility management through application of fertilizers at optimum rates (Rockström et al., 2010; Tittonell and Giller, 2013).

Since some crop models simulate the combined effect of environment and management on crop growth they can provide important information for crop water management strategies (Soltani and

Hoogenboom, 2007). Efficient use of crop models complements experimental research (Farahani et al., 2009; Matthews et al., 2013; Soltani and Hoogenboom, 2007). Simulation models provide information faster and require fewer resources compared to experimental studies. However, the tradeoff between simplicity and accuracy often limits the broad application of crop models (Farahani et al., 2009). Most mechanistic or deterministic models are suited for research and systems analysis, but tend to be technically demanding and input-intensive, and thus are not easily adopted by practitioners (Raes et al., 2011; Wiyo et al., 2000). The Food and Agriculture Organization of the United Nations (FAO) developed a conceptual generic model, named AquaCrop, which achieves a balance between simplicity, accuracy and robustness (Farahani et al., 2009; Raes et al., 2009; Steduto et al., 2009).

AquaCrop is based on a water-driven growth module, in which plant transpiration is converted into biomass through a water productivity parameter. The equation at the core of AquaCrop is: $B = WP \cdot \sum Tr$ where Tr is crop transpiration (mm) and WP is the water productivity parameter (kg of biomass m^{-2} land area and per mm of water transpired). For details on AquaCrop see Fereres et al. (2008) and Raes et al. (2012).

AquaCrop is menu-driven, with a set of input files that describe the soil-crop-atmosphere environment and seasonal field practices (Farahani et al., 2009). AquaCrop has been validated for maize in different locations and was declared non-cultivar specific and applicable to a wide range of conditions (Heng et al., 2009; Hsiao et al., 2009; Stricevic et al., 2011). Mhizha (2010) calibrated and validated AquaCrop in the higher rainfall areas of Zimbabwe Zinyengere et al. (2011) used AquaCrop together with a seasonal climate forecast tool (RAINMAN) to come up with a decision support tool based on predictions of rainfall and potential yields in Zimbabwe. Biazin and Stroosnijder (2012) used AquaCrop to conduct long-term simulations of the effect of tied ridges in response to different amounts of seasonal rainfall, sowing time and fertility levels on maize yields. Stricevic et al. (2011) concluded that due to the generic character of the model and the wide applicability of its conservative parameters, the model can be used even when data availability is limited.

Emphasis should now be on model application. Heng et al. (2009) concluded that AquaCrop is useful for design and evaluation of water management options and for studying the effect of location, soil type and sowing date on rainfed crop production.

In this study, the performance of AquaCrop was tested for semi-arid Zimbabwe without calibration before it was used for various applications. Testing was done by comparing simulated canopy development, biomass and soil water in the rootzone with field measurements at two experimental sites for two cropping seasons. The ability of the model to reproduce observed patterns without time-consuming and costly calibration is an indicator of model performance and may help model acceptance for practical-oriented users.

Furthermore, AquaCrop was applied to estimate effect of effective rooting depth, plant density and planting date on yield and WUE. Since rainfall amount and distribution vary strongly in semi-arid areas, simulations were done for 25 years with daily rainfall data from Rushinga district, Zimbabwe. Use was made of an extensive analysis of this data set (Nyakudya and Stroosnijder, 2011) that resulted in three categories of rainfall years; normal (456-857 mm), dry (< 456 mm) and wet (> 857 mm). Dry (drought or El Niño) years are years with total rainfall less than the mean minus the standard deviation. Wet or La Niña years are years with rainfall totals with 10% probability of exceedance (Nyakudya and Stroosnijder, 2011).

Effective rooting depth was selected because it is one of the user-specific parameters that show wide variability and has a strong influence on the crop water uptake. Non-productive water flows can be mitigated through conserving or increasing plant available water (PAW). Where PAW is calculated using Equation 5.1.

$$PAW = (\text{Field capacity} - \text{Wilting point}) * \text{Effective rooting depth} \qquad [5.1]$$

Field capacity less wilting point (mm/m) is a physical factor whilst effective rooting depth (m) is both a physical and a crop factor. Effective rooting depth may affect crop growth because shallow-rooted crops have less access to water and nutrients than deep-rooted crops. In addition, shallow-rooted crops may be affected more by evaporation than deep-rooted crops as ground cover may be lower due to water deficiency. Evans et al. (1996) define maximum rooting depth as "deepest rooting depth attained by a crop under specific soil conditions" and effective rooting depth as "the upper portion of the rootzone where plants get most of their water". Effective rooting depth is estimated as one half of the maximum rooting depth. Steduto et al. (2009) state that the root system in AquaCrop is simulated through its effective rooting depth and its water extraction pattern.

According to Hsiao et al. (1976) on good soils, maize can have a maximum rooting depth of 2.8 m or deeper near the time of maturity. Steduto et al. (2012) report that the maximum rooting depth is 1.5 to 2 m especially in regions with cold winter temperatures. Researchers in Sub-Saharan Africa report maximum rooting depths less or equal to 1.2 m: Biazin and Stroosnijder (2012), 0.6 m maximum rooting depth; Zinyengere et al. (2011), 1.2 m maximum rooting depth; Mhizha (2010), 0.8 m maximum rooting depth; Wiyo et al. (2000), 0.65 m maximum rooting depth; and Vogel (1993) reports effective rooting depths between 0.4 and 0.5 m under favourable conditions of tied ridges in Zimbabwe. Tillage research results in the smallholder farming sector of Zimbabwe suggest a shallower effective rooting depth than depths reported in literature. For example, Tsimba et al. (1999) established mean ploughing depths less than 0.15 m in two communal areas of Zimbabwe and existence of plough pans approximately 0.08 m below the mean ploughing depth on loamy soils at Chinyika. According to Tsimba et al. (1999) root penetration was restricted to 0.20 m due to penetration resistance of the plough pan. Vogel (1993) observed shallow effective rooting depths of only 0.15 to 0.25 m in places of very thin topsoil.

Plant densities also vary widely. Smallholder farmers in semi-arid areas often grow crops in fields with variable fertility levels and low crop densities, usually less or equal to 3 plants m^{-2} in sharp contrast to higher densities of 6 to 11.9 plants m^{-2} reported by Heng et al. (2009) and Hsiao et al. (2009).

Planting date depends on the onset of the rainy season. Delays in planting often occur under smallholder farming due to labour and draught power bottlenecks at the start of the season. Planting may also be postponed due to sociocultural reasons, for example cultural Sabbath, instruction to temporarily stop farming activities from spirit mediums and occurrence of a funeral or funerals in the family or neighbourhood. Therefore, it is very common for farmers to miss the first planting opportunity.

The objective of our study was to explore AquaCrop's applicability in selecting adaptive management practices for improving maize yields through efficient use of available water under rainfed smallholder farming in semi-arid Zimbabwe. If AquaCrop is to be adopted by practitioners such as extension personnel and farm managers it must be able to simulate crop yields reasonably well. This should be possible using appropriate climate, crop and soil files with no need for parameter adjustments in a non-transparent calibration process. Our test for feasibility of the use of the model in semi-arid smallholder farming areas hinges on this assertion.

5.2 Study area and experiments

5.2.1 Study area

Rushinga district (16° 40' 00'' S, 32° 15' 0''E, altitude 730 m a.s.l.) was selected for the study because it lies in a semi-arid region in Zimbabwe which is entirely a smallholder farming area. Most smallholder farmers in this area are prone to droughts and dry spells because they lack irrigation facilities. The district's seven-year: 2006/07 to 2012/13 mean minimum and maximum maize yields were 0.1 and 2.5 t ha^{-1}. The highest yield; 4.5 t ha^{-1} was obtained during the 2011/12 season. There is need to close the large yield gap between minimum and maximum yields in order to enhance household food security. The area lies in Natural Region

IV with a long-term mean annual rainfall of 450-650 mm (Vincent and Thomas, 1960). The rainy season is unimodal and stretches from November to March.

Data from conventional tillage plots of maize field experiments conducted during the 2010/11 through 2012/13 seasons (Nyakudya et al., 2013) were used as input data for AquaCrop model Version 4.0 Plus March 2012 and for comparison with simulated values. The experiments were conducted near Rushinga district offices (16^{0}37'.899S, 32^{0}1'.288, 1045 m a.s.l.) where an automatic meteo-station had been installed. The experimental sites were Chongoma (16^{0}35'.311S, 31^{0}59'.512E, altitude 912 m a.s.l.), Magaranhewe (16^{0}36'.888S, 32^{0}02'.512E, 1014 m a.s.l.) and Kapitawo (16^{0}38'.905, 31^{0}59'.769, altitude 940 m a.s.l.).

Data from two sites, Magaranhewe 2012/13 season, and Chongoma 2011/12 and 2012/13 season were selected for model performance testing. The two sites were selected on the basis of having most of the required input data for use in evaluating the performance of the model.

5.2.2 Determination of canopy cover progression and biomass accumulation

Canopy cover and above-ground biomass hereafter referred to as biomass were measured every ten days at Chongoma in the 2011-12 season and every seven days at Chongoma and Magaranhewe during the 2012-13 season from six to eight randomly selected plants per site. Leaf area was determined by measuring the green area of detached leaves using a combination of the Mangal table-top leaf area meter for smaller leaves and cut pieces (≤ 200 cm^2), and the graph paper method for the bigger leaves. For the graph paper method cardboard papers of known areas were superimposed on the leaves and the resultant areas summed up. The leaf area meter was calibrated using graph paper prior to use. Leaf area index (LAI) was calculated by multiplying the leaf area per plant by the plant density. Canopy cover was then calculated using the empirical relationship between CC and LAI for maize: $CC = 1.005 * [1 – \exp(-0.6\ LAI)]^{1.2}$ derived by Hsiao et al. (2009). Biomass was oven-dried for 48 hours at 70 ^{0}C after which it was weighed with a digital scale balance.

5.2.3 Measurement of effective rooting depth

Root depth measurements were done in the field at Chongoma and Magaranhewe after the start of senescence on six plants at Chongoma and eight plants at Magaranhewe. The plants were randomly selected from conventional tillage plots. Root depth was measured by excavating the soil close to the maize plant (0-25 cm) and measuring the depth to which roots grew from the soil surface. Considering limitations of the method we regarded the measured rooting depth as effective rooting depth as opposed to maximum rooting depth. Measured mean (SD) effective rooting depths were 32.5 (4.9) for Chongoma for the two seasons (2011/12 and 2012/13) and 32.8 (4.7) for Magaranhewe.

Working on a Zimbabwean sandy clay loam which is comparable to soils in this study, Chikowo et al. (2003) established that maize “Root length densities at depths greater than 60 cm were small, and were still less than 0.1 cm cm^{-3} by the eighth week after emergence...).” The actual values were 0.005 cm cm^{-3} for the zone 0-22.5 cm from the plant and 0.000 for the zone 22.5-45.0 cm from the plant. According to Chikowo et al. (2003) “By the ninth week after planting, there was severe depletion of nitrate-N in the 0-40 cm depth, and evidence of accumulation in the deeper soil layers where maize root length densities were still less than 0.1 cm cm^{-3}. This suggests that the effective rooting depth in the study by Chikowo et al. (2003) was about 0.40 m. Consequently modelling at 0.40 m can be justified considering that in the study by Chikowo et al. (2003) the method used to measure effective rooting depth was thorough.

5.2.4 Determination of plant density

Percentage plant emergence (SE), 60.2 (3.0) for Chongoma, 66.0 (2.5) for Magaranhewe, and 63.2 (2.0) for Kapitawo was determined on 22 December 2012 for the 2012/13 season, ten days after the latest plantings when crop emergence was assumed to be complete (Chapter 4, Table 4.4). Crop emergence was determined by counting plants in eight randomly selected rows per plot in all conventional tillage plots. Plant densities were then estimated from the emergence percentages and target plant densities. Plant emergence percentage mean (SE) for Chongoma 2011/12 season was estimated at 65.2 (2.0) by counting plants in four randomly selected rows per plot from five out of six conventional tillage plots ten days after planting.

5.2.5 Determination of final biomass and grain yield

Early cessation of rains or lengthy dry spells at the end of the season made it difficult to detect the actual time to physiological maturity especially at Chongoma; therefore, final biomass and grain yield were determined at harvest time. Harvesting and measurement of grain yield is described in Nyakudya et al. (2013) (Chapter 4). Days from planting to harvesting were: 114 for Chongoma 2011/12 season, 124 for Chongoma 2012/13 season, and 125 for Magaranhewe 2012/13 season.

5. 3 Methodology for model performance evaluation

As explained above we used Aquacrop (without calibration) in two steps: validation and application. To stress this difference, we describe the methodology and results for the two steps in different sections. We tested AquaCrop's performance using measured site and cultivar specific parameters. Below is a description of the model parameters, input data and evaluation of performance results.

5.3.1 Climate data

Reference evapotranspiration was calculated using FAO's ET_o calculator (Raes, 2009) using air temperature, solar radiation, wind speed at 2 m and relative humidity from the meteo-station. Thereafter, the ET_o, minimum and maximum air temperatures, and daily rainfall data were input into the AquaCrop model (Raes et al., 2009; Steduto et al., 2009). Experimental site-specific daily rainfall was measured using non-recording rain gauges that were installed at each site throughout the duration of the experiments (Figure 5.1). For long-term simulations, climate files for individual years were created using the average temperature and ET_o data for the 2010/11 through 2012/13 seasons combined with daily rainfall data for the individual years and the average atmospheric CO_2 concentration for the year 2000 measured at Mauna Loa observatory in Hawaii (369.47 ppm).

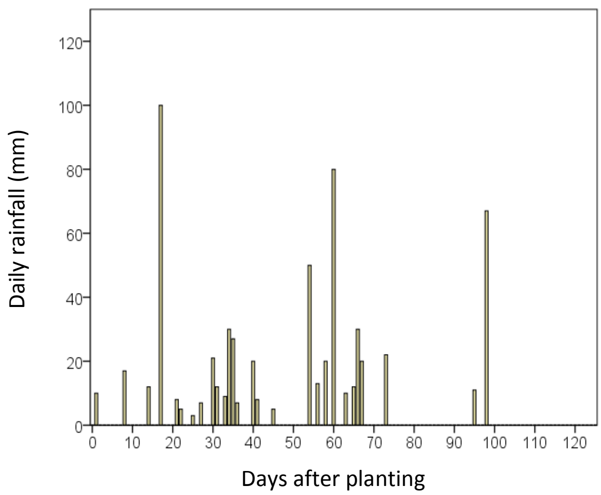
5.3.2 Soil data

Measured soil data from experimental sites (Table 5.1) were used. Soil sampling and laboratory analysis procedures are described in Nyakudya et al. (2013) (Chapter 4).

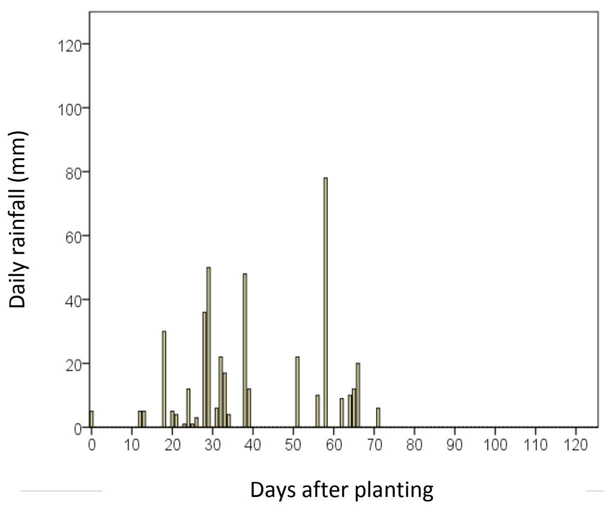
Table 5.1: Measured soil physical properties[a] of experimental fields in Rushinga district, Zimbabwe

Site	Soil layer (m)	[b]Soil texture	Bulk density (g cm^{-3})	Volumetric soil water content (mm/m)		
				SAT	FC	PWP
Chongoma	0.0-0.2	mSaL	1.64	340	218	114
	0.2-0.4	mSaCL	1.52	379	241	149
	0.4-0.6	mSaCL	1.65	344	265	158
	0.6-0.8	mSaCL	1.63	318	257	150
Magaranhewe	0.0-0.2	mSaL	1.56	346	158	69
	0.2-0.4	mSaCL	1.44	380	269	134
	0.4-0.6	mSaCL	1.58	380	260	130
	0.6-0.8	mSaCL	1.62	380	274	135
Kapitawo	0.0-0.2	fSaL	1.40	412	228	94
	0.2-0.4	fSaL	1.53	379	268	139
	0.4-0.6	fSaL	1.47	381	265	158
	0.6-0.8	fSaL	1.56	379	273	137

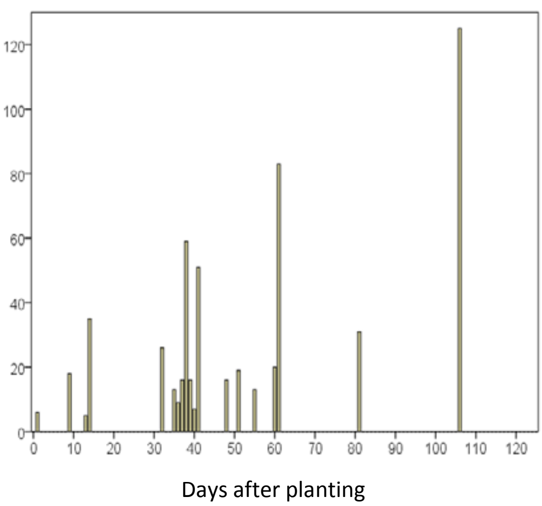
[a] SAT, water content at saturation; FC, field capacity; PWP, permanent wilting point.
[b]mSaL, medium sandy loam; mSaCL, medium sandy clay loam; fSaL, fine sandy loam



(a) Magaranhewe 2012/13 season



(b) Chongoma 2012/13 season



(c) Chongoma 2011/12 season

Figure 5.1: Daily rainfall for (a) Magaranhewe 2012/13 season (b) Chongoma 2012/13 season, and (c) Chongoma 2011/12 season in Rushinga district, Zimbabwe

In the soil profile menu, AquaCrop provides a default value for the Curve Number (CN) based on surface conditions. The CN is a dimensionless index, and can vary from 0 (no runoff) to 100 (all rainfall becomes runoff). Estimates of CN are based on the hydrologic soil group, cover, and landuse (Boonstra, 1994). Simanton et al. (1996) established that the CN for a small upland drainage area of 1 ha oscillated around 85. Maize is a row crop and farmers usually plough on-contour, therefore, we selected contour as practice in relation to hydrological condition. The category poor was selected due to frequent monocropping practices or rotations of mainly row crops that include cotton (*Gossypium hirsutum* L.). We chose hydrological soil group B described as soils having moderate infiltration rates when thoroughly wetted and a moderate rate of water transmission. Examples are moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures. We obtained CN 79 for antecedent moisture condition (AMC) Class II. This class was selected because during the rainy season the likelihood of the antecedent soil moisture content being average is high. Nearing et al. (1996) gives a CN of 81 for conventional corn for the hydrological soil group B used in his study and this is close to 79 that we used.

Soil water measurements in the 2012/13 season at Magaranhewe and Chongoma were used for model input and performance testing. Details of measurement procedures are presented in Nyakudya et al. (2013) (Chapter 4).

5.3.3 Crop parameters, phenology and development

Conservative parameters

The conservative (nearly constant) parameters (Table 5.2) were generated through multi-season parameterisation, testing and validation in different climatic zones (Heng et al., 2009) and are widely applicable for maize. These conservative parameters were used for all simulations.

The water productivity parameter is normalised for climate (WP*) and can be taken as conservative for a given crop (Steduto et al., 2009). The 'normalisation for climate' takes into account the ratio between transpiration and evapotranspiration of a reference crop. The WP* of C4 crops is about 30 to 35 g m^{-2}, (Raes et al., 2011). Hsiao et al. (2009) used a WP* of 33.7 g m^{-2}, Heng et al. (2009) used WP* values ranging from 31.3 to 33.2 g m^{-2}, Mhizha (2010) and Zinyengere et al. (2011) used 29 g m^{-2} and Biazin and Stroosnijder (2012) used WP* of 30.7 g m^{-2}. These figures, precise to the decimal point, were often obtained after some form of calibration of AquaCrop.

For nutrient limited situations the model provides categories ranging from slight to severe deficiencies corresponding to lower and lower water productivity. Calibration for soil fertility stress is based on field observations of biomass and CC between a reference and a stressed field, which were not available for this study. Our experimental fields were fertilised using mineral fertilizers based on recommendations from the Department of Agricultural, Technical and Extension Services (Agritex) (94.5 kg N ha^{-1}, 15.3 kg P ha^{-1} and 14.5 kg K ha^{-1}).

We designed our experiment to achieve the attainable yield. Attainable yield is the yield achieved in farmers' fields under best management practices including optimum supply of plant nutrients, timely and effective weed, pests and disease control. In practice however, our fields suffered from the negative effects of *Striga* species that was prevalent in the area. Hence we expected our experimental results to be lower than the achievable yield and considering the short season cultivar (SC513), we adopted the lower WP*, me ntioned in earlier studies in Zimbabwe, equal to 29.0 g m^{-2}.

User-specific parameters

User-specific crop data (crop parameters that vary with cultivars, environment and management) were based on observations of the maize cultivar, SC513, at Chongoma and Magaranhewe and are given in Table 5.3.

Table 5.2: Crop conservative input parameters of AquaCrop for maize

Description	Value	Units	Meaning/Remark
Conservative (generally applicable)			
Base temperature	8	^{0}C	
Cut-off temperature	30	^{0}C	
Canopy cover per seedling at 90% emergence (CC_0)	6.5	cm^2	
Canopy growth coefficient (CGC)	1.3	%	increase in CC relative to existing CC per growing degree day (GDD) function of plant density
Crop coefficient for transpiration at CC = 100%	1.03		full canopy transpiration relative to ET_0
Decline in crop coefficient after reaching maximum canopy cover (CC_x)	0.3	%	decline per day due to leaf ageing
Canopy decline coefficient (CDC) at senescence	1.06	%	decrease in CC relative CC_x per GDD
Leaf growth threshold p – upper	0.14		as a fraction of total available water (TAW), above this leaf growth is inhibited
Leaf growth threshold p- lower	0.72		as a fraction of TAW, leaf growth stops completely at this point
Leaf growth stress coefficient curve	2.9		moderately convex shape
Stomatal conductance threshold p – upper	0.69		above this, stomata begin to close
Stomata stress coefficient curve shape	6.0		highly convex curve
Senescence stress coefficient p –upper	0.69		above this, stomata begin to close
Senescence stress coefficient curve shape	2.7		Moderately convex shape
Anaerobiosis point	6	%	The difference in soil moisture content at saturation at the point when transpiration is not limited by lack of aeration. This values implies moderately tolerant to water logging
Considered to be conservative but can or may be cultivar specific			
Water productivity parameter is normalised for climate (WP*)	29.0	g m^{-2}	This lower value is based on Mhizha (2010).
Reference harvest index (HI_0)	48	%	
[a]GDD (Growing degree days) from 90% emergence to start of anthesis	800	^{0}C	earlier for short season cultivars
Duration of anthesis	190	^{0}C	
Coefficient, inhibition of leaf growth on HI	7		HI increased by inhibition of leaf growth at anthesis
Coefficient inhibition of stomata on HI	3		HI reduced by inhibition of stomata at anthesis

[a]Growing degree days describe crop growth and development in thermal time. Different crop development stages are completed once a given number of GDD are reached (Fereres et al., 2008). GDD = $(T_{max} + T_{min})/2 - T_{base}$ where, GDD is the number of temperature degrees determining crop growth and development, T_{max} is daily maximum air temperature, T_{min} is daily minimum air temperature and T_{base} is temperature below which crop development stops. AquaCrop uses GDD to compute thermal time.

Table 5.3: Phenological observations translated into user-specific parameters of AquaCrop for the maize cultivar SC513 in Rushinga district, Zimbabwe

Description	Value	Units
Time from sowing to emergence	6	Calendar days
Time from sowing to maximum canopy cover	65	Calendar days
Time from sowing to flowering	55	Calendar days
Duration of flowering	20	Calendar days
Time from sowing to start of senescence	95	Calendar days
Time from sowing to maturity	115	Calendar days
Effective rooting depth	0.40	Meter
Plant density Magaranhewe (2012/13)	32593	Plants ha^{-1}
Maximum canopy cover (CC_x) Magaranhewe (2012/13)	70	%
Plant density Chongoma (2011/12)	32099	Plants ha^{-1}
Maximum canopy cover (CC_x) Chongoma (2011/12)	57	%
Plant density Chongoma (2012/13)	27753	Plants ha^{-1}
Maximum canopy cover (CC_x) Chongoma (2012/13)	65	%

5.3.4 Evaluation of AquaCrop performance results

The performance of the model was evaluated using graphic and statistical tests. Data used to evaluate model performance consisted of CC, biomass, final biomass and grain yield, and soil water. Graphic comparisons of measured (observed) CC (%) and biomass with respective simulated values for the 2011/12 and 2012/13 seasons for Chongoma and 2012/13 season for Magaranhewe were used as visual measures of goodness of fit.

AquaCrop Version 4.0 has an in-built module that enables evaluation of simulation results for CC, biomass and soil water with the help of field data stored in an observations file. The evaluation results are in the form of graphical displays, numeric data, and statistical indicators. Five statistical indicators are provided but we selected only two that are commonly reported in literature in order to avoid cluttering the analysis with too many figures. The statistical indicators that were selected to evaluate the performance of the model are root mean square error (RMSE), and model coefficient of efficiency (CE) and they are defined and explained hereafter. The RMSE is calculated using Equation 5.2 and the Nash-Sutcliffe model coefficient of efficiency (CE) is calculated using Equation 5.3

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$$RMSE = \sqrt{\frac{\sum(O_i - S_i)^2}{N}} \qquad [5.2]$$

$$CE = 1 - \frac{\sum(S_i - O_i)^2}{\sum(O_i - \bar{O})^2} \qquad [5.3]$$

Where:

O_i and S_i are observed (measured) and simulated values respectively,

N is the number of observations,

$\bar{O}$ is the mean of O

The RMSE measures the average magnitude of the differences between observed and simulated values. An advantage of RMSE is that it summarises the mean difference in the units of observations and simulations. However, it does not differentiate between over- and underestimation. RMSE values range from 0 to positive infinity and the closer the value to zero the better the model simulation performance.

The CE measures the relative magnitude of the residual variance compared to the variance of the observations. According to Moriasi et al. (2007), CE indicates how well the plot of observed versus simulated data fits the 1:1 line. Values of CE range from minus infinity to 1. A CE of 1 indicates a perfect match between the model and the observations, a CE of 0 means that the model predictions are as accurate as the mean of the observed data and a negative CE implies that the mean of the observations is a better prediction than the model (Raes et al., 2012).

Canopy cover, biomass and soil water data measured at specific points in time (sections 5.2.2, Chapter 4 section 4.2.5) and their standard deviations were entered into a template in the observations file in the AquaCrop model. Number of measurement dates corresponding to observation-simulation combinations for each experiment were: nine for Chongoma 2011/12 CC; 11 for Chongoma and Magaranhewe 2012/13 CC; 10 for biomass in each of the three experiments; nine for Chongoma 2011/12 and Magaranhewe 2012/13 soil water, 10 for Chongoma 2012/13 soil water. When the model was run the RMSE and CE for each variable calculated by the in-built module were accessed through the observations file.

5.4 Results of model performance evaluation

Results for model performance evaluation are presented for three variables: CC, biomass and soil water. For each variable comparisons are made between measured (observed) and simulated values.

5.4.1 Canopy cover development

AquaCrop was able to simulate accurately CC development during the 2012/13 season for Magaranhewe (Figure 5.2). There were slight mismatches; firstly early in the season up to day 39 after planting (establishment to vegetative stage) when the simulated line underestimated canopy development and secondly after day 63 after planting with the measured CC declining faster compared to the simulated CC. The good agreement between the measured and simulated CC is reflected in the statistical analysis given in Table 5.4 with a relatively low RMSE value (6.1%) and high CE (0.92) at 0.40 m effective rooting depth.

At Chongoma, in the 2012/13 season up to day 69 the model underestimated CC but similar to Magaranhewe the measured CC declined earlier than the simulated CC up to about day 82 when there was a faster decline of simulated CC (Figure 5.2). Statistical analysis confirmed the relatively low model performance with larger RMSE values and smaller CE values. During the 2011/12 season, AquaCrop overestimated CC after day 44 (Figure 5.2). The model was unable to simulate the drastic decline in CC caused by a 19–day dry spell interrupted by 31 mm on day 81 and continued for 24 days. For Chongoma model performance during the 2011/12 and 2012/13 seasons was satisfactory.

5.4.2 Biomass accumulation

At Magaranhewe during the 2012/13 season AquaCrop consistently overestimated biomass accumulation but showing good agreement between the measured and simulated values (Figure 5.3). The overestimation is reflected in the relatively high RMSE of 2.0 t ha^{-1} whilst the good agreement is shown by the model CE of 0.71 at 0.40 m effective rooting depth.

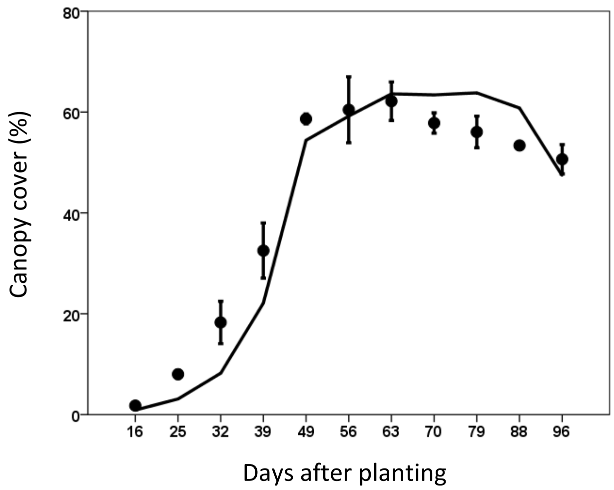
For Chongoma, during the 2012/13 season the model overestimated the measured values from day 48 to just after day 87 when simulated biomass accumulation reached a near constant value in response to early cessation of rains with only 6 mm on day 71 following a 4-day dry spell (Figure 5.1). However, on average there was good agreement between measured and simulated values Table 5.4. In the 2011/12 season, generally there was good agreement between the measured and simulated biomass (Figure 5.3). The good agreement is reflected in the high model CE (0.98) (Table 5.4) and low RMSE value of 0.5 t ha^{-1} for the 0.40 m effective rooting depth.

5.4.3. Final biomass and grain yield

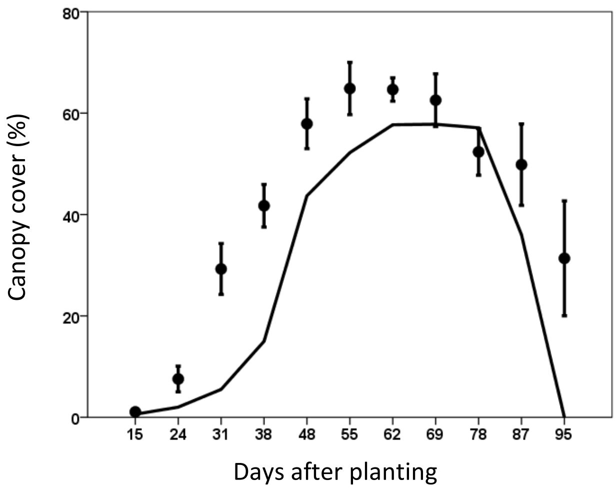
The model tended to overestimate attainable final biomass and final grain yield at both 0.40 m effective rooting depth (Table 5.5). The mean observed final biomass and mean grain yield were 96 and 92% of the mean of simulated values for 0.40 m effective rooting depth (Table 5.5).

5.4.4 Soil water

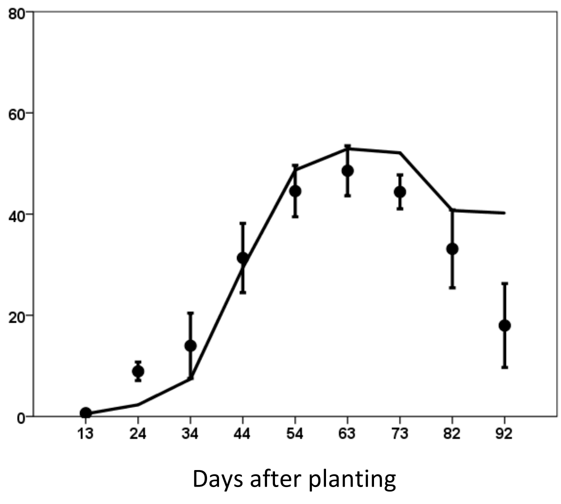
Results depict relatively large RMSE values and CE values close to 0 (Table 5.4).



(a) Magaranhewe 2012/13 season



(b) Chongoma 2012/13 season

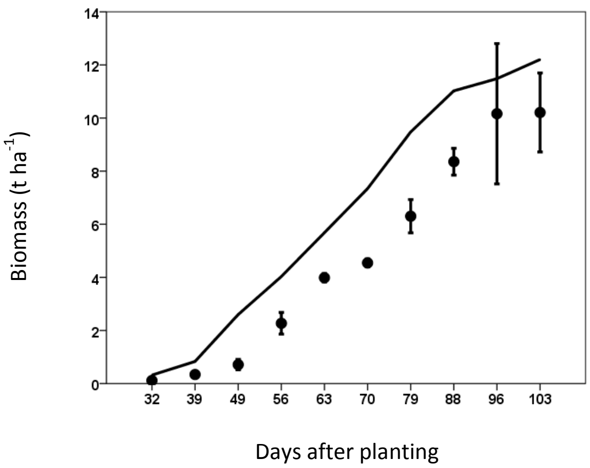


(c) Chongoma 2011/12 season

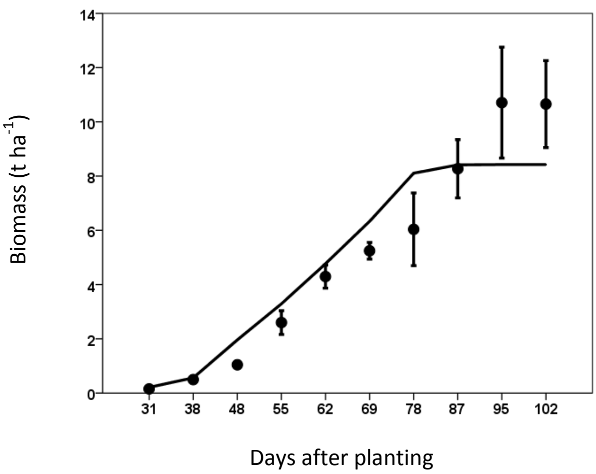
Figure 5.2: Observed (dots) and simulated (solid line) canopy cover (%) for rainfed maize cultivar SC513 at 0.40 m effective rooting depth and (a) 32593 plants ha^{-1} at Magaranhewe 2012/13 season, (b) 27753 plants ha^{-1} at Chongoma 2012/13 season, and (c) 32099 plants ha^{-1} at Chongoma 2011/12 season, in Rushinga district Zimbabwe. Error bars: standard deviation

Table 5.4: Root mean square error (RMSE) and coefficient of efficiency (CE) for comparisons between observed and simulated canopy cover (CC), biomass and soil water for rainfed maize at 0.40 m effective rooting depth, and (a) 32593 plants ha^{-1} at Magaranhewe 2012/13 season, (b) 27753 plants ha^{-1} at Chongoma 2012/13 season, and (c) 32099 plants ha^{-1} at Chongoma 2011/12 season, in Rushinga district, Zimbabwe

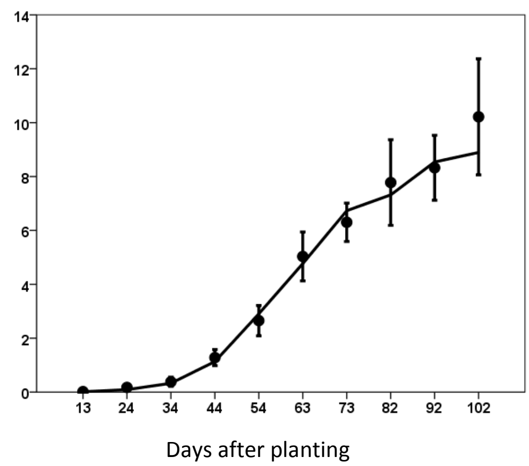
Site	**Season**	**Canopy cover**		**Biomass**		**Soil water**	
		RMSE (%)	CE	RMSE (t ha^{-1})	CE	RMSE (mm)	CE
Magaranhewe	2012/13	6.1	0.92	2.0	0.71	11.5	-0.78
Chongoma	2012/13	16.3	0.42	1.3	0.88	16.7	0.04
	2011/12	9.0	0.69	0.5	0.98		



(a) Magaranhewe 2012/13 season



(b) Chongoma 2012/13 season



(c) Chongoma 2011/12 season

Figure 5.3: Observed (dots) and simulated (solid line) biomass (t ha^{-1}) for rainfed maize cultivar SC513 at 0.40 m effective rooting depth and (a) 32593 plants ha^{-1} at Magaranhewe 2012/13 season, (b) 27753 plants ha^{-1} at Chongoma 2012/13 season, and (c) 32099 plants ha^{-1} at Chongoma 2011/12 season, in Rushinga district, Zimbabwe. Error bars: standard deviation

Table 5.5: Observed and simulated final aboveground biomass and grain yield and soil water for rainfed maize cultivar SC513 at 0.40 m effective rooting depth, and (a) 32593 plants ha^{-1} at Magaranhewe 2012/13 season, (b) 27753 plants ha^{-1} at Chongoma 2012/13 season, and (c) 32099 plants ha^{-1} at Chongoma 2011/12 season, in Rushinga district, Zimbabwe

Site	Season	Planting date	Seasonal rainfall	Final biomass (t ha^{-1})			Final grain yield (t ha^{-1})			Soil water (mm)		
			mm	Observed	Simulated	% Dev[a]	Observed	Simulated	% Dev[a]	Observed	Simulated	%, Dev[a]
Chongoma	2011/12	15 De 2011	778	8.4	8.9	6.0	2.6	3.4	30.8			
	2012/13	12 Dec 2012	516	9.3	8.4	-9.7	3.3	2.2	-33.3	70.7	80.5	13.9
Magaranhewe	2012/13	11 Dec 2012	767	11.1	12.7	14.4	4.7	5.9	25.5	70.5	73.5	4.3

[a]% Dev =% Deviation = (simulated – observed) * 100/observed

5.5 Methodology for model application

5.5.1 Simulated variables

The AquaCrop model was run using seasonal daily rainfall data for 25 years between 1980 and 2009 for each of the three soil types at the experimental sites (Table 5.1). Scenario simulations were performed for: (i) effective rooting depth (m) at five levels (0.30, 0.35, 0.40, 0.60 and 0.80) at 32500 plants ha^{-1}; (ii) plant density (plants ha^{-1}) at four levels (17500, 25000, 32500 and 44400) for 0.40 m, 0.60 m and 0.80 m effective rooting depths; (iii) planting date for the first and second planting opportunities within each season based on Agritex criterion i.e. planting after > 25 mm rainfall in 7 days (Nyakudya and Stroosnijder, 2011; Raes et al., 2004) at 32500 plants ha^{-1}; and (iv) curve number (CN) at three levels (40, 65 and 79) at 32500 plants ha^{-1} for 0.40 m, 0.60 m and 0.80 m effective rooting depth. Except for planting date comparisons, all other planting dates were based on the Depth criterion i.e. planting after receiving ≥ 40 mm in four days (Raes et al., 2004) and were obtained from (Nyakudya and Stroosnijder, 2011) (Chapter 3).

Selection of effective rooting depths was based on literature from Sub-Saharan Africa and field observations (sections 1 and 5.2.3). We assumed an ideal effective rooting depth of 0.60 m but we also performed simulations using 0.80 m effective rooting depth in order to assess effect on yield. Plant densities are based on field observations. Nyamudeza (1999) recommended a plant density of 22000 plants ha^{-1} for the drier Natural Region V with rainfall less than 450 mm. A density of 32500 plants ha^{-1}, equivalent to maximum density observed in conventional tillage experiments during the 2012/13 season (Chapter 4, Table 4.4) considering a sowing density of approximately 49000 plants ha^{-1} with 65% emergence was selected as the standard simulation plant density. The highest density, 44400 plants ha^{-1} represents 90% emergence attainable under best management practices. AquaCrop provides a default CN once soil data is input into the model, in our case a uniform default value of 65 was obtained for all sites, and we added 40, the lowest allowable value by the model. The selection of CN = 79 is explained in section 5.3.2. Modelling with CN was performed because it enables assessment of possible interventions that alter runoff quantities for example conservation tillage.

5.5.2 Definition of terms

Water use efficiencies, percentage runoff, soil evaporation and drainage below rootzone were derived from the AquaCrop model output data. The derived variables are defined hereafter.

Crop water use efficiency (WUE) was defined from a physiological perspective as the ratio of biomass to consumed water (Blum, 2005; Hatfield et al., 2001; Sinclair et al., 1984). Thus, for maize water use efficiency is described using Equation 5.4.

$$WUE = Y/ET \qquad [5.4]$$

Where:

Y is either total biomass or grain yield, and

ET is the evaporation of water from the soil surface plus transpiration from the crop. Thus WUE was expressed in kg ha^{-1} mm^{-1} i.e. crop biomass (kg ha^{-1})/water use (mm) (Twomlow and Bruneau, 2000).

We considered the evaporation of water during the simulation period which was linked to the crop growing cycle of 115 days from sowing to maturity.

Green-water use efficiency (GWUE) is defined as the ratio: transpiration/precipitation (Stroosnijder, 2009). The advantage of GWUE is that it avoids the compounding effect of the non-productive soil evaporation losses. The opportunities available to improve WUE can be assessed by comparing average values currently being achieved with those obtained under the best field practices and with estimates of potential values (Stanhill, 1986). For example, according Stroosnijder (2009), GWUE in rainfed systems in sub-Saharan Africa ranges from 5 to 15% but may be above 50% in comparable climates in the USA. In calculating GWUE we used the total seasonal (Nov – Mar) rainfall.

Runoff, soil evaporation and drainage below rootzone were expressed as percentages of the rainfall within the simulation period.

5.5.3 Data analysis

For the long-term rainfall simulations, analysis of variance, or the independent samples t-test, R^2, and graphic analyses were used to analyse simulated and derived variables for effective rooting depth, plant density, planting date, and CN. The coefficient of determination (R^2) is calculated using Equation 5.5.

$$R^2 = \left[\frac{\sum(O_i-\bar{O})(S_i-\bar{S})}{\sqrt{\sum(O_i-\bar{O})^2\sum(S_i-\bar{S})^2}}\right]^2 \qquad [5.5]$$

Where:

$\bar{S}$ is the mean of S and the other parameters are as defined in section 5.3.3.

The coefficient of determination (R^2) is the squared value of the Pearson correlation coefficient. The coefficient of determination gives the proportion of the variance in the measured data explained by the model (Field, 2005). It ranges from 0 to 1, with values close to 1 indicating a good agreement. A disadvantage of R^2 is that only dispersion is quantified, which means a model which systematically overestimates (or underestimates) the observations can still have a good R^2 value (Krause et al., 2005).

Post-hoc tests to identify statistically different means were performed using the Least Significant Difference (LSD) test.

5.6 Results of model application

Model application results are presented for effective rooting depth, plant density, planting date and CN.

5.6.1 Effective rooting depth

Normal years

The model shows that increasing maize effective rooting depth from 0.40 m (shallow rooted) to 0.60 m (shallow to medium rooted) at 32500 plants ha^{-1}, increases maize grain yield ($P \leq 0.05$) (Figure 5.4). The mean increase across sites from 0.40 m to 0.60 m is 16.7% i.e. from 6.0 to 7.0 t ha^{-1} corresponding to a yield increase of 1.0 t ha^{-1}. Increasing effective rooting depth from 0.60 m to 0.80 results in 0.3 t ha^{-1} yield gain which is not statistically significant. Doubling effective rooting depth from 0.40 m to 0.80 m results in 1.3 t ha^{-1} equivalent to a 21.7% increase in grain yield. The coefficient of variation ((standard deviation /mean)* 100%) shows a declining trend with increasing effective rooting depth (Figure 5.4). Increasing plant density (plants ha^{-1}) from 32500 to 44400 at 0.40 m effective rooting depth results in grain yield equal to 6.6 t ha^{-1} , an increase of 10% from 6.0 t ha^{-1}. Grain yield increases to 7.8 t ha^{-1} ($P < 0.001$) when the model is run at 0.60 m and 44400 plants ha^{-1}.

Biomass, grain and green-water use efficiencies generally increased ($P < 0.05$) with increasing effective rooting depth to 0.80 m at all sites. However, increasing effective rooting depth from 0.60 m to 0.80 m does not have an effect ($P > 0.05$) on all water use efficiencies at all sites. Mean percentage increases from 0.40 m to 0.60 m were; 9.7% for biomass water use efficiency; 12.4% for grain water use efficiency and 10.0% for GWUE respectively. Doubling the effective rooting depth from 0.40 m to 0.80 m results in mean increases ($P < 0.05$) across sites of biomass water use efficiency by 15.0% from 46.7 to 53.7

kg ha^{-1} mm^{-1}, grain water use efficiency by 17.7% from 22.0 to 25.9 kg ha^{-1} mm^{-1} and GWUE by 16.9% from 20.7 to 24.2%.

Increasing effective rooting depth from 0.40 m to 0.80 m reduced ($P < 0.05$) soil evaporation by 15.2% for Chongoma but there were no significant differences for the other sites.

Dry and wet years

For effective rooting depths 0.40 m to 0.80 m there were no differences ($P > 0.05$) in biomass and grain yield and water use efficiencies in dry (El Niño) and wet (La Niña) seasons for all. Though insignificant ($P > 0.05$) in dry years, increasing effective rooting depth from 0.40 m to 0.80 m resulted in grain yield increase from 4.0 to 6.4 t ha^{-1}. Increasing from shallower effective rooting depths ≤ 0.30 m to 0.80 m increases ($P < 0.05$) biomass and grain yield for Chongoma and Magaranhewe, and only biomass yield for Kapitawo in dry years.

General

Effective rooting depth did not have an effect ($P > 0.05$) on the non-productive water losses except for soil evaporation for Chongoma in normal years as described earlier in this section. At 0.80 m effective rooting depth, total non-productive water losses during the crop growing cycle expressed as a percentage of mean seasonal rainfall (631 mm), amount to 86% in wet seasons, 68% in normal seasons, and 39% in dry seasons (Figure 5.5). Drainage below effective rooting depth constitutes the bulk of non-productive water losses, ≥ 40% in normal and wet years whilst evaporation contributes 47% of non-productive losses in dry years. Runoff is constant by virtue of a constant CN. Mean drainage as a percentage of rainfall (SD) within the simulation period across sites for 0.40 m, 0.60 m and 0.80 m effective rooting depths respectively were: dry years, 27.4 (8.4), 24.9 (8.4), and 22.9 (9.2); normal years, 33.2 (5.6), 32.0 (6.1), 31.8 (6.7), and wet years 31.8 (2.7), 29.0 (4.7), and 28.6 (4.9).

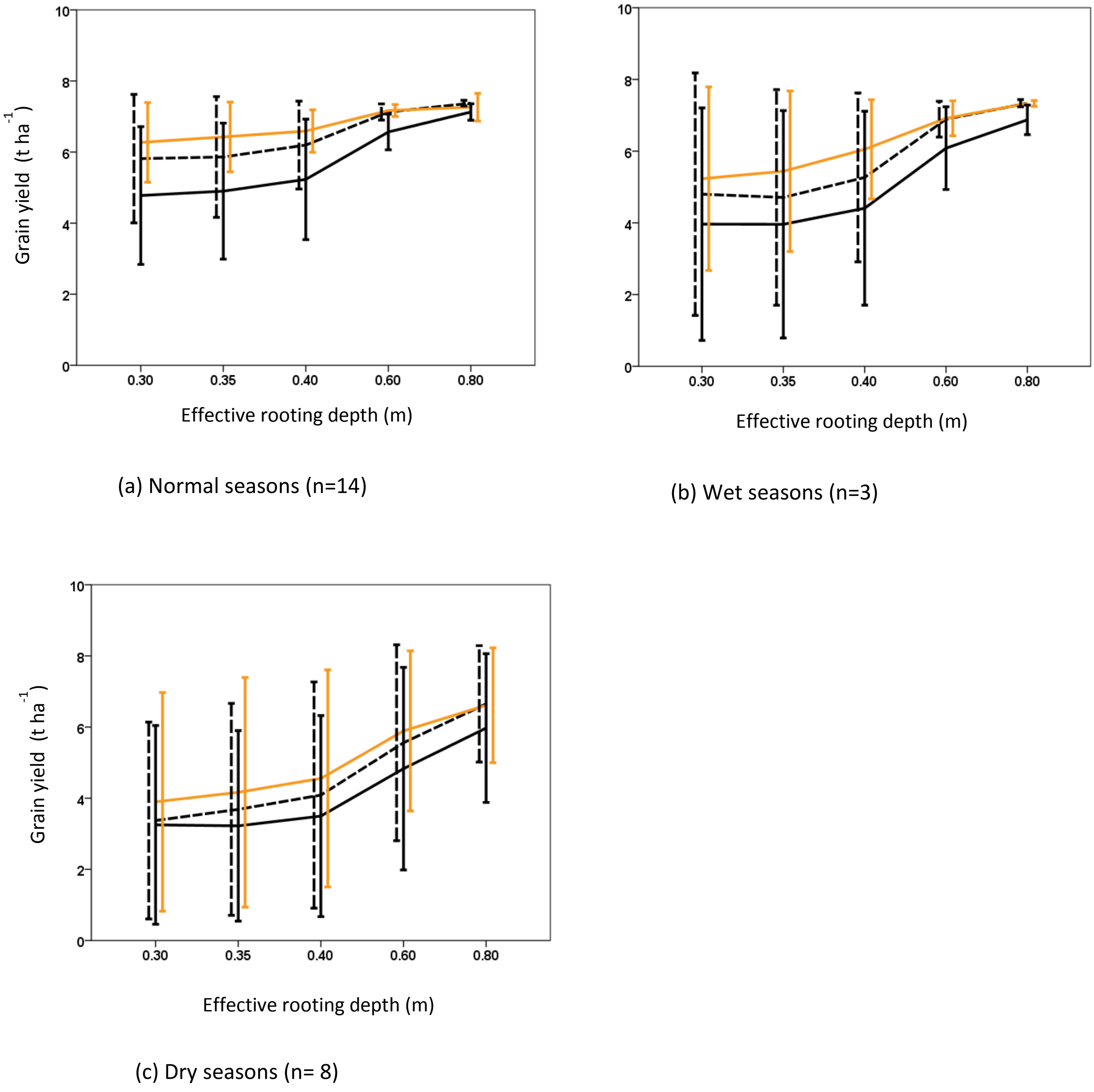


Figure 5.4: Simulated maize (cultivar SC513) grain yield (t ha^{-1})for 0.30 m, 0.35 m, 0.40 m, 0.60 m and 0.80 m effective rooting depths at 32500 plants ha^{-1}. Means for Chongoma (black solid line), Magaranhewe (dashed black line) and Kapitawo (light solid line) in Rushinga district, Zimbabwe. Error bars: standard deviation

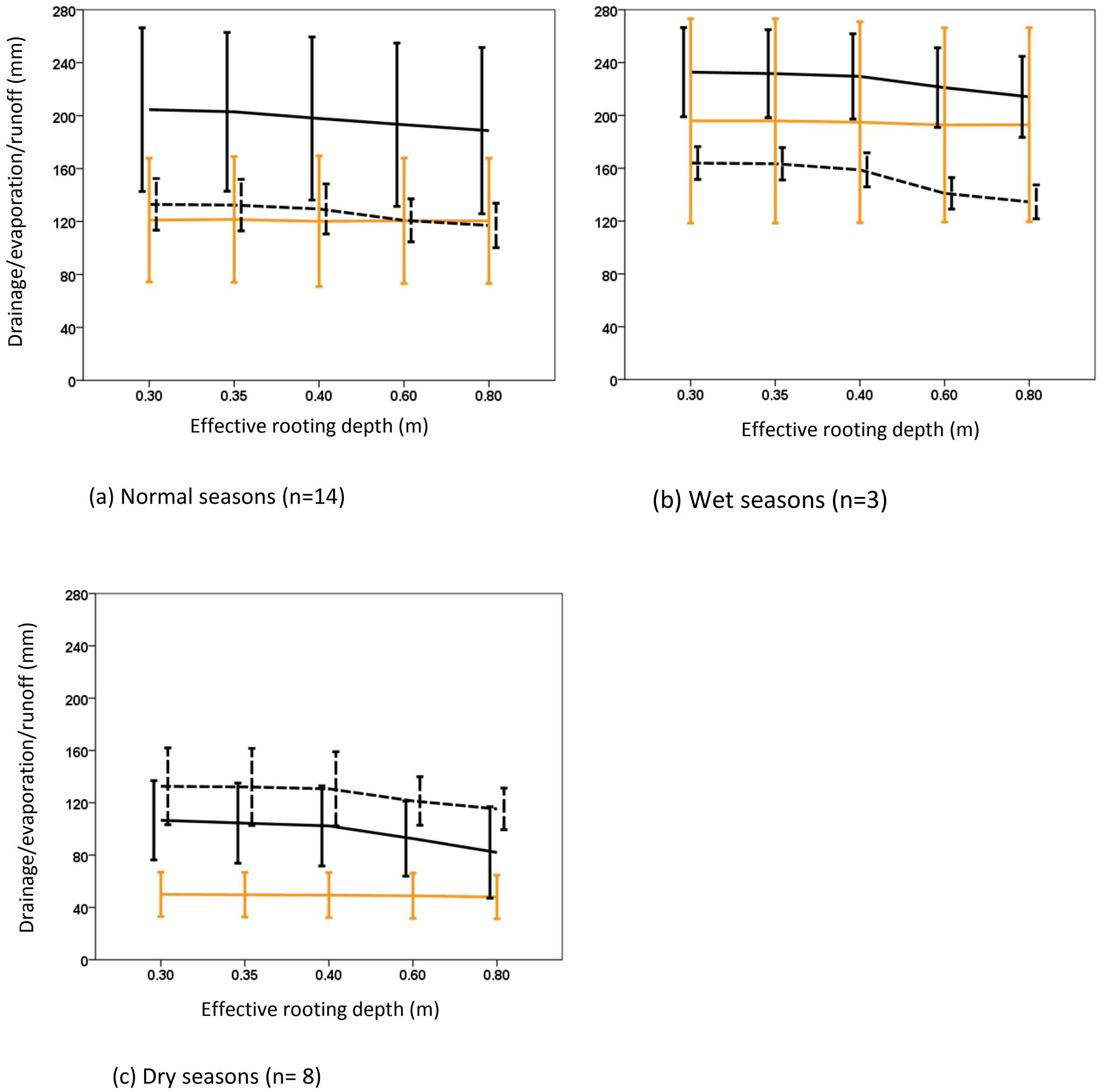


Figure 5.5: Simulated drainage below the rootzone (solid black line), evaporation (dashed black line) and runoff (solid light line) losses (mm) at 0.30 m, 0.35 m, 0.40 m, 60 m and 0.80 m effective rooting depths at a plant density of 32500 plants ha^{-1} for Chongoma, Magaranhewe and Kapitawo in Rushinga district, Zimbabwe. Error bars: standard deviation

5.6.2 Plant density

Normal years

For modelling based on 0.40 m effective rooting depth at 17500, 25000 and 32500 plants ha^{-1}, differences ($P < 0.05$) in biomass and grain yield were observed for all the three plant densities for Kapitawo. For Chongoma the higher densities had similar performance ($P > 0.05$) and performed better ($P < 0.05$) than the lower density. For Magaranhewe, biomass yield increased with increasing density (17500 < 25000 < 32500); for grain yield the higher densities outperformed ($P < 0.05$) the lowest density but performed similarly ($P > 0.05$). On average; increasing plant density (plants ha^{-1}) from 17500 to 32500 increased ($P < 0.05$) grain yield by 2.0 t ha^{-1} (from 4.0 to 6.0 t ha^{-1}) corresponding to a 50% increase. Though not significant ($P < 0.05$) at two of the three sites, increasing from 25000 to 32000 plants ha^{-1} resulted in additional 0.6 t ha^{-1} (from 5.4 to 6.0 t ha^{-1}) equivalent to 11.1% increase. Respective water use efficiencies followed a similar trend to biomass and grain yield for all sites (Table 5.6). On average increasing plant density (plants ha^{-1}) from 17500 to 32500 and from 25000 to 32500 increased biomass water use efficiency by 37.3 and 11.0%; grain water use efficiency by 46.7 and 9.6%; and GWUE by 41.4 and 11.9% respectively.

For all sites the lowest density had higher percentage soil evaporation ($P < 0.05$) than the two higher densities which had similar values ($P > 0.05$). Percentage soil evaporation values (SD) for the lowest and highest densities respectively were 29.3 (4.4) and 24.3 (4.4) for Chongoma; 27.2 (4.3) and 20.8 (3.1) for Magaranhewe; and 27.8 (4.2) and 21.3 (3.3) for Kapitawo.

Biomass and grain yield increased ($P < 0.001$) with increasing density when the model was run at 0.60 m and 0.80 m effective rooting depths (Figure 5.6) for plant densities from 17500 to 44400 plants ha^{-1} for all sites. Respective water use efficiencies followed a similar trend to biomass and grain yield, but depicted less significant ($P < 0.05$) results except for GWUE which was similar at 25000 and 32500 plants ha^{-1} for Kapitawo (Table 5.6). Generally percent soil evaporation decreased with increasing plant density, but from 25000 plants ha^{-1} successive densities had similar percentage soil evaporation values. Percentage soil evaporation values (SD) for 32500 and 44400 plants ha^{-1} respectively were 20.6 (3.4) and 18.1 (3.1) for Chongoma; 19.2 (3.4) and 16.6 (3.6) for Magaranhewe; and 20.3 (3.5) and 17.9 (3.3) for Kapitawo for modelling at 0.80 m effective rooting depth.

Dry and wet years

For modelling at effective rooting depth 0.40 m and 17500, 25000 and 32500 plant ha^{-1}, dry and wet seasons had similar performances for all variables ($P > 0.05$) except for Kapitawo where biomass water use efficiency for 32500 plant ha^{-1} was higher ($P < 0.05$) than for the two lower densities in wet seasons. Mean (SD) GWUE (%) was least in wet years; 10.5 (1.4) at 17500 plants ha^{-1}, 12.8 (1.6) at 25000 plants ha^{-1}, and 14.2 (1.7) at 32500 plants ha^{-1}; and highest in dry years 19.8 (2.2) at 17500 plants ha^{-1}, 23.8 (2.7) at 25000 plants ha^{-1} and 25.8 (2.6) at 32500 plants ha^{-1}.

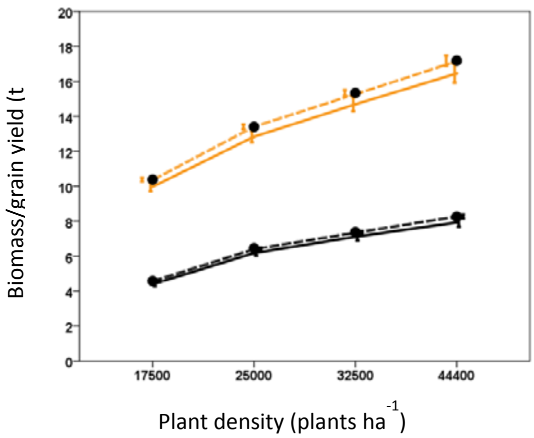
In dry years, modelling at 0.60 m effective rooting depth up to a maximum density of 44400 plants ha^{-1} generally shows that 32500 and 44400 plants ha^{-1} had lower ($P < 0.05$) percent soil evaporation rates than the lowest plant densities, 25000 and 17500 plants ha^{-1} at all sites. For Chongoma all other variables were similar ($P > 0.05$), but Magaranhewe and Kapitawo biomass yielded more ($P < 0.05$) at 32500 and 44400 plants ha^{-1} than 25000 and 17500 plants ha^{-1}. Similar trends were observed for water use efficiencies for Kapitawo, but water use efficiencies were not different ($P > 0.05$) for Magaranhewe.

For modelling at 0.80 m effective rooting depth, in dry years percent soil evaporation was lower ($P < 0.05$) for all other densities than 17500 plants ha^{-1} for Magaranhewe and Kapitawo. Middle densities had similar ($P > 0.05$) percent soil evaporation values which were higher ($P < 0.05$) than the value for 44400 plants ha^{-1} for Magaranhewe, but 32500 plants ha^{-1} equalled 44400 plants ha^{-1} at Kapitawo and Chongoma. Biomass and grain yield increased ($P < 0.001$) with increasing density for Magaranhewe, and water use effciencies followed a similar trend. For Chongoma a consistent trend was observed for biomass, grain yield and water use efficiencies where the lowest density 17500 plants ha^{-1} had similar (P > 0.05) values to 25000 plants ha^{-1} which in turn had similar (P > 0.05) values to 32500 plants ha^{-1} which had a similar values to 44400 plants ha^{-1}. For Kapitawo, biomass, grain yield and GWUE a consistent trend was observed where 17500 had lower (P < 0.05) values than 25000 which had similar values to 32500 but lower than 44400 plants ha^{-1}. For grain water use efficiency the lowest density had a lower value than all other densities which were similar (P > 0.05).

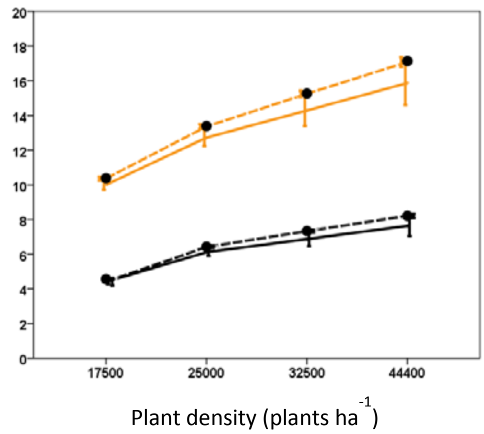
For wet years, simulations at 0.60 m effective rooting depths showed that in general the lowest density (17500 plants ha^{-1}) differed from the highest density (44400 plants ha^{-1}) for all variables except GWUE for Chongoma. Differences were more pronounced for Magaranhewe and Kapitawo. Simulations at 0.80 effective rooting depth resulted in significant differences for all variables at all sites.

General

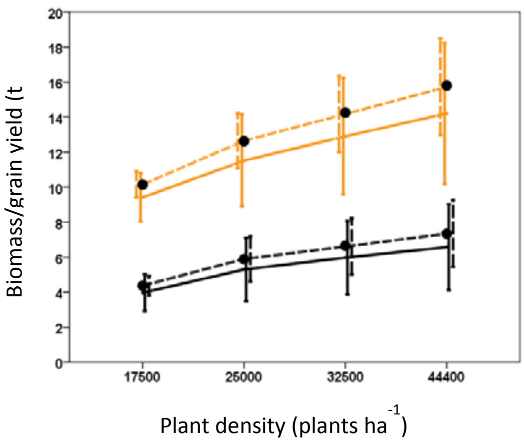
Runoff and drainage below rootzone were similar across sites, effective rooting depths, plant densities and seasons (P > 0.05).



(a) Normal seasons (n=14)



(b) Wet seasons (n=3)



(c) Dry seasons (n= 8)

Figure 5.6: Relation between plant density and mean simulated maize biomass and grain yield (t ha^{-1})at 0.80 effective rooting depth for Chongoma (solid lines: lower line represents grain yield and upper line represents biomass), Kapitawo (dashed lines: lower line represents grain yield and upper line represents aboveground biomass), and Magaranhewe (filled circles:lower circles represent grain yield and upper circles represent biomass) in Rushinga, Zimbabwe. Error bars: standard deviation.

Table 5.6: Plant density of maize (cultivar SC513) and mean (SD) water use efficiencies derived from simulations with AquaCrop at 0.40 m, 0.60 m and 0.80 m effective rooting depths in [n]normal years for three sites in Rushinga district, Zimbabwe

Site	Plant density	Biomass water use efficiency	Grain water use efficiency	Green water use efficiency	Biomass water use efficiency	Grain water use efficiency	Green water use efficiency	Biomass water use efficiency	Grain water use efficiency	Green water use efficiency
	(plants ha^{-1})	(kg ha^{-1} mm^{-1})	(kg ha^{-1} mm^{-1})	(%)	(kg ha^{-1} mm^{-1})	(kg ha^{-1} mm^{-1})	(%)	(kg ha^{-1} mm^{-1})	(kg ha^{-1} mm^{-1})	(%)
		0.40 m			0.60 m			0.80 m		
Chongoma	17500	30.7 (5.8)[a]	13.5 (2.6)[a]	13.1 (3.3)[a]	35.6 (2.6)[a]	15.7 (1.1)[a]	15.3 (1.6)[a]	37.9 (3.2)[a]	16.7 (1.4)[a]	16.2 (1.6)[a]
	25000	37.9 (6.7)[b]	17.8 (4.1)[b]	16.5 (4.1)[b]	43.9 (2.7)[b]	21.1 (1.3)[b]	19.5 (2.4)[b]	46.3 (2.7)[b]	22.3 (1.3)[b]	20.9 (2.1)[b]
	32500	41.8 (8.4)[b]	19.3 (5.3)[b]	18.3 (4.9)[b]	48.9 (2.8)[c]	23.6 (1.3)[c]	22.2 (2.9)[c]	51.8 (2.6)[c]	25.1 (1.4)[c]	23.9 (2.4)[c]
	44400	47.1 (16.9)[b]	21.3 (9.4)[b]	18.3 (8.4)[b]	53.8 (2.7)[d]	26.0 (1.4)[d]	24.8 (3.3)[d]	57.0 (2.4)[d]	27.5 (1.2)[d]	26.8 (2.8)[d]
Magaranhewe	17500	35.5 (3.4)[a]	15.6 (1.5)[a]	15.1 (2.5)[a]	38.6 (2.8)[a]	17.0 (1.2)[a]	16.5 (1.6)[a]	39.4 (2.9)[a]	17.3 (1.3)[a]	16.9 (1.6)[a]
	25000	44.1 (4.4)[b]	21.0 (2.7)[b]	19.1 (3.4)[b]	48.0 (5.5)[b]	23.5 (2.2)[b]	20.4 (3.3)[b]	48.8 (2.9)[b]	23.5 (1.6)[b]	21.7 (2.1)[b]
	32500	49.1 (4.0)[c]	22.9 (3.6)[b]	21.6 (3.6)[b]	53.0 (2.7)[c]	25.5 (1.3)[c]	24.1 (2.6)[c]	54.4 (3.0)[c]	26.1 (1.4)[c]	24.9 (2.4)[c]
	44400	53.5 (5.7)[d]	24.6 (5.3)[d]	24.1 (4.1)[d]	58.1 (2.6)[d]	28.0 (1.2)[d]	26.9 (3.0)[d]	61.2 (3.0)[d]	29.4 (1.4)[d]	27.8 (2.9)[d]
Kapitawo	17500	36.0 (2.6)[a]	15.9 (1.1)[a]	15.8 (1.8)[a]	37.3 (2.7)[a]	16.5 (1.2)[a]	16.5 (1.6)[a]	37.5 (2.9)[a]	16.5 (1.3)[a]	17.4 (3.0)[a]
	25000	44.4 (3.0)[b]	21.4 (1.4)[b]	20.0 (2.7)[b]	46.5 (2.7)[b]	22.4 (1.3)[b]	21.1 (2.1)[b]	47.6 (3.1)[b]	22.7 (1.5)[b]	21.7 (2.1)[b]
	32500	49.4 (3.2)[c]	23.8 (1.6)[c]	22.3 (3.1)[c]	52.0 (2.7)[c]	25.0 (1.3)[c]	24.2 (2.5)[c]	54.9 (5.8)[c]	26.4 (2.9)[c]	23.6 (3.9)[b]
	44400	54.5 (2.8)[d]	25.9 (2.0)[d]	28.9 (8.2)[d]	57.2 (2.6)[d]	27.6 (1.2)[d]	27.2 (2.9)[d]	58.0 (3.0)[d]	28.0 (1.6)[d]	28.0 (2.8)[c]

Means with a common superscript for each variable within a single site and effective rooting depth are not different ($P > 0.05$); whilst means without a common superscript are different ($P < 0.05$).

[n]Seasonal rainfall 456-857 mm (Nyakudya and Stroosnijder, 2011)

5.6.3 Planting dates

All simulated and derived variables were similar (P > 0.05) for the first and second planting opportunities for normal, wet, and dry seasons and for all sites. Accordingly, linear regression between the first planting yield and the second planting yield for biomass and grain yield showed significant relationships (P < 0.001).

Simulations at 0.60 m effective rooting depth showed that for Chongoma, grain yield, R^2 = 0.96, RMSE =0.0, biomass, R^2 = 0.89, RMSE = 0.0 t ha^{-1}; for Magaranhewe, grain yield R^2 = 0.96, RMSE = 0.1 t ha^{-1}, biomass R^2 = 0.96, RMSE =0.2 t ha^{-1}; and for Kapitawo, grain, R^2 = 0.98, RMSE =0.0 t ha^{-1}, biomass, R^2 = 0.97, RMSE = 0.2 t ha^{-1}.

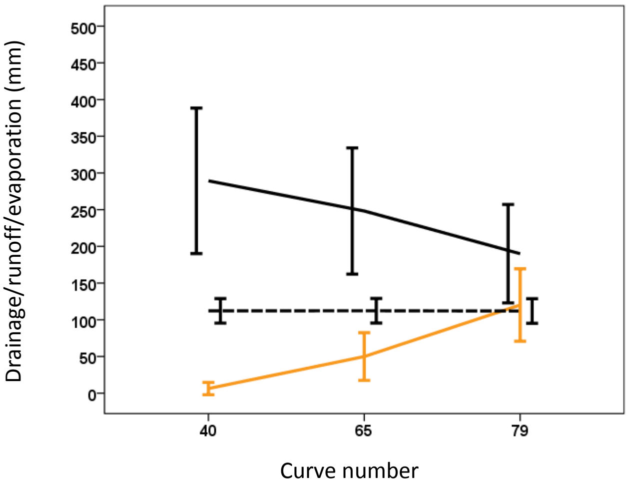
On average the first planting opportunities occurred 28 days after November 1 and second occurred 12 days later. The cropping season has a declining temperature regime from the onset to the end but there were no differences (P > 0.05) in the growing degree days (GDD) within the growing cycle defined by calendar days, mean (SE) for the first planting opportunity was 1754 (9) ^{0}C and that for the second was planting 1748 (9) ^{0}C.

5.6.4 Curve number (CN)

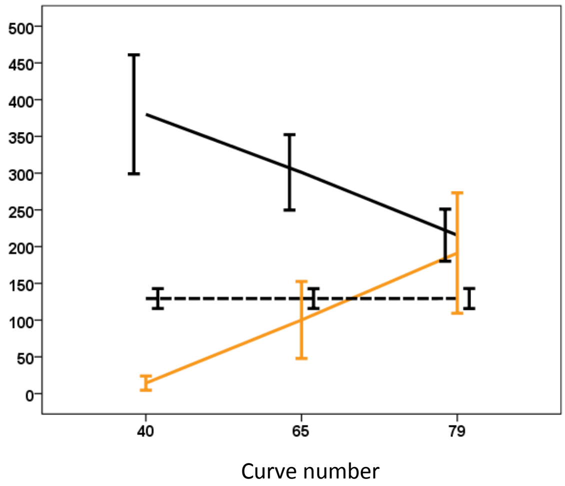
For all sites and from dry to wet years, there were no differences (P > 0.05) among curve numbers for all variables except runoff and drainage below rootzone (P < 0.05). Due to proximity between values obtained among sites it was difficult to plot all sites in one graph so we present results for Magaranhewe as an example. As anticipated runoff increased with increasing CN whilst drainage below rootzone had an inverse relation with CN. Although, the relation between runoff and drainage below rootzone with CN is obvious, we present Figure 5.7 in order to show the estimated water quantities involved. Soil evaporation is included as another non-productive flow of water and it is constant for a given season quality. Mean (SD) drainage below rootzone (%) for CN = 79 in dry years and CN = 40 in wet years was: 28.2 (9.3) and 54.7 (6.7) for the 0.40 m effective rooting depth; 25.1 (8.6) and 50.6 (10.5) to for 0.60 m effective rooting depth; and 22.8 (9.7) and 49.5 (10.1) for 0.80 m effective rooting depth.

Normal years

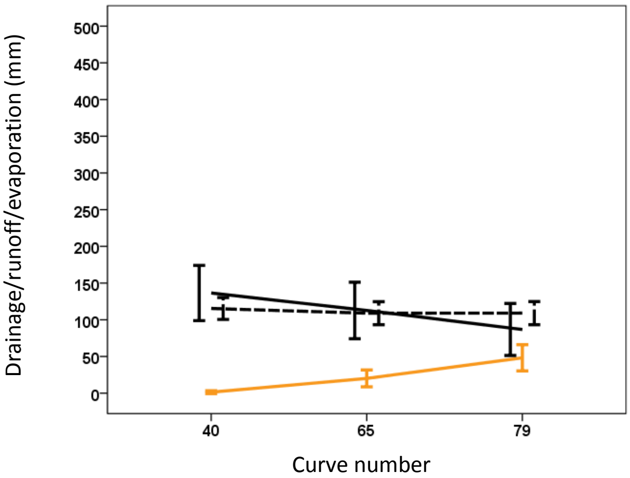
For all effective rooting depths and curve numbers there were differences in runoff (P < 0.001) and drainage below rootzone (P < 0.05). Simulations with a CN = 79 representing maize production under conventional tillage resulted in 31.4% loss of rainfall (about 190 mm) in the crop growing cycle as drainage below rootzone (Figure 5.7).



(a) Normal seasons (n=14)



(b) Wet seasons (n=3)



(c) Dry seasons (n= 8)

Figure 5.7: Relationship between curve number and simulated non-productive water losses (mm) at 0.80 m effective rooting depth: drainage below rootzone (solid black lines), runoff (solid light lines) and soil evaporation (dashed black lines) for Magaranhwe, Rushinga district Zimbabwe. Error bars: standard deviation.

Wet years

For the 0.40 m effective rooting depth, curve numbers 40 and 65 had similar percent runoff amounts ($P > 0.05$) which were lower ($P < 0.05$) than that for CN 79. At higher effective rooting depths CN 79 had higher runoff than CN 40 which had similar runoff to both CN 40 and CN 65. Drainage exhibited a similar trend to runoff for all effective rooting depths.

Dry years

Percentage drainage below rootzone was larger for CN 40 than 79 ($P < 0.05$) with the middle CN having similar ($P > 0.05$) values with the lower and the higher CN at all effective rooting depths. Runoff at all sites increased ($P < 0.05$) in the order (40 < 65 < 79).

5.7 Discussion

5.7.1 Model performance

AquaCrop simulated canopy cover (CC) development fairly well at both Magaranhewe and Chongoma. Stress induced decline in CC is a highly demanding test for the model since a small deviation in simulated timing can lead to a significant difference in CC duration (Heng et al., 2009). Hsiao et al. (2009) state that the model has difficulties in simulating water stress induced early senescence. This could be a contributory factor in the lag period observed for responding to water stress induced senescence between the simulated values and the measured values (Figure 5.2). In this study, the situation was compounded by *Striga* spp. (maize witch weed) stress induced senescence. The witch weed is a parasite of maize and causes wilting of plant leaves thus reducing the green CC. This leads to observed early canopy senescence or stunted canopy growth. The weed emerged from February onwards and was triggered by dry spells. In spite of the timing challenges, at Magaranhewe, during the 2012/13 season the model simulated canopy senescence at day 79, six days into a 21-day dry spell (Figures 5.1 and 5.2). At Chongoma the model also showed good sensitivity to dry spells when canopy decline began at 78 days after planting after a 10-day dry spell interrupted by only 6 mm on day 71. The differences in CC may also be partly due to sampling and measurement errors.

Stricevic et al. (2011) reported that in a year where there was sufficient precipitation to support high yield AquaCrop simulated rainfed yield excellently. The 2011/12 season at Chongoma had a 17-day dry spell from day 15 to day 31 in addition to terminal dry spells (Figure 5.1). The model was unable to correctly simulate the expected stunted growth and drastic decline in CC (Figure 5.2).

On average there was good agreement between simulated and measured biomass values as reflected by CE values 0.71 to 0.98 (Table 5.4) for simulations at 0.40 m effective rooting depth. Heng et al. (2009) obtained a CE of -2.01 for CC and 0.77 for biomass accumulation under rainfed conditions for maize. We obtained CE values for CC ranging from 0.42 to 0.69 for the drier Chongoma site (Table 5.4) without calibration and our simulation of biomass accumulation compared favourably with their results. The high CE values obtained in this study, however, need to be treated with caution because values used to calculate them were obtained from the same crop within a year. This implies strong dependency and auto-correlation.

The model overestimated soil water in contrast to findings by Biazin and Stroosnijder (2012) who observed underestimation of measured soil water by the model with RMSE values of 7.3 mm and 8 mm compared to our results (11.5 mm to 17.2 mm). The reason for overestimation of soil water is that measurements in some cases missed the peak soil water as they were not always taken just after each rainfall event. Hsiao et al. (2009) observed a similar trend. Relatively large RMSE values and CE values close to 0 implied that the model predictions are as accurate as the mean of the observed data. Differences between simulated and observed values also arise due to the natural variability of field soils which is not considered in the model.

On average the model overestimated final biomass and grain yield. For the 2011/12 season at Chongoma the terminal dry spells reduced harvest index (HI) and resulted in lower measured final biomass and grain yield. The 778 mm seasonal rainfall (Nov-Mar) (Figure 5.1) is misleading since the crop did not use 125 mm of this amount that fell on 30 March after drying prematurely due to water stress. Biazin and Stroosnijder (2012) report positive deviations up to 17.7% for final biomass and 11.8% for final grain yield. Hsiao et al. (2009) obtained deviations ranging from -20.6% to + 21.9%. For our data, without calibration we obtained larger deviation (%) (Table 5.5). However, with the mean observed final biomass and grain yield at 96 and 92% of the mean simulated values respectively for the 0.40 m effective rooting depth (Table 5.5) without calibration we considered the model performance to be good enough for the model to be used for exploring options for improving rain water use efficiency in semi-arid Zimbabwe.

The observed HI ranged from 0.22 to 0.42 with a mean = median of 0.33 (Chapter 4, Table 4.5). Mhizha (2010) observed HI ranging from 0.31 to 0.41 from higher rainfall areas in Zimbabwe. However, there was no basis for changing the HI_0 to a lower figure.

5.7.2 Model Application

The large maize grain yield gap of 2.4 t ha^{-1} observed in farmers' fields from 0.1 t ha^{-1} minimum to 2.5 t ha^{-1} maximum is largely attributed to management factors. We observed none or minimal application of fertilizers, late planting and weeding and low plant densities in fields of most farmers in the district. In most cases fertilizers are only applied to some but not all fields. Thus, low crop yields in farmers' fields are attributed to these management factors among others.

The mean maximum maize yield for Rushinga district, 2.5 t ha^{-1} is comparable to the mean yield of 2.7 t ha^{-1} that we obtained under field experiments. In addition the maximum measured yield in the experiments was 5.0 t ha^{-1} (Chapter 4, Table 4.5) and it falls within simulated yield range at the 0.40 m effective rooting depth (Figure 5.4).

For modelling at 0.40 m effective rooting depth and a final plant density of 32500 plants ha^{-1}, in general differences in variables ($P < 0.05$) were observed in normal years (56.0% of the seasons). This suggests that agronomic manipulations will not have an effect ($P > 0.05$) in dry and wet years in most cases. This is expected because in wet seasons there is sufficient and usually well distributed rainfall and in dry seasons rainfall is simply inadequate to meet crop water requirements. However, modelling at larger effective rooting depths 0.60 m and 0.80 m and higher plant density such as 44400 plants ha^{-1} also resulted in differences in most variables in wet years.

Modelling showed that increasing effective rooting depth from 0.30 m to 0.60 m improved biomass and grain yield and respective crop water use efficiencies, and GWUE at all sites in normal years ($P < 0.05$) and stabilizes crop yields as reflected by the lower standard deviations for the 0.60 m effective rooting depth (Figure 5.4). This is attributed to larger amount of plant available water under a deeper root system. In situations where high drainage losses are prevalent (Figures 5.5, 5.7) a deeper root system enables plants to extract water that would otherwise be lost through drainage below the rootzone at a shallower effective rooting depth. At Chongoma, soil evaporation losses were reduced by increasing effective rooting depth possibly due to larger canopy cover developed under the deeper rooting maize crop. Therefore, farmers can achieve better yields at 0.60 m effective rooting depth. Large grain yield fluctuations in dry years as shown by large standard deviations even at 0.60 m effective rooting depth (Figure 5.4) lead to yield instability and lack of yield difference ($P >0.05$) between 0.30 m and 0.60 m despite a large yield gap of 1.9 t ha^{-1} from 3.5 to 5.4 t ha^{-1}. The fact that increasing effective rooting depth from 0.60 m to 0.80 m at 32500 plants ha^{-1} did not increase ($P > 0.05$) biomass and grain yield implies that farmers may not benefit much from maize effective root depth beyond 0.60 m at ≤32500 plants ha^{-1}.

Simulation results showed better grain and biomass yield performance with increasing final plant density up to highest plant density considered in this study, 44400 plants ha^{-1} (Figure 5.6), and water use efficiencies followed a similar trend (Table 5.6). Percentage crop emergence under smallholder farming conditions is often low; therefore, farmers can achieve a final plant density of 32500 plants ha^{-1} by planting at the Agritex recommendation of about 50000 plants ha^{-1} assuming 65% plant emergence. Farmers who achieve 90% (44400 plants ha^{-1} final density) will benefit more. Runoff and drainage below rootzone percentages were similar at all plant densities and this is attributed to the constant CN. However, drainage below the rootzone was large (Figures 5.5 and 5.7) and we attributed this to the generally shallow to medium effective rooting depths considered in this study and the heavy storms that are typical of semi-arid Zimbabwe especially during the December to January period when the maize crop is still in the early development stage (Munodawafa and Zhou, 2008; Nyakudya and Stroosnijder, 2011). In normal years GWUE ranged from 13.1% at 17500 plants ha^{-1} to 22.3% at 32500 plants ha^{-1} at 0.40 m effective rooting depth. GWUE increases from a minimum of 16.2% at 17500 plants ha^{-1} to 28.0% at 44400 plants ha^{-1} and 0.80 m effective rooting depth (Table 5.6). Green water use efficiency drops to 12.4% at 17500 plants ha^{-1} and 21.2% at 44400 plants ha^{-1} at 0.80 effective rooting depth in wet years (not shown). These figures are close to a high of 20% estimated by Stroosnijder (2009) for East Africa and are within the range of 10 to 30% estimates by Falkenmark and Rockström (2006). Farmers may benefit by increasing the plant density (plants ha^{-1}) from 32500 to 44400 if a wet season is anticipated. The fact that increasing effective rooting depth from 0.60 m to 0.80 m whilst maintaining a plant density (plants ha^{-1}) of 32500 did not lead to grain yield increase implies that at low plant densities an increase in effective rooting depth should be coupled with an increase in plant density. Probably the optimum effective rooting depth for the cultivar under study is 0.60 m at 44400 plants ha^{-1} because this effective rooting depth - plant density combination produced high grain yield 7.8 t ha^{-1} which is similar to a mean maximum of 8.0 t ha^{-1} produced at 0.80 m and 44400 plants ha^{-1} (Figure 5.6) and in normal and wet years.

The high simulated yield of 7.8 t ha^{-1} at 0.60 m effective rooting depth and 44400 plants $ha^{-1}$is interesting because it exceeds the yield potential of 3 to 5 t ha^{-1} that corresponds to the fertilizer application rates used in this study. We are cognisant of the fact that this can only be achieved in seasons with adequate and well distributed rainfall. We used as most important yield driving variables (as explained in section (3.3) values of 29.0 g m^{-2} for WP* and 48% for HI_0 because our aim was to simulate attainable yield using long-term rainfall data. The question arises how realistic a value of 7.8 t ha^{-1} for attainable yield is. Of course it would have been easy to suppress the yield level by calibrating the model. But since it was our goal to use AquaCrop without calibration we deliberately did not consider this option. Instead we ask ourselves the question whether our current idea of attainable is still correct. Maybe there are still production limiting factors that we have not yet considered and taken into account. And maybe the yield gap is larger than we think. If correct, this would imply that there is even more to gain in proper crop husbandry than we think. Food for thought!

Lack of differences ($P > 0.05$) in all variables except percentage runoff and drainage below rootzone with CN suggests that under a sole maize crop, practices that alter CN for instance, conservation tillage and rainwater harvesting alone, will not have a significant effect on biomass and grain yield and respective water use efficiencies under the soils, effective rooting depth and plant density scenarios used in this study. Innovative strategies are required to manipulate the field water balance effectively by reducing non-productive water losses particularly drainage below the rootzone in all seasons and soil evaporation in dry seasons (Figures 5.5 and 5.7).

In an experiment comparing conventional tillage, mulch ripping and conservation basins (planting pits) Mupangwa et al. (2012) reported that tillage method had no effect ($P > 0.05$) on maize grain yield, but mulching increased grain yield. Mulching reduces soil evaporation losses and this is important for mitigating effects of dry spells. Lack of effect of CN may also be attributed to the relatively low available water capacity of the soils (Equation 5.1): 61-74 mm for 0.60 m effective rooting depth (Table 5.1) that renders them less responsive to field water balance manipulations. Addition of organic fertilizers increases soil water retention in coarse to medium textured soils (Rawls et al., 2003) which are typical of soils at the experimental sites. Where a restrictive soil layer that impedes root growth exists due to a plough pan for example, deep ripping can be done to increase the effective rooting depth. In places with shallow soils ridge/furrow systems where planting is done on the ridge also increase maize effective rooting depth (Vogel, 1993). Selection of and/or breeding for deep rooting maize cultivars is an example of manipulation of the crop factor in the PAW equation (Equation 5.1). In addition intercropping systems incorporating legumes with deeper rooting systems for example pigeonpea (*Cajanus cajan* (L.) Millsp.) can be explored as options for improving WUE and GWUE. Simulated drainage below the rootzone in normal years ranging from 31.8 to 33.2% of rainfall in the crop growing cycle may lead to nutrient losses through leaching. Simulated drainage below the rootzone exceeds the maximum of 25% estimated by Falkenmark and Rockström (2006).

Planting in November at the onset of the rains is the safest under rainfed conditions in Zimbabwe as the crop is able to utilise the full length of the rainy season. Early maturing enables the crop to escape debilitating end of season dry spells. Nyagumbo (2007) reported grain yield losses of 5% per week delayed. AquaCrop simulations produced insignificant differences in grain yield between the first plantings and second plantings based on the Agritex criterion. In Zimbabwe there are other reasons why late plantings often give lower yields than early plantings which the model could not capture. These include higher incidence of pests for example stalk borer (*Busseola fusca* (Fuller)), and diseases for example maize streak disease caused by the *Maize streak virus* in late planted crops. Thus, simulations with planting dates exemplify the need to consider other biophysical conditions that are outside the scope of crop models.

5.8 Conclusions

AquaCrop was able to simulate CC development fairly well and simulated biomass accumulation values showed good agreement with measured values. On average, the model overestimated soil water, final biomass and grain yield. However, the reasonably good model performance without parameter adjustments (calibration) implies that the model can be applied in semi-arid Zimbabwe as a tool for selecting adaptive water management practices.

In general differences in variables ($P < 0.05$) were only observed in normal years for simulations at 32500 plants ha^{-1} at 0.40 m effective rooting depth. However, at deeper effective rooting depths, 0.60 m and 0.80 m and a higher plant density of 44400, plants ha^{-1} differences in variables were also observed in wet years.

Increasing effective rooting depth (m) for simulation from 0.40 to 0.60 increased maize grain yield by 16.7% from 6.0 to 7.0 t ha^{-1}. Increasing effective rooting depth (m) from 0.60 to 0.80 at 32500 plants ha^{-1} results in 0.3 t ha^{-1} yield gain which is not statistically significant. Doubling effective rooting depth from 0.40 m to 0.80 m results in 1.3 t ha^{-1} equivalent to a 21.7% increase in grain yield.

Drainage below rootzone simulated at 0.80 m effective rooting depth constitutes the bulk of non-productive water losses and is ≥ 40% in normal and wet years whilst soil evaporation contributes 47% of non-productive losses in dry years.

Increasing plant density (plants ha^{-1}) from 17500 to 32500 increased ($P < 0.05$) simulated grain yield from 4.0 to 6.0 t ha^{-1} at 0.40 m effective rooting depth. Increasing plant density (plants ha^{-1}) from 32500 to 44400 at 0.40 m effective rooting depth results in grain yield equal to 6.6 t ha^{-1}, an increase of 10% from 6.0 t ha^{-1}. Grain yield increased to 7.8 t ha^{-1} ($P < 0.001$) when the model was run at 0.60 m effective rooting depth and 44400 plants ha^{-1}.

All simulated and derived variables were similar ($P > 0.05$) for the first and second planting opportunities based on the Agritex criterion for all years, seasons and sites for simulations up to 0.60 m effective rooting depth. Accordingly, linear regression between the first planting yield and the second planting yield for biomass and grain yield showed significant relationships ($P < 0.001$).

We recommend the following in order to improve water use efficiency: a plant density of approximately 44400 plants ha^{-1} (which can be achieved by improving the emergence percentage); incorporation of legumes preferably deeper rooting legumes such as pigeonpea; adopting deeper rooting (≥ 0.60 m effective rooting depth) maize cultivars and adoption of cultural practices such as deep ripping that improve maize effective rooting depth. Addition of organic fertilizers to improve available water capacity; and mulching to reduce evaporation from the soil surface should also be practised where resources are available.

Future focus should be on multisite participatory field testing of results from this study with farmers in order to put theory into practice.

Chapter 6

Synthesis

Synthesis

6.1 Introduction

Despite being home to the first maize (*Zea mays* L.)-based green revolution in Sub-Saharan Africa (Eicher, 1995), Zimbabwe still experiences low and unstable yields in the semi-arid regions (Natural Regions IV and V, mean annual rainfall 450-650 mm and less than 450 mm respectively) (Vincent and Thomas, 1960). Inadequate and poorly distributed rainfall and in some instances poor soil fertility are the major biophysical yield-limiting factors. Given, the adverse biophysical conditions it is expected that crop yields will be low. However, it has been argued that though rainfall is marginal, low productivity is more due to management-related sub-optimal performance than low physical potential (Rockström and Falkenmark, 2000; SIWI, 2001). Lessons from the smallholder green revolutions worldwide including Zimbabwe show that success is achieved by developing a system of interrelated policies, improved technology and institutional innovations (Dorward et al., 2004; Eicher, 1995). In this study we focussed on water management. We tried to answer the question "What can be done in terms of water management to improve rainfed maize yields?" We are cognisant of the fact that inadequate resources against competing uses limit available options for smallholder farmers to increase crop yields. The extent to which resource availability limits viable options for different categories of smallholder farmers varies with resource-endowment. Therefore, there should be no standard recommendation or package for soil and water management promotion in semi-arid areas. We present a basket of options as opposed to "silver bullet" solutions (Giller et al., 2011).

In search of multiple options, we combined literature review of maize conservation tillage research, long-term rainfall analysis, field experimentation and crop modelling to determine strategies for optimising rainwater management for improving maize yields in semi-arid Zimbabwe. Research questions and respective answers are outlined below.

(a) Which conservation tillage options are worthy pursuing in semi-arid Zimbabwe?

Literature review revealed that for semi-arid Zimbabwe conservation tillage options worthy pursuing are the 1.0 m tied ridging and mulch ripping. The two conservation tillage methods retain water in the field by reducing surface runoff and increasing infiltration. Mulching further improves rain water use efficiency by reducing evaporation of soil water (Stroosnijder et al., 2012; Thierfelder and Wall, 2009). Monodawafa and Zhou (2008) observed that tied ridges retained 62% and mulch ripping 61% of total seasonal rainfall in the field compared to 51% for conventional tillage.

(b) What are the water management options for rainfed maize production based on long-term rainfall for Rushinga district in semi-arid Zimbabwe?

Rainfall analysis confirmed Rushinga as a low potential area for maize production: dry years, seasonal rainfall < 456 mm, occur at least 3 out of every 10 years; high incidence of dry spells, dry spells > 20 days occurred in 36% of the seasons; 6 to 10-day dry spells occurred on average 3 times per season; and the period during which rainfall exceeds ET_0 is only 110 days. We suggested the following water management options to mitigate droughts, dry spells and the short growing season: rainwater harvesting (RWH); conservation tillage; mulching with dead organic matter; best agronomic practices (maintenance of soil depth, optimum fertilization, weed control, early planting, adjusting plant density to expected rainfall, etc.); use of early maturing cultivars that mature in less than 132 days; adoption of a resilient cropping system that incorporates more drought-tolerant cereals: sorghum (Sorghum bicolor L. (Moench)) and pearl millet (Pennisetum glaucum (L.) R. Br.) and other carbohydrate sources like cassava (Manihot esculenta).

(c) Do infiltration pits really improve soil water content and maize yields?

Infiltration pits did not improve soil moisture content in the cropping area and hence maize yield. We are convinced that special conditions should exist for infiltration pits to benefit field crops. For example, presence of underlying rock outcrops (*dwalas*) and soil depth ≥ 1 m.

(d) Are planting pits a viable tillage option for cultivating maize in semi-arid Zimbabwe?

Planting pits performed similarly to conventional tillage in some years at two of the three sites but consistently yielded lower maize grain and stover yield at the other site. On average grain yield was 45% higher for conventional tillage (mean 2697 kg ha^{-1}) than planting pits (mean 1852 kg ha^{-1}) (Chapter 4, Table 4.5). However, conventional tillage/planting pits grain yield ratio decreased in the order 1.9 for 2010/11 > 1.7 for 2011/12 > 1.3 for 2012/13. Planting pits face constraints with respect to labour for digging and weed control and this renders them unviable. We, therefore, recommend them only for farmers without access to adequate draught power and as a coping tillage method in the event of livestock loss to disasters. In difficult times, when livestock are lost to disasters most smallholder farmers resort to tilling the land with the hoe, see (Hagmann, 1996).

(e) How useful is FAO's AquaCrop as a decision making tool for adaptive practices in rainfed maize production?

AquaCrop performed well without calibration and during agronomic management scenario simulations the model was able to produce results comparable to previous experimental studies (Munodawafa and Zhou, 2008; Nyamudeza, 1999; Vogel, 1993). Therefore, the model can be applied in semi-arid Zimbabwe as a tool for selecting adaptive water management practices. For example with the help of the model we showed positive effects of increasing maize effective rooting depth and optimising plant density on maize yield and water use efficiency.

6.2 Emerging issues

In general, there is agreement between Chapters in this thesis and progressive reinforcement of ideas and results.

6.2.1 Soil fertility and yield level

Literature review (Chapter 2) showed that in Zimbabwe, smallholder farmers commonly apply fertilizers at sub-optimal rates (Mapfumo and Giller, 2001) and in some cases they do not apply fertilizer at all claiming that applying fertilizers burns their crops due to low and unpredictable rainfall (Ncube et al., 2007; Nyamudeza, 1999). Yet, research in the region shows that addition of mineral and organic fertilizers increases maize yield (Ncube et al., 2007; Nyakatawa, 1996; Nyamangara and Nyagumbo, 2010; Nyamudeza, 1999). Without fertilizer or long fallow periods yield of maize falls below 500 kg ha^{-1} (Kwesiga et al., 2003). In Chapter 4 we report the adverse effects of the maize witch weed (*Striga* spp.) which aggravates the effect of low soil fertility. Jamil et al. (2012) state that nutrient deficiency aggravates *Striga hermonthica* infestation may be due to secretion of *Striga* germination stimulants into the soil by host plants. Giller et al. (2006b) note that soil fertility gradients caused by differences in parent material, position on the slope and management exist on African smallholder farms. Large yield gaps for example 0.1 t ha^{-1} minimum and 2.5 t ha^{-1} maximum yield reported in Chapters 1, 4 and 5 for Rushinga district are partly due to these fertility gradients. In wet years and under conditions of high drainage below the rootzone leaching losses exacerbate the effects of sub-optimal fertilizer application. Thus, without adequate fertilizer application, maize yields in wet years can be as low as those for dry years due to nutrient leaching. Through application of adequate fertilizer, a substantial part of the yield gap between lowest performing fields and highest performing fields can be closed.

6.2.2 Combining field-edge and in-field technologies

In Chapter 2, following up on recommendations from literature (Hagmann, 1996; Mupangwa et al., 2012a; Nyagumbo, 1999), we advocate for combinations of in-field and field-edge technologies rather than comparisons between them. By combining these complementary technologies more rainwater is retained in the field and there is better protection of the soil from erosion. It is possible to propose cropping systems for the best use of the combined technologies. For example, planting of horticultural crops inside and close to infiltration pits makes use of water that will not be accessed by conventional field crops. Mupangwa et al. (2012a) citing the predominantly crop-livestock systems in semi-arid southern Zimbabwe proposed strip cropping of deep-rooted food and fodder crops.

6.2.3 Seasonal rainfall and selection of tillage method

In Chapter 3 we recommended RWH and conservation tillage among the management options for maize production. Variation of yield with seasonal rainfall for different tillage methods was noted Chapter 2 (Figure 2.6), where most experiments produced better yields under 1.0 m tied ridging and mulch ripping than conventional tillage, particularly for yield levels ≤ 2.5 t ha^{-1} which occurred under rainfall ≤ 500 mm. Conventional tillage did better than conservation tillage methods for grain yield > 2.5 t ha^{-1} and rainfall > 500 mm. Performing rainfall analysis as a planning and decision making tool, therefore becomes imperative as farmers will know how often their efforts through conservation tillage are likely to be rewarded. For example for Rushinga district with a seasonal mean rainfall of 631 mm for 1980 to 2009 (Nyakudya and Stroosnijder, 2011) conservation tillage would be beneficial in all dry seasons (≥ 30% of the seasons) and some normal years.

In Chapter 5, we show through modelling how increasing maize rooting depth increases maize yield and water use efficiency. Whilst planting on top of the ridge (Vogel, 1993) and possibly in the furrow on the sides of the ridge in tied ridging is in tandem with increasing rootable soil depth (Figure 2.2, Chapter 2) it may not necessary be so for other conservation tillage techniques for example planting pits. If seasonal forecasts are reliable, the farmer can choose the tillage method to suit the season.

6.2.4 Occurrence of large non-productive water losses

From Chapter 3 through 5 a major similarity is prediction of large non-productive water losses as runoff, evaporation and drainage below the rootzone. Through long-term rainfall analysis we illustrate high frequency of the seasonal largest single day and the longest wet spell rainfall amounts in December during the initial development stage of maize that predisposes the soil to degradation by rainfall and leads to high non-productive field water losses. Similar predictions are made in field experiments in Chapter 4 especially for the wetter Magaranhewe site and were reinforced through modelling with AquaCrop. Modelling shows that drainage below rootzone constitutes the bulk of non-productive water losses amounting to ≥ 40% in normal (456-857 mm rainfall) and wet (≥ 858 mm rainfall) years whilst evaporation contributes 47% of non-productive losses in dry years at 0.80 m effective rooting depth. The simulated drainage below the rootzone exceeds a maximum of 25% estimated by Falkenmark and Rockström (2006). High runoff predicted in Chapter 3 associated with large storms reinforce the need for field-edge structures for regulating runoff water particularly from heavy storms by slowing it down, partially redirecting it for safe disposal and allowing it to filter into the cropping area in less erosive quantities. This is reiterated in Chapters 4 and 5.

At field level drainage below the rootzone is a loss, but at farm level the 'drainage losses' recharge the groundwater making it possible to have water in shallow wells and ephemeral streams. The shallow wells and streams are vital water sources at farm level for both domestic and livestock watering.

6.2.5 Effect of agronomic practices

In Chapters 2 and 3 recommendations are made for appropriate agronomic practices including adequate fertilization, timely and effective weed control, early planting, and adjusting plant density to expected rainfall in order to improve maize yield and water use efficiency. In Chapter 5, we estimate through modelling that increasing effective rooting depth (m) for simulation from 0.40 to 0.60 at 32500 plants ha^{-1} increased maize grain yield from 6.0 to 7.0 t ha^{-1}; increasing plant density (plants ha^{-1}) from 17500 to 32500 increased ($P < 0.05$) simulated grain yield from 4.0 to 6.0 t ha^{-1} at 0.40 m effective rooting depth. Increasing plant density (plants ha^{-1}) from 32500 to 44400 at 0.40 m effective rooting depth results in grain yield equal to 6.6 t ha^{-1}. Grain yield increased to 7.8 t ha^{-1} ($P < 0.001$) when the model was run at 0.60 m effective rooting depth and 44400 plants ha^{-1}. For all sites the lowest density had larger percentage evaporation ($P < 0.05$) than the two higher densities which had similar values ($P > 0.05$). By altering curve numbers we also showed how practices such as RWH and tillage method can manipulate the field water balance. Thus, our results reinforce the general agreement that crop yields in smallholder farming systems can be improved through proper agronomic management (Rockström et al., 2010; Tittonell and Giller, 2013).

6.2.6 Length of crop growing period

Tensions between Chapters exist but we attribute them to differences between postulations based on theory and practical realities. From a theoretical perspective using rainfall analysis we recommended short-season cultivars maturing in ≤130 days that fit in the rainy season in all but dry years. However, field experimentation showed that early cessation of the rains at two of the three sites actually leads to even shorter growing periods even in normal years. The 2012/13 season had short crop growth periods with rainfall, 92 days for Chongoma and 72 days for Kapitawo. As depicted in the soil moisture trends graphs (Figure 4.5, Chapter 4) a period of inadequate soil moisture ensued at Chongoma. Soil moisture content fell below wilting point 92 days after planting and the crop dried prematurely. Thus, it may be necessary to plan with a growing period of at most 120 days.

6.3 Reflections

6.3.1 Adapting cropping systems

It is apparent from this thesis that the current cropping system largely based on sole maize crop with minimal intercropping and/or rotations with shallow rooting legumes, for example cowpeas (*Vigna unguiculata* (Walp) L.) and groundnuts (*Arachis hypogaea* L.) and in some cases cotton (*Gossypium hirsutum* L.) is not resource use efficient including land, water and nutrients. The situation is worsened by limited use of mineral and organic fertilizers (Mapfumo and Giller, 2001; Ncube et al., 2007) and the prevalence of degraded non-responsive soils (Tittonell and Giller, 2013) in some cases. Intercropping with deep-rooting legumes for example pigeonpea (*Cajanus cajan* (L.) Millsp.) will improve resource use efficiency whilst at the same time building the soil's organic N capital and reducing the risk of crop failure. In addition, intercropping with pigeonpea helps suppress the maize witch weed (*Striga asiatica* (L.) Kuntze) infestation (Rusinamhodzi et al., 2012). In situations where high drainage below rootzone exist as shown in this thesis, RWH and/or conservation tillage alone may actually increase the losses. For example, Monodawafa and Zhou (2008) observed more drainage water below the rootzone under conservation tillage treatments (78 mm y^{-1} under mulch ripping and 77 mm y^{-1} under tied ridging) compared to conventional tillage with 64 mm y^{-1} ($P < 0.001$). The high drainage water may lead to yield loss due to leaching under sandy soils and more water retained in the field may cause low yields due waterlogging in heavier textured soils.

In some dry seasons or seasons with long dry spells maize fails completely (Nyakatawa, 1996; Nyamudeza, 1999); this was predicted through rainfall analysis (Chapter 3) and reinforced through modelling (Chapter 5). In order to guarantee household food security there is need to provide a buffer against drought years and poor rainfall distribution through a quota system where the more drought-tolerant sorghum and/or pearl millet crop is planted on a prescribed area in addition to the preferred maize crop.

6.3.2 Agronomic options for improving maize yields

Whilst achievement of better yields and improved soil water under tied ridging and mulch ripping is well documented (Motsi et al., 2004; Munodawafa and Zhou, 2008; Nyakatawa, 1996; Nyamudeza, 1999; Thierfelder and Wall, 2009; Twomlow and Bruneau, 2000) adoption of these conservation tillage methods has been low. Adoption has largely been hampered by smallholder farmers' resource constraints particularly labour. As migration of the able-bodied man and women to urban centres within and outside the country continues, the situation may remain the same for the foreseeable future.

We believe that innovation is required but it must be founded on proven agronomic basics. In crop production for example, there is general agreement that crop yields in smallholder farming systems can be improved through proper agronomic management including selection of deep rooting cultivars, appropriate planting dates and plant density (Rockström et al., 2010; Tittonell and Giller, 2013). This implies that even without tillage innovations adoption of these agronomic practices by farmers coupled with application of fertilizers at optimal levels will substantially narrow the yield gap between actual and attainable yields. In this thesis we contribute to this proposition by showing the effect of plant density, rooting depth and planting date on yield through modelling with AquaCrop. Our results show significant effects for rooting depth and plant density as described under section 6.2.

6.3.3 Putting rainwater harvesting into context

From this thesis we learn that success stories of RWH in semi-arid Zimbabwe need to be put into proper context in order to avoid misleading generalisations. This calls for well-designed field experiments and surveys in order to generate quality data. For example, Zimbabwe's RWH icon, Mr Zephania Maseko Phiri utilises a naturally treated runoff area (*dwala*) for harvesting runoff water. Without the *dwala* the harvested runoff water would be much less. Mr Phiri realises crop yield benefits more than 150 m downslope from the *dwala* suggesting that slope position may be critical. Farmers using similar technologies in different environments may not derive similar benefits.

6.3.4 Wide range in maize rooting depth

Tillage research results in the smallholder farming sector of Zimbabwe suggest a shallower rooting depth than depths reported in literature. For example, Tsimba et al. (1999) established mean ploughing depths less than 0.15 m in two communal areas of Zimbabwe and existence of plough pans approximately 0.08 m below the mean ploughing depth on loamy soils at Chinyika. According to Tsimba et al. (1999) root penetration was restricted to 0.20 m due the penetration resistance of the plough pan. Vogel (1993) observed shallow rooting depths of only 0.15 to 0.25 m in places of very thin topsoil. Furthermore, Richards et al. (2007) mention insufficient time to grow deep roots among impediments to water and nutrient use. This may be true for semi-arid Zimbabwe where growing degree days required to reach maturity are attained in a shorter period due to warmer temperatures compared to the Highveld.

Correct rooting depths are important for application of crop models and determination of crop water requirements. Modelling with AquaCrop showed that increasing effective rooting depth to 0.60 m increases and stabilises maize yield and water use efficiency.

Literature provides varying rooting depths, for instance, according to Hsiao et al. (1976) on good soils, maize can have a maximum rooting depth of 2.8 m or deeper near the time of maturity. Steduto et al. (2012) report that the more commonly observed rooting depth is 1.5 to 2 m especially in regions with cold winter temperatures. Researchers in Sub-Saharan Africa report maximum rooting depths less or equal to 1.2 m: Biazin and Stroosnijder (2012), 0.6 m maximum rooting depth; Zinyengere et al. (2011), 1.2 m maximum rooting depth; Mhizha (2010), 0.8 m maximum rooting depth; Wiyo et al. (2000), 0.65 m; and Vogel (1993) reports maximum rooting depths of 0.5 m under favourable conditions of tied ridges in Zimbabwe.

Given the low ploughing depths that often lead to development of plough pans and shorter growing seasons in semi-arid Zimbabwe failure to attain deep rooting depths could be a major yield limiting factor for maize. The wide difference in maize rooting depth reported in literature ; where the highest is more than ten times the least leads to the question “Is the wide difference in maize rooting depth solely due to variations in environmental conditions or germplasm also contributes?”

6.3.5 Integrated soil and water management

Innovative and adaptive integrated soil and water management, encompassing soil fertility and tillage management and water harvesting (Falkenmark and Rockström, 2006; Rockström et al., 2010) should be developed. This study is in line with the paradigm of integrated soil and water management in the sense that we propose rainwater management through combined in-field and field-edge technologies, and soil fertility management through application of adequate mineral and organic fertilizers and incorporation of deep rooting legumes for example pigeonpea. Pigeonpea leaf fall if incorporated provides up to 40 kg N ha^{-1} (Kananji et al., 2009). Tittonell and Giller (2013) single out soil quality as the most urgent of the three pillars of ecological intensification in Africa (the other two being yield potential and precision agriculture), and note that in some regions most poor farmers’ fields have degraded and poorly responsive soils. They argue that substantial investment to build soil organic matter is needed to restore the soils to a responsive state. However, in sandy soils there is limited potential to store soil organic matter resulting in little potential to build soil organic N capital (Mapfumo and Giller, 2001) and crop production has to largely rely on mineral fertilizers.

6.3.6 The tragedy of dwindling government support

It has long been established (Twomlow et al., 1999) and reiterated (Araya and Stroosnijder, 2010; Lal, 2013; Mupangwa et al., 2012a) that technologies which increase labour will be rejected by most smallholder farmers. In an environment where the youthful and capable individuals generally migrate to urban areas to escape the vicious cycle of rural poverty (Mupangwa et al., 2012a; Whitlow, 1980) leaving behind the elderly and children there is need to search for labour saving technologies and other options that lessen the labour burden. Researchers, development practitioners and policy makers should recognise this painful reality. Ideally, subsidies and/or food for work programmes should be availed to implement important rainwater management structures, for example field-edge structures. Previous successful soil and water conservation initiatives in Zimbabwe were backed by government support, for example, Whitlow (1988) reports that in Zimbabwe’s large-scale commercial farms government subsidies in the 1940s encouraged construction of contour ridges, grassed waterways and stormwater drains along roads. Mazvimavi and Twomlow (2009) also concluded that active support by NGOs and government change agents through provision of inputs and training increased the likelihood of technology adoption. Such support should be sustained in the case of resource-poor farmers. Unfortunately, what was possible with a smaller population in the past is no longer affordable today. There are no more easy solutions i.e. the low hanging fruit has been harvested (Van Ittersum, 2011). Developing countries' governments are unable to provide subsidies consistently, timeously and adequately due to budgetary constraints which continue to contract against growing populations. The tragedy is that land degradation continues uncontrolled leading to a vicious rural poverty cycle.

6.3.7 Retrogressive fashion legacy

In our view, research in sub-Saharan Africa has tended to be 'fashionable' in the sense that instead of building on prior knowledge about best practices and introducing new methods incrementally the tendency has been to follow the 'clothing fashion trends approach' where one type of jean is replaced by another. This has led to inappropriate designs where in some cases complementary tillage methods were compared against each other for example in-field and field-edge technologies as in Motsi et al. (2004). There has also been complete omission of well-established best practices in some farming systems being promoted, for example absence of field-edge structures in the conservation agriculture package currently being promoted in semi-arid Zimbabwe. The omission of field-edge structures exists despite existing knowledge that they reduce rill and gully erosion that can destroy the smaller in-field technologies on sloping land (≥ 2%). Giller et al. (2009) cite experiments in which a full conservation agriculture package including additions of external inputs such as fertilizers, herbicides and/or improved seeds was compared with a 'farmer's practice' control plot that lacks these inputs. Hence, it is common to find the word rediscovering in literature where researchers revisit old best practices probably after years of misdirected efforts. This can be partially attributed to overreliance on donor funding because interventions are based on donor-perceptions and not on the felt needs of the communities.

6.4 Contribution to science

6.4.1 No decline in rainfall

In semi-arid Zimbabwe, this is the first study that combines rainfall analysis and crop modelling to provide a framework for planning and selection of optimum management options and appropriate cropping systems. More detailed information than just departures from a mean state is provided. As demonstrated in Chapter 5, the detailed information and disaggregation of seasons into wet, normal and dry enable identification of suitable climatic conditions for specific interventions. Where reliable seasonal forecasts exist, farmers are able to adapt farm practices to suit the season.

Through long-term rainfall analysis we provide information essential for assessing effect of climate change on seasonal rainfall amount using time series data from Rushinga district, Zimbabwe. For 25 years of daily rainfall data between 1980 and 2009; comparison of seasonal rainfall means of the first thirteen seasons, (1980/81-1992/93), mean (SD), 624 (173) mm; and the last twelve seasons (1993/94-2008/09), mean (SD), 640 (184) mm showed no difference $t(23) = 0.221$, ($P > 0.05$). Therefore, declining maize yields in Rushinga district are due to some other factors not declining rainfall amount. Our results contradict farmers' perceptions of declining rainfall amounts. During interviews with farmers in southern Zimbabwe, Wilson (1995) states that farmers did not accept analysis of rainfall records from local meteorological stations which showed that there was no decline in rainfall. Stroosnijder (2012) refers to 'proven' rainfall changes due to climate change as one of the popular myths in land degradation and development.

We also quantify and present occurrence of dry spells of varying durations (days): 5; 6-10; 11-15; 16-20; and > 20. On average the 6-10 dry spells occurred three times per season whilst the rest occurred once. Baron et al. (2003) consider a dry spell between 5 and 15 days to be harmful for Sub-Saharan Africa. Stroosnijder (2007) reports that a 10-day dry spell has potential to damage a maize crop.

6.4.2 Seasonal rainfall thresholds for conservation tillage

The effect of seasonal rainfall on performance of tillage methods in Zimbabwe is well documented (Munodawafa and Zhou, 2008; Mupangwa et al., 2012b; Mupangwa et al., 2007; Nyakatawa, 1996; Nyamudeza, 1999; Vogel, 1993) however, hitherto no attempts have been made to determine threshold levels for conservation tillage. In this study we show that 500 mm is the seasonal threshold rainfall for better yield performance of conservation tillage methods (1.0 m tied ridging and mulch-ripping) than conventional tillage.

6.4.3 The infiltration pits mystery

Rainwater harvesting is recommended for combating land degradation (Siegert, 1994; Vohland and Barry, 2009) and it is important for meeting Millennium Development Goals (MDGs) in Africa (Kahinda et al., 2008; Ochola and Kerkides, 2003). We quantified benefits of contour ridges modified by inclusion of infiltration pits with respect to soil moisture content and maize yield. Results from this study indicate that effect of infiltration pits on soil moisture content are minimal being experienced up to only 2 m downstream from the centre of the infiltration pit or contour ridge channel. The benefits of infiltration pits have been a grey area as exemplified by less explicit statements in literature: Hughes and Venema (2005) state that they "benefit crops during dry spells" without specifying the crops and Mutekwa and Kusangaya (2006) express uncertainty in stating that they "..seem to retain water in the soil and allowed growing a variety of crops".

6.4.4 The controversial planting pits

This PhD project ran concurrently with vigorous promotion of planting pits from 2010 through 2013 nationwide in Zimbabwe as part of a conservation agriculture package. The conservation agriculture package was promoted by the Zimbabwean Task Force on Conservation Agriculture (ZTFCA), coordinated by the Food and Agriculture Organisation of the United Nations (FAO) Emergence Office in Zimbabwe and implemented through partner NGOs with support from the government's Department of Agricultural, Technical & Extension Services (Agritex). The promotion of planting pits in Zimbabwe started during the 2004/05 season (Twomlow et al., 2008). We noticed that that most farmers only practised conservation agriculture as far as digging planting pits in anticipation of receiving free inputs. The constraints for farmers to adopt all principles of conservation agriculture make it necessary to evaluate the benefits of each principle (Giller et al., 2009). We therefore, quantified soil moisture content and maize yield under planting pits and discussed constraints they face under smallholder farmers' conditions. At the drier Chongoma site conventional tillage and planting pits had similar soil moisture content but there was no consistent trend at the wetter Magaranhewe site. Similarly, tillage methods did not show consistency in performance for maize yield (Chapter 4, Table 4.5), but on average conventional tillage (mean yield 2697 kg ha^{-1}) performed better than planting pits (mean yield 1852 kg ha^{-1}). However, the yield gap decreased from 90% in the first year to 30% in the third year due to cumulative benefits of precision farming i.e. planting was done in the same station where fertilizer was applied each year for planting pits. The highest grain yield achieved under planting pits was 4531 kg ha^{-1} and the lowest was 723 kg ha^{-1} during the experiments from 2010/11 through 2012/13 season.

Widespread promotion of planting pits attracted criticism from politicians and academics who viewed the intervention with suspicion and claimed that it subjects the smallholder farmers to drudgery. Practically, in addition to their appropriateness for poor households without access to adequate draught power as recommended by ZTFCA (Twomlow et al., 2008); planting pits are a fall-back tillage method for smallholder farmers in the event of livestock loss. However, when the smallholder farming sector is viewed as a whole, investment in mechanization is required if conservation agriculture is to achieve its full potential in semi-arid Zimbabwe.

6.4.5 A model that can be used without calibration

We tested the performance of AquaCrop in simulating canopy cover and biomass development without calibration and established that the model performed well. Mean final biomass and mean grain yield were 96 and 92% of the mean simulated values respectively. We contend that in AquaCrop we have a generic model that can be used satisfactorily without the costly and non-transparent calibration process often fraught with equifinality problems. For deterministic-conceptual simulation, equifinality refers to more than one parameter set providing an equally good (or poor) representation of the response (Ebel and Loague, 2006). For model application purposes it may suffice to ensure accurate input data and compare simulations with measured data. However, we observed that AquaCrop still faces difficulties in simulating water stress induced early senescence as reported Hsiao et al. (2009). The response of the model lagged behind that of field observations leading to overestimation of variables by the model (Chapter 5, Figure 5.2).

6.4.6 Increased water use efficiency

Through modelling with FAO's AquaCrop as a tool for research and decision support (Matthews et al., 2013) we simulated soil water and maize yield, under a sole maize crop for different agronomic management practices. Effects of varying rooting depth and plant density ($P < 0.05$) were observed in normal seasons. Increasing maize rooting depth from 0.30 to 0.60 m increased: simulated maize grain yield from 5.6 to 7.0 t ha^{-1}; biomass water use efficiency by 14.3%; grain water use efficiency 20.3% and (green-water use efficiency) GWUE by 19.1%. Increasing plant density (plants ha^{-1}) from 17500 to 32500 increased grain yield from 4.0 to 6.0 t ha^{-1}; biomass water use efficiency by 37.3%; grain water use efficiency by 46.7% and GWUE by 41.4%. For all sites the lowest density had higher percentage evaporation ($P < 0.05$) than the two higher densities which had similar values ($P > 0.05$). Drainage below the rootzone was at least 40% of the non-productive water losses in normal (456-857 mm rainfall) and wet seasons (> 857 mm rainfall) whilst evaporation contributed 46% in dry seasons.

6.5 Limitations of the study

Although this thesis provides information on opportunities for optimising rainfed maize based on review of previous experiments, rainfall analysis, field experimentation and modelling; there are limitations of scope, temporal and spatial nature. For example, availability of few published experimental results in semi-arid Zimbabwe limited the amount of information available for drawing stronger conclusions; and rainfall analysis and crop modelling were based on a single 25-year rainfall dataset, multiple datasets covering a larger part of semi-arid Zimbabwe could have enhanced wider applicability of the conclusions. Furthermore, field experiments were conducted over only three seasons in Natural Region IV, long-term experiments including Natural Region V could have provided more insights.

Field experiments were conducted on sandy loam soils and sandy loam soils overlying sandy clay loams with a narrow range of available water capacity (Chapter 5, Table 5.1). Therefore, it is inappropriate to extrapolate the recommendations of the study in areas with heavier textured soils without prior modelling and field testing. Furthermore, soils with restrictive impermeable layers in the subsoil would probably yield different results.

6.6 Institutional, policy and research implications

Notwithstanding the above-mentioned limitations, findings from this thesis are important for Zimbabwean government institutions involved in agriculture and natural resources management extension and/or policing. The relevant government departments are Environmental Management Services (EMS) responsible for enforcing construction and monitoring compliance of conservation works from the Ministry of Environment and Natural Resources Management; Mechanization responsible for designing and pegging conservation works and Agritex responsible for crops extension from the Ministry of Agriculture, Mechanization and Irrigation. Rainfall analysis and crop modelling results imply that perceived decline in rainfall amount attributed to climate change is not real; what farmers are experiencing are symptoms of land degradation that lead to loss of a large proportion of rainwater to runoff (Nyakudya and Stroosnijder, 2011; Wilson, 1995) and soil nutrient mining due to suboptimal or non-application of fertilizers. Therefore, institutions should encourage and facilitate rainwater management through a combination of field-edge and in-field technologies that conserve water and soil in the fields of smallholder farmers. In order to develop appropriate designs, practitioners should make use of rainfall analysis and modelling with the Curve Number method. Farmer field schools (FFS) (Braun et al., 2006) or demonstration fields may be employed in order to help in changing farmers' perceptions and encourage adoption of appropriate water management within the farm enterprises. Because poor soil fertility is a key limitation to improved maize yields in Zimbabwe; soil fertility management through adequate fertilization using mineral and where available organic fertilizers should be promoted in conjunction with rainwater management technologies under all cropping systems.

Recommendations based solely on current in-field practices like those promoted under conservation agriculture in semi-arid Zimbabwe are insufficient for land slopes ≥ 2%. Such farming systems should be adapted to include field-edge structures in order to control soil rill and gully erosion.

Policy makers should avail resources for training of extension personnel and acquisition of equipment for designing and pegging of field-edge structures (conservation works). The government can merge Agritex and Mechanization departments and channel savings from the merger towards operations. Agritex is well represented on the ground; what is required is specialist in-service training to enable taking over the role currently performed by Mechanization. This should be possible because in most cases district personnel from the two departments graduate from the same colleges with the same qualifications. Subsidies should be provided for implementing field-edge structures through "food for work" programmes.

There is also need for flexibility in use of other structures for example stonelines and grass strips where applicable in addition to the conventional contour ridges. Zimbabwe's Environmental Management Act [Chapter 20:27] does not specify the conservation works but only specifies the purpose for which they should be constructed, thus providing for flexibility in the selection of rainwater management structures.

Giller et al. (2006b) bemoans the absence of widespread testing of and experimentation with technologies by farmers. Research institutions including the government Department of Research and Specialist Services (DR&SS) and Universities should conduct long-term experiments with farmers in farmers' fields for technology adaptation and testing. Universities can augment the scarce local financial resources through accessing international funding. In this way, research and extension can correctly inform farmers on the benefits and limitations of technologies for example RWH methods such as infiltration pits and planting pits. Given the wide variability in rooting depth of maize, where feasible the input data for this parameter should be based on field measurements rather than extrapolations from other areas.

In view of the high labour demands, planting pits, maybe an option for poor farmers without access to adequate draught power or in case of loss of draught animals to disasters. For other smallholder farmer categories, the ZTFCA should promote access to conservation tillage equipment for example ripper tines and direct planting seeders and lobby for opening of credit lines and availing of such equipment in outlets close to the farmers. Munamati and Nyagumbo (2010) report that farmers suggested that government should subsidize tillage equipment and reintroduce food for work programmes.

We recommend mitigation of dry spells through conserving or increasing plant available water (PAW) by manipulating equation 5.1 Chapter 5: PAW = (Field capacity – Wilting point) * Effective rooting depth. Field capacity less wilting point can be altered physically, for example through adding organic matter; whilst rooting depth can be enhanced physically by increasing the rootable soil depth through deep tillage or biologically by selecting or breeding cultivars with large rooting depths. Deep tillage can be achieved by tilling the land at the end of the rainy season when draught animals are still strong and the soil is relatively moist. However, under the mixed crop-livestock systems free grazing in crop fields during the dry season causes soil compaction due to trampling by livestock.

Optimising plant density is another practical option for increasing yield and water use efficiency as illustrated through modelling with AquaCrop. In addition, innovative cropping systems that utilise water that would otherwise be lost as drainage below rootzone whilst at the same time helping to restore soil fertility are required. These cropping systems should include deep-rooting legumes, for example pigeonpea.

Research institutions should popularise use of crop models as tools for benchmarking yields and scenario simulations among extension personnel, and Farm Managers.

Bearing in mind that inevitably maize fails completely in some years; a quota system where the more drought tolerant sorghum and/or pearl millet crop is planted on a prescribed area in addition to the preferred maize crop should be encouraged.

At personal level I will try to influence policy through publishing results from my thesis through the national print media. At the time of approval of my thesis I will submit a “Press Release”. I am currently employed as a University Lecturer, therefore I will use the opportunity to incorporate research results from this thesis into university courses and encourage discussions on policy issues. I will also use other avenues for example presenting papers during seminars at the University and at the annual National and Intellectual Exposition. Through the University extension services, I also have the opportunity to communicate research results by interacting with Agritex and smallholder farmers during training sessions and field days. I will also endeavour to influence the University Research and Extension agenda through participation in meetings in order to encourage widespread testing and experimentation with technologies by farmers.

6.7 Recommendations for further research

Results from this thesis suggest that conservation tillage performs better than conventional tillage under rainfall ≤ 500 mm. However, since crop damaging dry spells are not restricted to this rainfall threshold there is need to develop a versatile conservation tillage system that performs well under both wet and dry conditions. Such systems should also stimulate deep rooting.

The current conservation agriculture promotion drive by the ZCATF offers opportunities for further testing of conservation agriculture practices. As a follow-up to findings from this study; there is need for further testing of the threshold seasonal rainfall amounts for conservation tillage methods. In addition in view of labour constraints under smallholder farming systems in semi-arid Zimbabwe, there is need for further research in low cost labour saving conservation agriculture tillage equipment and testing of existing tillage equipment such as ripper tines and direct planting seeders being introduced into new areas.

Infiltration pits soil moisture and maize yield benefits should be determined in fields with impermeable layers that impede downward flow of water and enhance lateral flow in or just below the subsoil. In addition runoff analysis based on long-term rainfall data should be performed in order to quantify percentage of additional water stored in the field for crop use and determine rainfall thresholds for this RWH technology.

AquaCrop modelling results show positive effects of increasing maize rooting depth and optimising plant density. There is need for multisite participatory field testing of crop modelling results from this study with farmers in order to put theory into practice.

This study suggests that maize yield is to some extend limited by maize effective rooting depth. Research is required to determine maize effective rooting depth under different tillage and farming systems and relate it to crop yields.

Research is also required in order to determine appropriate designs for maize/deep-rooted grain legumes intercropping under different soil types and rainfall conditions.

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Summary

Zimbabwe has a tropical climate with a unimodal rainfall season from November to March. About 64% of the total land area (25 million hectares) is semi-arid and 74% of the communally owned land (communal areas) is located in these areas(Whitlow, 1980)(Whitlow, 1980). Smallholder farming mostly takes place in the communal areas and is typically a mixture of small-scale subsistence and commercial production. In the semi-arid communal areas, inadequate and poorly distributed rainfall and poor soil fertility are the major constraints to crop production. Rainfall exhibits high spatial and temporal variability; in addition excessive non-productive water losses through evaporation, surface runoff and drainage below the rootzone occur.

In most cases, the situation is exacerbated by degraded soils which are prone to surface crusting, have shallow depths, and low infiltration, cation exchange and water holding capacity. Thus in addition to resource constraints; in these areas smallholder farmers have to cope with adverse biophysical conditions. With irrigated agriculture limited both in extent and feasibility, rainfed agriculture is the main livelihood option for the inhabitants of these areas for the foreseeable future. Maize (*Zea mays* L.), the staple and important cash crop; is a high-risk crop susceptible to both drought and waterlogging. The length of the growing season can be shorter than 100 days; therefore maize is more likely to fail than sorghum (*Sorghum bicolor* L. (Moench)) and pearl millet (*Pennisetum glaucum*. (L.) R. Br.) which generally take less than 100 days to mature, yet smallholder farmers prefer maize to the small grains. Success in rainfed cropping in these areas depends on adopting appropriate management techniques which minimise non-productive water losses, improve the soils' available water capacity, and maximize water uptake capacity of plants. Literature review of maize conservation tillage research, long-term rainfall analysis, field experimentation and crop modelling were combined in order to determine strategies that can be used by policy makers and farmers to optimise rainwater management for improving maize crop yields by smallholder farmers in semi-arid Zimbabwe.

Chapter 2 presented field-edge and in-field tillage methods experimented with in semi-arid Zimbabwe, compared the tillage methods performance in terms of maize yield and synthesized the research results. Conventional tillage methods included cultivation on the flat using the mouldboard plough and holing out (digging) using a hand hoe. Infield-conservation tillage methods included tied ridging (furrow diking), mulch ripping, clean ripping and planting pits. Field-edge methods included *fanya juus* (bench terraces with retention ditches) and infiltration pits. Results showed small yield advantages of conservation tillage methods below 500 mm rainfall. For grain yields ≤ 2.5 t ha^{-1} and rainfall ≤ 500 mm, 1.0 m tied ridging produced about 140 kg ha^{-1} and mulch ripping about 340 kg ha^{-1} more than conventional tillage. Above 2.5 t ha^{-1} and for rainfall > 500 mm, conventional tillage had ≥ 640 kg ha^{-1} yield advantage. Tied ridges retain water within the furrows between ties by reducing surface runoff and increasing infiltration. Better performance of 1.0 m tied ridging than 1.5 and 2 m tied ridging was attributed to better edaphic conditions because of less topsoil removed from the root zone and less waterlogging or leaching than under wider ridge spacing when planting is done in the furrow. Mulching improves rain water use efficiency by reducing evaporation of soil water and improving infiltration through reduced soil surface crusting. Literature review also revealed yield limitations due to none or sub-optimal application of fertilizers. The study recommends combinations of in-field and field-edge technologies rather than their comparisons, and development of a versatile conservation tillage system that performs well under both wet and dry conditions. In view of resource constraints of the better performing conservation tillage methods, it is suggested that best agronomic practices under conventional tillage should be promoted while work on adoption of tested conservation tillage methods and development of new ones continues.

Chapter 3 assessed opportunities and limitations for rainfed maize production in Rushinga district using 25 years of daily rainfall data between 1980 and 2009. In view of climate change, periodical assessment of rainfall and other climate variables in relation to crop production is required in order to

develop adaptive strategies timely and to check if recommendations from the past are still relevant. Data was analyzed using graphic trends analysis, t-test for independent samples, rank-based frequency analysis, Spearman's correlation coefficient and Mann Whitney's U test. The results showed no evidence of change in rainfall amount and pattern over time. The mean (SD) seasonal rainfall was 631 (175) mm. December, January and February remained the major rainfall months. As expected results depicted high inter-annual variability for annual and seasonal rainfall totals, high incidence of droughts (seasonal rainfall less than mean minus SD) ≥ 3 in 10 years and ≥ 1 wet year (10% probability of exceedance 858 mm season rainfall) in 10 years. Using the planting criteria recommended in Zimbabwe, most of the plantings would occur from the third decade of November with the mode being the first decade of December. This predisposes the rainfall to high evaporation and runoff losses especially in December when maize is still in its initial stage of growth. On average 5 to more than 20 days dry spells occupied 56% of the rainy season. Seasonal rainfall exhibited negative correlation ($p < 0.001$; $r = -0.746$) with cumulative dry spell length, and wet years were free from dry spells exceeding 20 days. The most common dry spells (6-10 days), are in the range in which crops survive on available soil water. Therefore, the 6-10 dry spells can be mitigated by in-situ rainwater harvesting (RWH) and water conservation. The potential evapotranspiration of a 140-day maize crop was estimated at 540 mm. Although short season maize cultivars that mature in less than 140 days could be grown successfully in this area in all but drought years based on rainfall amount; sustainable maize production is only feasible with improved infiltration of rainwater and larger water holding capacity in soils in order to buffer against dry spells. To this end soil restorative farming systems such as conservation farming in addition to *in-situ* RWH were recommended. Maize fails completely in some years; a cropping system that includes drought-tolerant cereals for example sorghum and pearl millet and perennial carbohydrate sources as for example cassavas (*Manihot esculenta*) were recommended in order to provide stable crop yields. Results of this study implied that due to the large amounts of runoff generated during the initial crop development stage, soil and water conservation structures located at field edges are critical for both crop and soil protection.

Chapter 4 assessed benefits in terms of soil moisture and maize yield improvement of combining infiltration pits (a popular field-edge RWH method among smallholder farmers in southern Zimbabwe) and planting pits (a tillage method and component of conservation agriculture that was being promoted nationwide by the Zimbabwean Conservation Agriculture Task Force (ZCATF) during the duration of the study). Field experiments were conducted in Rushinga district, in northern Zimbabwe from 2010/11 through 2012/13 season. Infiltration pits were combined with planting pits because the technologies complement each other by virtue of their different dimensions and locations. A split-plot design with the main-plot factor being the field-edge rainwater management method i.e. contour ridges only or contour ridges with infiltration pits and the split-plot factor being the tillage method: conventional tillage or planting pits was used. The experiment was replicated three times at three sites (Chongoma, Magaranhewe and Kapitawo). Infiltration pits, 1 m wide, 2 m long, and 0.75 m deep spaced at 10-m intervals were dug in the contour ridge channel. Conventional tillage ploughing was done at 0.20 to 0.23 m depth. The plant spacing was 0.90 m x 0.45 m. Planting pits were 0.15 m deep and 0.20 m diameter, spaced at 0.9 m × 0.5 m. Basal fertilizer dressing rate (kg ha^{-1}) was 17.5 for N, 15.3 for P, and 14.5 for K. Split application of ammonium nitrate fertilizer was done in two applications of 33.5 kg N ha^{-1} in order to minimize leaching losses during the wet December to January period. Soil moisture content was measured weekly using the gravimetric and the Time Domain Reflectometry methods at 0.2-m depth intervals up to 1.4 m. Results showed that lateral movement of soil water occurred up to 2 m downslope from infiltration pits; hence infiltration pits did not improve soil moisture content in the cropping area and maize yield. Maize yield (kg ha^{-1}) was 45% higher under conventional tillage (2700) than planting pits (1850) but the yield gap decreased from 90 to 30% in the first and third year respectively. It was concluded that the value of infiltration pits is in reducing soil erosion by water and growing high value horticultural crops inside and close to pits, a view shared by host farmers and other stakeholders. Planting pits face labour constraints for digging pits and weed control. They were therefore, recommended for farmers without adequate access to draught power and for coping with draught power shortages in the event of livestock loss to disasters. In line with limitations posed by soil fertility in semi-arid communal area crop production systems in Zimbabwe high incidence of *Striga* spp. at all sites and high Ca to Mg ratio (4:1) at Magaranhewe were observed. Further research to determine soil moisture, maize yield benefits and waterlogging risk in fields with underlying impermeable layers that enhance lateral flow of water was recommended.

Chapter 5 explored the use of FAO's AquaCrop model in selecting adaptive practices for improving maize yields and crop water use efficiency (WUE) under rainfed smallholder farming conditions in semi-arid Zimbabwe. AquaCrop's usefulness was challenged by using it without calibration and comparing simulated canopy development, biomass and rootzone soil water with field measurements over three years at three sites. After judging its value; the model was subsequently applied to estimete effect of effective rooting depth, planting density and date on yields and WUE. Simulations were done with daily rainfall data for 25 seasons from Rushinga, Zimbabwe. AquaCrop simulated canopy cover development fairly well and simulated biomass accumulation showed good agreement with measured values. The model overestimated soil water; and the mean observed final biomass and grain yield were 96 and 92% of the simulated values respectively. Increasing effective rooting depth (m) from 0.40 to 0.60 at 32500 plants ha^{-1} increased grain yield from 6.0 to 7.0 t ha^{-1}. Grain yield increased to 7.8 t ha^{-1} when the model was run at 0.60 m effective rooting depth and 44400 plants ha^{-1}. Grain water use efficiency and green water use efficiency (GWUE) at 0.60 m effective rooting depth and 44400 plants ha^{-1}, 26.0-28.0 kg ha^{-1} mm^{-1}, and 24.8-27.2% compare favourably with 27.5 -29.4 kg ha^{-1} mm^{-1} grain water use efficiency and 26.8-28.0% GWUE at 0.80 m effective rooting depth. Drainage below the rootzone was ≥ 40% of non-productive water losses in normal seasons (456-857 mm rainfall) and wet seasons (> 857 mm rainfall) whilst soil evaporation contributed 47% in dry seasons (< 456 mm rainfall) at 0.80 m effective rooting depth. Incorporation of deep-rooting legumes e.g. pigeonpea (*Cajanus cajan* (L.) Millsp.), adopting deeper-rooting cultivars (≥ 0.60 m), and practices that improve rooting depth for example deep ripping were recommended to improve yield and WUE. Farmers should also be advised to: target a plant density of 44400 plants ha^{-1}, adopt practices that reduce evaporation in dry years and during dry spells for example mulching, and add organic fertilizers to improve soils' available water capacity and enhance response to mineral fertilizers. Further research on participatory field testing of results from this study with farmers was recommended.

Overall, the outcome of this study indicated that although conservation tillage particularly 1.0 m tied ridging, and mulch ripping increases maize yields in seasons with rainfall < 500 mm in semi-arid Zimbabwe, the two tillage methods face resource constraints under smallholder farming. With optimum application of mineral fertilizers; it is possible for farmers to significantly improve yields by optimising plant density, adopting deeper-rooting cultivars and practices that improve rooting depth, addition of organic fertilizers to improve soils' available water capacity and enhance response to mineral fertilizers. Planting pits face labour constraints for digging pits and weed control; they are therefore, recommended for farmers without access to adequate draught power and as a fall-back method. For the other farmer categories there is need to mechanise conservation agriculture.

Because maize fails completely in some years; a quota system where the more drought tolerant sorghum and/or pearl millet crop is planted on a prescribed area in addition to the preferred maize crop should be encouraged in order to improve household food security. Furthermore intercropping maize with deep rooting legumes such as pigeonpea improves WUE and the soil N capital and reduces the risk of crop failure. Further research should include participatory field testing and crop modelling with farmers in order test the conservation tillage rainfall threshold and agronomic recommendations presented in this thesis.

Samenvatting

Zimbabwe heeft een tropisch klimaat met een regenseizoen van november tot maart. Ongeveer 64 % van het totale landoppervlak (25 miljoen hectare) en 74 % van het communaal grondbezit ligt in de semi-aride klimaatzone. De meeste kleinschalige landbouw vindt plaats in deze communale gebieden, en is vaak een mix van teelt voor zelfvoorziening en commerciële productie. Onvoldoende en slecht verdeelde regenval en slechte bodemvruchtbaarheid zijn hier de belangrijkste beperkende factoren voor gewasproductie. Neerslag vertoont een grote ruimtelijke en temporele variabiliteit, daarnaast is er veel waterverlies door bodemverdamping, oppervlakkige afstroming en drainage onder de wortelzone.

Vaak wordt de situatie verergerd door gedegradeerde bodems die gevoelig zijn voor korstvorming aan het bodemoppervlakte. Er is sprake van een geringe bodem diepte, met als gevolg een lage infiltratie capaciteit, lage kationenuitwisseling en beperkt waterhoudend vermogen. Bovenop de beperkte middelen hebben kleine boeren in deze gebieden dus te kampen met ongunstige biofysische omstandigheden. Omdat geïrrigeerde landbouw beperkt is in omvang en haalbaarheid, is regenafhankelijke landbouw de belangrijkste bron van levensonderhoud. Maïs (*Zea mays L.*), dat zowel basisvoedsel als belangrijkste handelsgewas is, is een risico gewas omdat het gevoelig is voor zowel droogte als wateroverlast. De lengte van het groeiseizoen kan niet veel korter zijn dan 100 dagen, waardoor maïs meer kans heeft om te mislukken dan sorghum (*Sorghum bicolor L. (Moench)*) en parelgierst (*Pennisetum glaucum (L.) R. Br .*). Deze laatste gewassen hebben over het algemeen minder dan 100 dagen nodig om te rijpen. Toch hebben kleine boeren liever maïs. Succes in regenafhankelijke gewasgroei in deze gebieden is afhankelijk van landbouwtechnieken die niet-productieve waterverliezen beperken, die de beschikbare wateropslagcapaciteit van de bodem verbeteren, en die de wateropname capaciteit van planten maximaliseren.

Literatuuronderzoek van maïs en van bodem- en waterconservering, langjarige regenval data, veld experimenten en gewasmodellering zijn in deze studie gecombineerd. Het doel was om strategieën te ontwikkelen die gebruikt kunnen worden door beleidsmakers en boeren om regenwatergebruik te optimaliseren voor het verbeteren van maïsopbrengsten door kleine boeren in semi-aride Zimbabwe.

In Hoofdstuk 2 worden grondbewerkingsmethoden beschreven waarmee al eerder is geëxperimenteerd in semi-aride Zimbabwe. Dit betreft zowel methoden welke over het hele veld (area measures), als technieken die alleen op veldgrenzen (field-edge) worden toegepast. Onderzoeksresultaten worden in dit hoofdstuk samengevat met als beoordelingscriterium de opbrengst van maïs. Conventionele grondbewerking methoden omvatten het gebruik van de ploeg en de handschoffel. Conserverende bewerkingsmethoden omvatten aarden ruggen welke onderling zijn verbonden (tied-ridges), het scheuren van de grond met (mulch ripping) en zonder (clean ripping) gewasresten, en het maken van plantgaten (planting pits). Field-edge methoden welke behandeld worden zijn terrassen met infiltratie sleuven (Fanya juus) en infiltratie kuilen (infiltration pits) in de kanaaltjes achter ruggen welke de hoogtelijnen volgen (contour ridges). De resultaten tonen kleine opbrengst voordelen bij conserverende bodembewerking bij minder dan 500 mm neerslag. Voor graan opbrengsten ≤ 2,5 t ha^{-1} en regenval ≤ 500 mm, produceert een afstand van 1 m tussen de tied-ridges ongeveer 140 kg ha^{-1} meer, en mulch rippen ongeveer 340 kg ha^{-1} meer dan conventionele grondbewerking. Boven de 2,5 t ha^{-1} en voor neerslag > 500 mm, geeft conventionele grondbewerking ≥ 640 kg ha^{-1} opbrengst voordeel. Tied-ridges houden water in de voren vast, verminderen de oppervlakkige afstroming en verhogen de infiltratie. De betere resultaten van tied-ridges op 1,0 m dan op 1,5 en 2 m wordt toegeschreven aan het minder verstoren van de bovengrond en aan minder wateroverlast en uitspoeling dan bij grotere afstanden waarbij in de vore wordt geplant.

Het aanbrengen of laten liggen van gewasresten (mulchen) verbetert de efficiëntie van het gebruik van regenwater door het verminderen van de bodemverdamping, en door het verbeteren van de infiltratie als gevolg van minder korstvorming aan het bodemoppervlak. In Hoofdstuk 2 bevelen we combinaties aan van area en field-edge technologieën, in plaats van het ene of het andere. Ook belangrijk is om een veelzijdig conserveringssysteem te ontwikkelen dat goed presteert onder zowel natte als droge omstandigheden. Gezien de hoge investering en lage meeropbrengst van conserverende bodembewerking methoden, wordt voorgesteld om de best beschikbare agronomische praktijken toe te passen in combinatie met conventionele grondbewerking. Tegelijkertijd moet de ontwikkeling en het verder testen van nieuwe conserveringsbewerking methoden worden bevorderd. Naast beperkingen door watertekort toont literatuuronderzoek ook opbrengstbeperkingen als gevolg van geen of sub-optimale toepassing van bemesting.

In Hoofdstuk 3 worden mogelijkheden en beperkingen onderzocht voor regenafhankelijke maïsproductie in het district Rushinga (Noord-Oost Zimbabwe). We maken daarbij gebruik van 25 jaar gegevens van de dagelijkse neerslag tussen 1980 en 2009. In het licht van klimaatverandering, wordt periodieke beoordeling van de neerslag en andere klimaatvariabelen met betrekking tot de productie van gewassen steeds relevanter. Dit om tijdig adaptieve strategieën te ontwikkelen en om te controleren of de aanbevelingen uit het verleden nog geldig zijn. De 25 jaar neerslaggegevens werden geanalyseerd met behulp van grafische trendanalyse, t-test voor onafhankelijke steekproeven, ranking op basis van frequentie-analyse, Spearman's correlatie coëfficiënt en de Mann Whitney U test. De resultaten tonen geen bewijs van verandering in de hoeveelheid neerslag en het patroon ervan in de tijd. De gemiddelde (SD) seizoensgebonden neerslag was 630 (175) mm. December, januari en februari zijn de grote regenval maanden. Zoals verwacht bestaat er een grote variabiliteit voor de jaarlijkse en seizoensneerslag. Ook is er een grote kans op droogte (seizoensneerslag minder dan gemiddeld minus SD); ≥ 3 droge jaren in 10 jaar en ≥ 1 nat jaar (10 % overschrijdingskans = 858 mm seizoens regenval) in 10 jaar. Volgens de door de voorlichtingsdienst aanbevolen zaaicriteria voor Zimbabwe, begint het zaaien vanaf de derde decade van november en valt het zwaartepunt in het eerste decennium van december. Dit zorgt voor hoge verdampingsverliezen en verlies als gevolg van oppervlakkige afvoer (runoff) in de periode dat de maïs in de beginfase van de groei is. Droge periodes van 5 tot meer dan 20 dagen vormen 56 % van het regenseizoen. Seizoensregenval kent een negatieve correlatie ($p < 0{,}001$; $r = -0{,}746$) met de lengte van de droge periode terwijl in natte jaren droge periodes van meer dan 20 dagen ontbreken.

Gedurende de meest voorkomende droge periodes (6-10 dagen), kunnen gewassen overleven dankzij het water dat is opgeslagen in het bewortelbare deel van de bodem. Daarom kan schade door dit soort droge periodes worden beperkt door in-situ opvang van regenwater (RWH; rain water harvesting) en door waterconservering. De potentiële verdamping (evapotranspiratie: verdamping door bodem en gewas) van een 140 dagen maïsgewas wordt geschat op 540 mm. Er worden in dit gebied ook maisvariëteiten verbouwd welke in minder dan 140 dagen rijpen in alle, behalve in droge jaren. De conclusie is dat duurzame productie van maïs alleen mogelijk is met een verbeterde infiltratie van regenwater en een grotere waterretentie van bodems als buffer tegen droge periodes. Daarom worden bodem herstellende landbouwsystemen zoals ecologische landbouw in aanvulling op in-situ RWH aanbevolen. Maïs faalt volledig in sommige jaren. Daarom worden ook teeltsysteem welke droogte tolerante granen zoals sorghum en parelgierst en meerjarige koolhydraat rijke gewassen zoals bijvoorbeeld cassava (*Manihot esculenta*) aanbevolen om via stabielere gewasopbrengsten de voedselzekerheid te verhogen. Resultaten van deze studie impliceren dat als gevolg van de grote hoeveelheden afstromend water (runoff) tijdens de eerste gewas ontwikkelingsfase, bodem-en waterconserveringsstructuren aan de akkerranden van cruciaal belang zijn voor zowel de gewasteelt als ook voor de bodembescherming.

In Hoofdstuk 4 worden voordelen beschreven (in termen van bodemvocht en maïs opbrengst) van het combineren van infiltratie kuilen (een populaire RWH methode onder de kleine boeren in het zuiden van Zimbabwe) en plantgaten (een grondbewerking methode en component van duurzame landbouw die landelijk werd aanbevolen door de Zimbabwaanse Conservation Task Force Landbouw (ZCATF) tijdens de duur van de studie). Veldexperimenten werden uitgevoerd in het district Rushinga, in het noorden van Zimbabwe vanaf het seizoen 2010/11 tot en met 2012/13. Infiltratie kuilen werden gecombineerd met plantgaten omdat de technologieën elkaar aanvullen vanwege hun verschillende afmetingen en locaties Een split-plot proefopzet werd gebruikt met als plotfactor alleen contour dijkjes tegenover dijkjes met infiltratie kuilen achter de dijkjes. De split-plot factor is de grondbewerking methode: conventionele grondbewerking tegenover plantgaten. Het experiment werd driemaal herhaald op drie locaties (Chongoma, Magaranhewe en Kapitawo). Infiltratie kuilen, 1 m breed , 2 m lang en 0,75 m diep met een onderlinge afstand van 10 meter werden gegraven in het kanaal achter de contour dijkjes. Conventionele grondbewerking d.w.z. ploegen werd gedaan op 0,20-0,23 m diepte. Plantafstand van de mais is 0,90 m x 0,45 m. De plantgaten waren 0,15 m diep en 0,20 m in diameter met een onderlinge afstand van 0,9 m x 0,5 m. De initiële meststof gift was (in kg ha^{-1}) 17,5 voor N , 15,3 P en 14,5 K. Ammoniumnitraat werd daarna toegediend in twee giften van 33,5 kg N ha^{-1} om uitlogingverliezen tijdens de natte december – januari periode te minimaliseren. Vochtgehalte van de bodem werd wekelijks gemeten met behulp van gravimetrische en de Time Domain Reflectometry methoden met 0,2 m diepte intervallen tot 1,4 meter.

De resultaten tonen aan dat de zijwaartse beweging van de bodemwater niet verder komt dan 2 m van de infiltratiekuilen. Daarom kunnen infiltratiekuilen het bodemvocht gehalte en de opbrengst van maïs in het naastgelegen veld niet verbeteren. De conclusie is dat de waarde van infiltratiekuilen ligt in het verminderen van bodemerosie door water en in de mogelijkheid om hoogwaardige tuinbouwgewassen in en dichtbij kuilen te kunnen verbouwen. Deze mening wordt gedeeld door tal van boeren en andere belanghebbenden. Opbrengst van maïs (kg ha^{-1}) was 45 % hoger onder conventionele grondbewerking (2700 kg ha^{-1}) dan bij het gebruik van plantgaten (1850 kg ha^{-1}). Maar het verschil daalde met 90-30 % tussen het eerste en derde jaar. Het gebruik van plantkuilen wordt bemoeilijkt door de hoeveelheid arbeid nodig voor het graven van de kuilen en voor onkruidbestrijding. Ze worden daarom alleen aanbevolen voor boeren zonder voldoende toegang tot dierlijke trekkracht. En in geval van vee verlies als gevolg van rampen. Zoals verwacht bij de lage bodemvruchtbaarheid in de semi -aride communale gebieden wordt bij de gewasproductie in Zimbabwe een hoge intensiteit van Striga spp. waargenomen op alle locaties en vooral bij de hoge Ca/Mg verhouding (4:1) in Magaranhewe. Verder onderzoek naar bodemvocht, maïsopbrengst en risico op wateroverlast in gebieden met een ondoordringbare bodemlaag die laterale stroming van het water bevordert wordt aanbevolen.

In Hoofdstuk 5 wordt het gebruik van de FAO AquaCrop model beschreven. Dit model wordt gebruikt voor het selecteren van methoden voor het verbeteren van de maïs opbrengt en de watergebruiksefficiëntie (WUE) onder regenafhankelijke kleinschalige landbouw omstandigheden in semi-aride Zimbabwe. Onze uitdaging was om de bruikbaarheid van AquaCrop te testen door het te gebruiken zonder kalibratie. Het testen is gedaan door het vergelijken van gesimuleerde bedekkingsgraad, biomassa en bodemvocht met veldmetingen gedurende meer dan drie jaar en op drie locaties. Nadat AquaCrop 's waarde als voldoende was beoordeeld, is het model vervolgens toegepast voor een optimalisatie van worteldiepte, plantdichtheid en zaaidatum. Doel van de optimalisatie was een hogere opbrengsten en WUE. Simulaties werden gedaan met de dagelijkse neerslaggegevens voor 25 jaar in Rushinga , Zimbabwe.

AquaCrop simuleert de ontwikkeling van de bedekkingsgraad vrij goed en ook de gesimuleerde biomassa accumulatie bleek goed overeen te komen met de gemeten waarden. De waargenomen uiteindelijke biomassa en graan opbrengst waren 81 en 75 % van de gesimuleerde waarden. Het model overschat bodemvocht. Toenemende bewortelingsdiepte van 0,30 naar 0,60 m verhoogt de gesimuleerde maïs opbrengst van 5,6 naar 7,0 t ha^{-1}; de watergebruiksefficiëntie van de biomassa als geheel met 14,3 % , de graan watergebruiksefficiëntie met 20,3 % en de groen water efficiëntie (GWUE) met 19,1 %. Toenemende plantdichtheid (planten ha^{-1}) van 17.500 naar 32.500 doet de gesimuleerd graanopbrengst stijgen van 4,0 naar 6,0 t ha^{-1}; de biomassa watergebruiksefficiëntie met 37,3 %, de graan watergebruiksefficiëntie met 47,6 % en de GWUE met 41,4 %. Een variatie in zaaidatum toont geen significant effect op de opbrengst van maïs en de WUE.

Drainage onder de wortelzone is ten minste 40 % van het niet-productieve waterverlies in normale en natte seizoenen (456-857 mm). In droge jaren is bodemverdamping de grootste verliespost met 46 %. Aanbevelingen om opbrengst en WUE te verhogen zijn: incorporatie van diep wortelende peulvruchten bijv. pigeonpea (*Cajanus cajan (L.) Millsp.*) in de gewasrotatie, het gebruik van dieper wortelende mais cultivars en praktijken die worteldiepte bevorderen zoals bijvoorbeeld het scheuren van de grond (deep ripping). Men kan ook boeren adviseren om naar een plantdichtheid van 32.500 planten ha^{-1} te streven. Ook kunnen praktijken toegepast worden welke de bodemverdamping verminderen in droge jaren en tijdens droge periodes bijvoorbeeld door te mulchen. Het gebruik van organische meststoffen zal zowel het vochthoudend vermogen van de bodem als de efficiency van minerale meststoffen verbeteren. Verder onderzoek met participatieve veldproeven om de resultaten van deze studie aan boeren te tonen wordt eveneens aanbevolen.

Alhoewel de resultaten van deze studie aantonen dat conserveringsbewerking (in het bijzonder de 1,0 m ‘tied-ridges’ en het mulch rippen) de opbrengst van maïs in seizoenen met neerslag < 500 mm in semi -aride Zimbabwe verhogen, wordt toepassing van genoemde methoden geconfronteerd met de beperkte middelen in de kleinschalige landbouw. Met een optimale toepassing van minerale meststoffen, is het mogelijk voor boeren om een aanzienlijke verbetering van de opbrengsten te verkrijgen. Dit wordt bereikt door het optimaliseren van plantdichtheid, gebruik van dieper wortelende cultivars, toepassing van methoden die bewortelingdiepte verbeteren, toevoeging van organische meststoffen om het vochthoudend vermogen van de bodem en de efficiency van minerale meststoffen verbeteren. Het gebruik van plantgaten wordt beperkt door de grote investering van arbeid voor het graven van de kuilen en de onkruid te bestrijden. Plantkuilen worden daarom alleen aanbevolen voor de boeren die geen toegang hebben tot voldoende trekkracht en als fall-back in geval van het verlies van vee als gevolg van een langdurige droge periode. Voor de overige categorieën boeren is er behoefte aan het mechaniseren van duurzame landbouwpraktijken.

Omdat maïs volledig mislukt in sommige (droge) jaren, wordt een quota systeem voorgesteld waarbij een minimale oppervlak met de droogtetolerantere sorghum en/of parelgierst wordt aangeplant. Dit om, naast het favoriete gewas maïs, de voedselzekerheid van huishoudens te verbeteren. Verder kan mengteelt van maïs met diep wortelende peulvruchten zoals pigeon pea de WUE en de voorraad stikstof in verhogen. Hierdoor zal het risico van misoogsten verminderen. In een verder onderzoek, zouden de resultaten van deze studie zoals de regenval drempel waarbij conserveringsbodembewerking lonend wordt en de andere agronomische aanbevelingen uit dit proefschrift in samenwerking met boeren getest kunnen worden m.b.v. participatieve veldproeven in combinatie met gewas modellering.

Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment

C E R T I F I C A T E

The Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment
(SENSE), declares that

Innocent Wadzanayi Nyakudya

born on 28 July 1969 in Goromonzi, Zimbabwe

has successfully fulfilled all requirements of the
Educational Programme of SENSE.

Wageningen, 18 March 2014

the Chairman of the SENSE board

Prof. dr. Rik Leemans

the SENSE Director of Education

Dr. Ad van Dommelen

The SENSE Research School declares that **Mr. Innocent Wadzanayi Nyakudya** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 35 ECTS, including the following activities:

SENSE PhD Courses

- Environmental Research in Context
- Research Context Activity: Writing of accessible press release on PhD research results and co-organisation of graduation ceremony at Bindura University of Science Education in Zimbabwe

Other PhD and Advanced MSc Courses

- Multivariate analysis
- Information Literacy PhD, including EndNote introduction
- Techniques for Writing and Presenting a Scientific Paper
- Production Ecology & Resource Conservation (PE & RC) Weekend School
- Erosion Processes and modelling

Management and Didactic Skills Training

- Teaching undergraduate course "Irrigation and Water Management (AGC 303)" at Bindura University of Science Education Zimbabwe
- Supervision of B.Sc. thesis "Prevalence and effect of planting pits on maize yield in Rushinga district, Zimbabwe"
- Supervision of M.Sc. thesis " Evaluating rainwater harvesting as an adaptation strategy to dry spells in smallholder rainfed *Zea mays L.* production in Rushinga district, Zimbabwe"

Oral Presentations

- *Evaluating benefits of rainwater harvesting using infiltration pits for improved crop yield in rainfed cropping systems: the case of Rushinga district, Zimbabwe.* Agro Environ 2012, 1-4 May 2012, Wageningen, Netherlands
- *Experiences with infiltration and planting pits in Rushinga district.* Provincial conservation agriculture coordinating committee Workshop 2012, 19 September 2012, Bindura, Zimbabwe

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Curriculum vitae

Innocent Wadzanayi Nyakudya was born in Goromonzi district, Zimbabwe on 28 July 1969. For his primary and secondary education he went to: Chipindura Primary School in Bindura district, Pote Primary School and Parirewa High School in Goromonzi district and Kutama Mission in Zvimba district. Innocent graduated from the University of Zimbabwe with a B.Sc. in Agriculture Honours degree specializing in Soil Science in 1992.

During his undergraduate studies he was awarded a University Book Prize in the second year of his three-year study. In August 1993 he started studies for the M.Sc. degree in Soil and Water specializing in Irrigation at Wageningen University under the Zimbabwe Programme on Women Studies, Extension, Sociology and Irrigation (ZIMWESI) which he completed in 1995. The title of his M.Sc. thesis is: *Technical performance of field irrigation: the case of Chibuwe Irrigation Scheme, Zimbabwe*.

After completing his M.Sc. degree he worked for the government Agricultural, Technical & Extension Services department (Agritex) as an Agricultural Extension Officer responsible for soil and water conservation and irrigation in Chivi district in semi-arid southern Zimbabwe. His responsibilities included: staff and farmer training; and designing small dams and irrigation schemes. During his tenure in Agritex Innocent was trained in and implemented participatory rural appraisals and participatory irrigation scheme appraisals and environmental evaluation. Innocent was responsible for the day to day management of the Smallholder Irrigation Support Programme (SISP) in Chivi district. He also participated actively in the Southeastern Dry Areas Support Project (SEDAP). Innocent is credited with the revival of the Smallholder Drought Mitigation Programme in Chivi district funded by the Swedish Cooperative Centre. During the last year of his tenure in Agritex Innocent was the Acting District Agricultural Extension Officer. In this capacity he chaired the Land Use Sub-Committee of the Chivi Rural District Development Committee. He also chaired the district SISP and SEDAP committees. Innocent worked with various government an non-governmental organizations (NGOs). His experiences in the semi-arid southern Zimbabwe dominated by recurrent crop failures motivated him to pursue a career in rainfed water management.

In September 2003, Innocent joined Bindura University of Science Education. He has taught undergraduate courses including introductory soil science, irrigation and water management, land reclamation and revegetation, rural development and gender issues in agriculture and land use and natural resources evaluation. Innocent also supervised four M.Sc. theses. In 2007 he attended the International Course on Land Drainage offered by ILRI, and took the opportunity to meet Professor Leo Stroosnijder to discuss his intentions to study for a PhD. In 2009 he was awarded a PhD scholarship by NUFFIC and embarked on his PhD programme in January 2010.

Innocent married Rhodah in 1996 with whom he has four children Rudo, Nyasha, Tapiwa and Tendayi.

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