EVALUATING IN-FIELD RAINWATER HARVESTING WITH A SUNFLOWER - COWPEA INTERCROP ON A SEMI-ARID ECOTOPE IN LIMPOPO PROVINCE

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EVALUATING IN-FIELD RAINWATER HARVESTING WITH A SUNFLOWER - COWPEA INTERCROP ON A SEMI-ARID ECOTOPE IN LIMPOPO PROVINCE

By

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Promoter: Prof. L.D. van Rensburg

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DECLARATION

I declare that the dissertation hereby submitted by me for the Doctor of Philosophy in Soil Science degree at the University of the Free State is my own independent work and has not previously been submitted at another university/faculty. I further cede copyright of the dissertation in favour of the University of the Free State.

Jestinos Mzezewa

Signature

Date: 05/10/2012

Place: BLOEMFONTEIN

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DEDICATION

I dedicate this dissertation to my beloved wife, Memory, for all she has done and does.

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LIST OF SYMBOLS AND ABBREVIATIONS

ARC = Agricultural Research Council

CEC = cation exchange capacity (cmol^{+}kg^{-1} soil)

CON = conventional tillage

CPF = cumulative probability function

CS = cropping season

C_s = Standard count

CRS = cropping system

CV = coefficient of variation

CYP-SA = Crop Yield Predictor for Semi-Arid areas

D = deep drainage (mm)

DAP = days after planting

D_b = bulk density (g cm^{-3})

D-statistic = Anderson-Darling statistic

DUL = drained upper limit of plant available water

E_s = evaporation from the soil surface (mm)

ET = evapotranspiration (mm)

ET_o = reference crop evaporation (mm)

Ev = evaporation from the crop surface (transpiration) (mm)

h = matric suction

H = hydraulic head (mm)

GGP = gross geographical product

GY = grain yield (kg ha^{-1})

HSD = honest significant difference

ICSW = Institute for Climate, Soil and Water

IDM = internal drainage method

ISC = sunflower x cowpea intercrop

IRWH = in-field rain water harvesting

K = unsaturated hydraulic conductivity

K_s = saturated hydraulic conductivity

$K(\theta)$ = hydraulic conductivity as a function of soil wetness (mm h^{-1})

KS = Kolmogorov-Smirnov test

LER = land equivalent ratio

LL = lower limit of plant available water (mm)

NT = no-till

NWM = neutron water meter

$\theta(h)$ = soil water content as a function of matric suction (mm mm^{-1})

$\theta_{h(n-1)}$ = root zone water content at harvesting of previous crop (mm)

θ_m = soil water content determined gravimetrically (mm)

θ_r = soil water content of the root zone determined by NWM (mm)

θ_p = root zone water content at planting

$\theta_{p(n)}$ = root zone water content at planting of current crop (mm)

θ_s = water content at saturation (mm)

θ_{sf} = field measured θ_s

θ_{sl} = laboratory measured θ_s

θ_v = volumetric water content

P = precipitation (mm)

P_i = Plasticity index

PAW = plant available water (mm)

P_f = rainfall during the fallow period (mm)

PUE = precipitation use efficiency (kg ha^{-1} mm^{-1})

PUE_g = precipitation use efficiency during the growing period (kg ha^{-1} mm^{-1})

q = soil water flux (mm h^{-1})

R = runoff (mm)

R^2 = correlation coefficient

RMSE = root mean square error

$RMSE_s$ = systematic root mean square error

$RMSE_u$ = unsystematic root mean square error

SAW_a = initial soil profile water content (mm)

SAW_b = final soil profile water content (mm)

SC = sole cowpeas

SS = sole sunflower

ΔS = water stored in the root zone (mm)

S-value = the sum of exchangeable Ca, Mg, Na and K (cmol (+) kg^{-1} soil

SWC = soil water content(mm)

SWRC = soil water retention curve

t = time after drainage starts at a root zone water content of θ_{sf} (days)

TS = tillage system

Univen = University of Venda

WU = water use (mm)

WUE = water use efficiency (kg ha^{-1} mm^{-1})

z = vertical depth (mm)

ABSTRACT

A field study was conducted during the 2007/2008 and 2008/2009 cropping seasons in order to evaluate the in-field rainwater harvesting (IRWH) production technique with sunflower (*Helianthus annuus* L.) x cowpea (*Vigna unguiculata* L.) intercrop. The IRWH is a special crop production technique that promotes runoff on 2 m wide no-till strip between crop rows and collects the runoff water in basins where it infiltrates into the soil profile. The IRWH was tested against the conventional tillage (CON).

The study was carried out at the University of Venda (22°58' S, 30°26' E at 596 m above sea level) in Thohoyandou in the Limpopo Province of South Africa at the University of Venda-Shortlands ecotope. The potential for food production in the Limpopo Province is limited by low and erratic rain fall. The smallholder farmers in the province are the most vulnerable because they depend on dryland agriculture for livelihood. Crop yields in the province are typically low. It was therefore hypothesized that (i) IRWH will increase crop yields compared to the CON system, and (ii) cowpea intercropped as living mulches with sunflower will increase water use (WU), water use efficiency (WUE), PUE and grain yield of sunflower.

The relationship between soil water content (θ) and matric suction (h) or soil water release curve (SWRC) was obtained using the hanging water column ($h \leq 800$ mm water). The drainage patterns as well the relationship between θ and unsaturated hydraulic conductivity (K) for each diagnostic soil horizon was evaluated using the internal drainage method (IDM). Field saturated hydraulic conductivity (K_s) of each diagnostic soil horizon was determined using a double ring infiltrometer. Results from this study indicated that soil hydraulic properties were unique for

each diagnostic horizon. The saturated hydraulic conductivity in the orthic A and structured B-horizons was 30 mm h^{-1} and 12 mm h^{-1}, respectively. The difference was largely attributed to the crumb microstructure observed in the orthic A-horizon. The results of the study also indicated that Shortlands the soil had good water retention properties as 19% (average for the profile) of the water was released between saturation and 8 kPa. It was further concluded that the plant available water (PAW) (267 mm) in the root zone was high and surpassed the soils tested for IRWH, making the University of Venda-Shortlands ecotope suitable for this production strategy.

Rainfall on the ecotope was characterized using historical data (1983 - 2005) in Chapter 3. The statistical analysis of rainfall at the study site revealed that the annual rainfall was highly variable (CV of 315% for annual rainfall). Further analysis revealed that the probability of receiving high rainfall amounts was low with small storms (<20 mm) accounting for a large proportion of rainfall

The field experiment to evaluate the IRWH with sunflower x cowpea intercrop production is reported in Chapter 4. The experiment was laid out as a split plot design. Tillage systems formed main plots with cropping systems (CRS) as sub-plots. The treatments in the CRS consisted of a sole crop (sunflower or cowpea) and an intercrop (sunflower x cowpea). The IRWH led to a significant ($P < 0.05$) increase in sunflower grain yield in the second season but cowpea grain yield was not influenced by tillage systems (TS). IRWH resulted in significantly higher water use (WU), water use efficiency (WUE) and precipitation use efficiency (PUE) of both crops compared to the CON system. The CRS had significant effects on sunflower grain yield in both seasons, but none on the cowpea grain yield.

The effect of IRWH production on runoff was studied using a rainfall simulator in Chapter 5. Results of this study indicated that IRWH was superior in runoff generation compared to the CON system and it could supply 1% of maize water requirements under the conditions of this ecotope.

The Crop Yield Prediction for Semi-arid Areas (CYP-SA) model was applied to assess risk associated with IRWH on the ecotope. Using cumulated probability functions (CPFs), the results indicated that simulated sunflower yield was significantly influenced by initial profile water content. The IRWH was significantly better than CON at all levels of initial profile water content.

Key words: drainage; hydraulic conductivity; living mulch; rainfall analysis; risk assessment; runoff; tillage

CHAPTER 1

INTRODUCTION

1.1 Background and motivation

In water-scarce regions of Sub-Saharan Africa (SSA), rainfed agriculture covers more than 95% of the crop - lands (Rockstrom, 1999). Crop yields continue to be low, typically revolving around 1 ton ha^{-1} for maize (Stroosjnider, 2003). One of the factors limiting food production over large semi-arid areas of SSA is shortage of water (Stroosnijider, 2003; Botha, 2006). The semi-arid production systems of SSA are characterized by a low, unreliable, single seasonal rainfall regime with large variability in both time and space, requiring particular focus on soil water storage and water use efficiency. Climatic constraints such as high summer temperatures, low, erratic rainfall and high evaporation rates often lead to low crop yields and sometimes total crop failures (Beukes *et al.*, 1999; Bennie & Hensley, 2001; Stroonsjder, 2003). The stability of food production in the semi-arid areas requires interventions to increase precipitation use efficiency (PUE) (Hatfield *et al.*, 2001). In order to ensure increased PUE, efficient capture and storage of rainwater and also the reduction of non-productive losses such as run-off and evaporation from the soil surface are required. By reducing runoff and evaporation and increasing soil water storage, PUE can be improved (Bennie & Hensley, 2001; Stroosnijder, 2003).

Research conducted in the semi-arid areas has shown that good soil and crop management practices can considerably increase the efficiency with which the limited amount available from precipitation is used (Beukes *et al.*, 1999; Mzezewa *et al.*, 1999).

South Africa's semi-arid production systems are characterized by erratic and unevenly distributed rainfall that decreases from east to west. Mid-summer drought is a common phenomena. Drought often coincides with the flowering period, leading to low crop yields (Beukes *et al.*, 1999). According to Bennie and Hensley (2001) most of the dryland production occurs in the semi-arid zones where the aridity indices vary between 0.2 and 0.5. The adoption of agricultural practices by farmers that ensure efficient rainfall utilization for dryland production is essential for production, economic and social sustainability (Bennie & Hensley, 2001). A simplified water balance equation for dryland in soils without a water table and without significant lateral water movement for specific period can be written according to Botha (2006), as follows:

$$Ev = (\pm \Delta S + P) - (E_s + R + D) \qquad 1.1$$

Where:

Ev = evaporation from the crop (transpiration) (mm)

ΔS = change in water stored in the rootzone (mm)

P = precipitation (mm)

E_s = Evaporation from the soil (mm)

R = runoff (mm)

D = deep drainage (mm)

According to Bennie and Hensley (2001), transpiration water can be maximized, hence maximizing crop production, by optimizing parameters on the right hand side of Equation 1.1. A wide range of soil and water management practices are currently being applied or tested in South Africa to achieve these goals.

In the semi-arid production systems of South Africa, two major unproductive losses, which are R and E_s must be minimized in order to optimize PUE (Botha, 2006). Deep drainage is usually negligible in clayey soils. E_s is by far the most important water loss contributing to inefficient water-use in dryland crop production (Beukes *et al.*, 1999). Bennie *et al.* (1994) reported that under semi-arid climatic conditions in South Africa, evaporation from bare soils during the fallow period can amount to between 60 and 75% of the rainfall in the driest summer-cropping areas. They reported that evaporation was highest for conventionally tilled treatment (CON) on the Westleigh soil with a more clayey topsoil. Bennie and Hensley (2001) presented research results indicting the importance of thick surface crop residue mulch on decreasing short-term evaporation. Literature cited by Botha (2006) indicated that water loss by E_s is most severe especially during the fallow period and thus contributing to low rainfall storage.

Research results from semi-arid areas have shown that runoff losses can be as high as 50% of the rainfall on bare untilled lands (Stroosnijder, 2003). A number of South African researchers have documented their findings concerning the extent of runoff losses from agricultural fields. For example, runoff losses between 6 and 30% of the annual rainfall on various soils under conventional tillage (CON) have been reported (Haylett, 1960; Du Plessis & Mostert, 1965; Hensley *et al.*, 2000; Bennie and Hensley, 2001). Runoff losses can be minimized by adopting practices that increase the infiltration capacity of the soil and increase contact time (Unger, 1990).

A production technique, in-field rain water harvesting (IRWH) was developed to address problems of R and E_s water losses (Hensley et al., 2000). The technique promotes rainfall runoff on 2 m wide no-till strip between crop rows and collecting the runoff water in basins where it infiltrates deep into the soil. This is in-field rainwater harvesting as opposed to ex-field rainwater harvesting whereby rainwater is collected somewhere and brought to the field for crop use. The technique combines the advantages of water harvesting from the no-till, flat, crusted runoff strip, and decreased evaporation from the deeply infiltrating runoff water which accumulates in the basin. Thus the IRWH partitions rainfall into runoff (on the no-till runoff strip) and run-on (in the basin). The technique is illustrated in Figure 1.1.

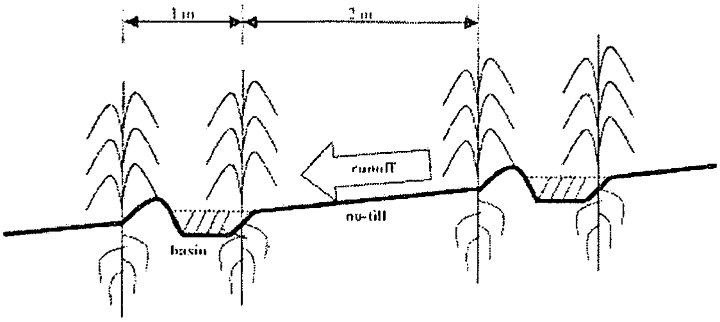

Figure 1.1 In-field rainwater harvesting technique (Hensley *et al.*, 2000).

IRWH has been tested in South Africa on clay and duplex soils in semi-arid areas where it has given maize yield increases of between 25% and 50% compared to CON practices (Hensley *et al.*, 2000; Botha *et al.*, 2003). IRWH has been applied successfully to increase crop yields in homestead gardens east of Bloemfontein, in Thaba Nchu (Botha *et al.*, 2003). Despite the increase in crop yields, the researchers continued to record high evaporation losses of water from the fields. Therefore in order to derive maximum benefit from water harvesting there is a need to suppress evaporation from the soil. Experiments at Glen near Bloemfontein showed that PUE above the best values of 7.4 and 4.8 kg ha^{-1} mm^{-1} for maize and sunflower respectively, it would be necessary to reduce evaporation from the soil surface even further. Thus, a major setback found in the successful application of IRWH production technique was the excessive loss of soil water from the soil profile by evaporation (Hensley *et al.*, 2000; Botha *et al.*, 2003). This limitation has also been reported among other *in-situ* water conservation techniques (Li *et al.*, 2002). Adequate soil cover is necessary for achieving the benefits of IRWH. Previous research efforts in South Africa focused on suppressing evaporative soil water losses from IRWH plots by using organic and stone mulches (Botha *et al.*, 2003). Despite these efforts, results to date indicate that water loss by evaporation remains problematic. Living soil cover between crop plants (living or green mulches) has been proposed as an environmentally viable option to suppress water loss from the soil surface. This is a sound option if living mulches are integrated in an intercropping design in order to derive other benefits of inter-cropping, such as increased yield under conditions of water stress, protection against risks of drought and pests and provision of more balanced human diet (Lima Filho, 2000) and weed suppression (Aladesanwa & Adigun, 2008).

IRWH has the potential to increase food production in the semi-arid environments of the Limpopo Province. The Limpopo province has a semi-arid climate with mean annual rainfall ranging between 450 – 800 mm (Simalenga & Mantsha, 2003). Low and erratic rainfall negatively affects the suitability of the area for rainfed cropping yet 89% of the population depends on agriculture for their livelihoods (Oni *et al.*, 2003). Although sunflower (*Helianthus* *annuus* L..) yield in the province among the smallholder sector is not documented it is expected to follow maize yield trends which are typically low (Simalenga & Mantsha, 2003).

Sunflower is the most important oilseed crop in South Africa. It is the third largest grain crop produced in South Africa after maize and wheat (Grains South Africa, 2003). Sunflower seed is primarily used for manufacturing of sunflower oil and oilcake for animal feed. In South Africa, sunflower is well adapted in both hot and dry climate, making Limpopo province one of the ideal producing area (Thomas, 2003). In South Africa sunflower is grown mainly as a sole crop under commercial production (Botha, 2006). Information on sunflower production practices by the smallholder sector is not readily available. Sunflower residue is fragile and does not provide a lot of ground cover. Legumes intercropped in sunflower could increase soil cover, reduce soil erosion, and add nitrogen and organic matter to the soil (Kendel *et al.*, 1997).

By virtue of its spreading growth habits, cowpea (*Vigna unguiculta* L. Walp.) has been proposed to play a significant role in water conservation, land use maximization and protein generation when intercropped with field crops like sunflower (Awe & Abegunrin, 2009). Little is known about sunflower x cowpea intercropping systems. This could be due to the fact that cowpea is grown mainly by smallholder farmers whilst sunflower is mainly a commercial crop. Studies on cowpea intercropping systems have mainly focused on yield benefits although little has been done in this area in South Africa (Ayisi *et al.*, 2004). Where such studies were conducted with cowpea as a companion crop, results have been mixed and often inconclusive. In Botswana intercropping sorghum with cowpeas had little effect on total seasonal water use (Rees, 1986), but intercropping cowpea with millet increased rainfall utilization in north east Nigeria (Grema & Hess, 1994).

1.2 Hypotheses

- It was hypothesized that IRWH will increase crop yield on the clayey soils, compared to CON, due to the fact that enhanced runoff on the flat, crusted no-till runoff strip shown in Figure 1.1 will result in a large fraction of the rainfall being stored in the basins, resulting in a higher PUE efficiency than with CON which will have ex-field runoff losses as well as higher water losses due to soil water evaporation.
- It was further hypothesized that cowpea intercropped as living mulches with sunflower will increase water use (WU), water use efficiency (WUE), PUE and grain yield of sunflower.

In this study sunflower was intercropped with cowpeas in order to investigate the role of cowpea green mulching on reducing evaporation from the soil. The study was based at the University of Venda Experimental Farm in Thohoyandou, Limpopo Province (Figure 1.2) with latitude 22° 58' S, longitude 30° 26' E and altitude of 596 m above sea level. The farm is located at about 2.5 km west of Thohoyandou town. The soils belong to the Shortlands form (Soil Classification Working Group, 1991) and approximately equivalent to the Ferralsol according to the World Reference Base for Soil Resources (2006). Thohoyandou falls under the Thulamela Municipality in Vhembe District. The study area falls in the eastern part of the Lowveld which forms part of the greater Limpopo River Basin. The experimental farm is on undulating topography with average slopes of about 8% in north-south direction. Rainfall is highly seasonal with 85%

occurring between October and March (summer) (Table 3.3). The mean maximum temperature (T_{max}) is around 30°C while the mean minimum temperature (T_{min}) is about 20°C during the growing period. The highest evaporative demand also occurs from October to March. The mean annual aridity index (AI) is 0.52 making the area to fall on the borderline between semi-arid and sub-humid according to the UNESCO classification criteria. Average annual rainfall is about 781 mm.

Agricultural industry in the Limpopo Province is made up of two sectors, namely, the large scale commercial and the small holder farming system. There were 5 000 commercial farming units and 273 000 small-scale farmers operating in the Limpopo Province in the year 2002 (Statistics South Africa, 2002). It was estimated that agriculture contributed 4% to the gross geographical product (GGP) of Limpopo Province in 2002 and the small holder sector provided about 43% of total agriculture income in the province. Smallholder farmers operate from the former homelands. However, it could not be established how many of these farmers cultivate on the Shortlands. Nevertheless, previous studies indicate that the majority of small-scale farmers in the northern Vhembe District (study area) depend on the Shortlands soil for crop and fruit farming (Simalenga & Mantsha, 2003). Vhembe District is largely rural and is one of the five districts in the Limpopo Province where a large village population rely on agriculture for livelihood. The area is marginal for crop production because of relatively low and erratic rainfall. This study site was chosen as a representative of major farming activities in the region. The site also represents the farming areas where the majority of smallholder farmers operate in the region. In Vhembe District research results have shown that the average yield of maize was approximately 12 bags per ha ($\approx$ 600 kg ha^{-1}) (in a good year) and was about 5 bags per ha ($\approx$ 250 kg ha^{-1}) in a bad year.

Poverty and food insecurity is therefore a major challenge facing small holder farmers in the province. One of the recommendations of Simalenga & Manstha (2003) study was that the farmers need to adopt water management strategies to mitigate effects of the unpredictable weather.

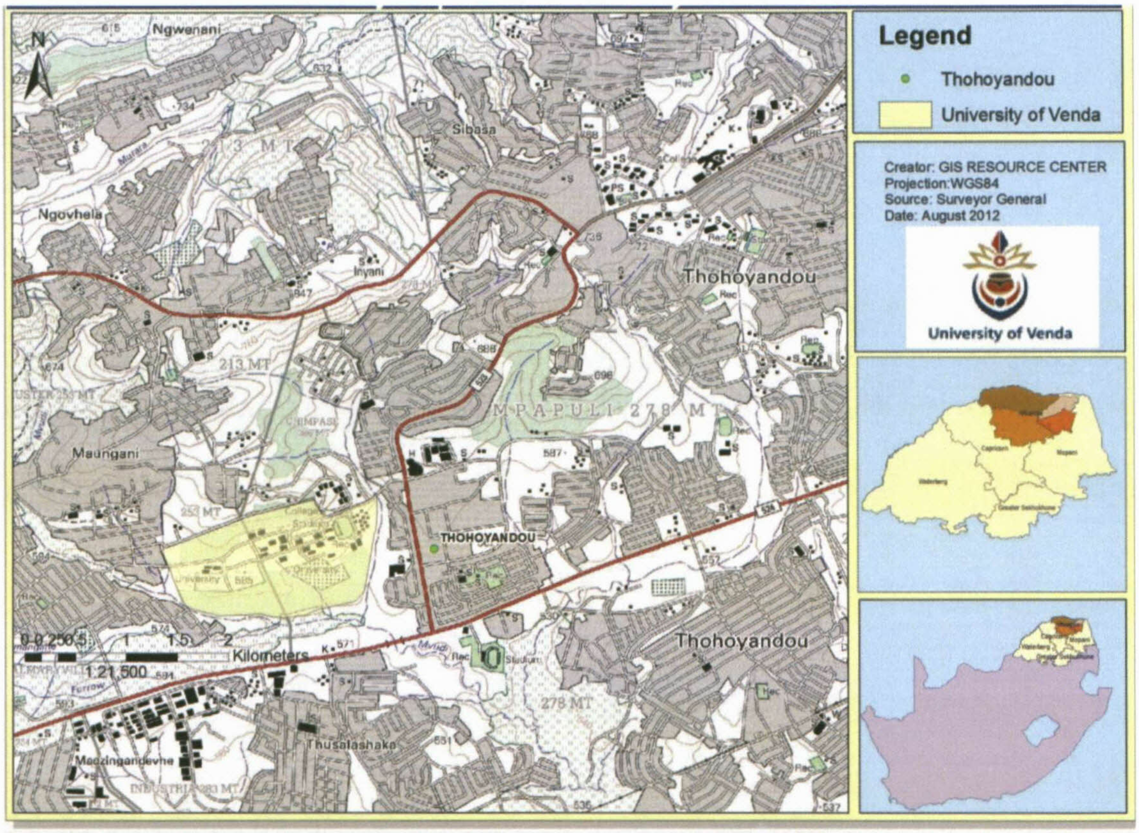

Figure 1.2 Location map of the University of Venda and its environs.

1.3 Objectives of the study

The general objective of the study was to evaluate IRWH using sunflower x cowpea intercrop on the University of Venda-Shortlands ecotope. Specific objectives of the study were to:

(i) Characterize soil hydraulic properties of the Shortlands soil , and

(ii) Relate the measured hydraulic properties to the pedological features of the Shortlands soil.

(iii) Analyze the on-station climate and rainfall using 23 years of data from Thohoyandou weather stations as a basis for water harvesting studies.

(iv) Evaluate the grain yield, seasonal WU, WUE and PUE of sunflower (*Helianthus annuus* L.) intercropped with cowpea (*Vigna unguiculata* L.) under IRWH and CON practices in a Shortlands soil.

(v) Determine the effect of IRWH technique on runoff from a Shortlands soil.

(vi) Assess the long-term crop production risks of sunflower using IRWH technique at the University of Venda-Shortlands ecotope using an empirical model.

1.4 Organization of thesis

This thesis is organized into seven chapters. Chapter 1 is the general introduction to the thesis providing background information and justification for the research as well as objectives of the study and outline of the thesis.

Chapter 2 provides a detailed characterization of hydraulic properties of the University of Venda- Shortland ecotope. The implications of these properties on IRWH development are also discussed.

Chapter 3 presents a detailed analysis of rainfall and climate of the ecotope. It includes a thorough analysis of probability distribution of rainfall, probability of dry spells and cumulative frequency of daily rainfall.

Chapter 4 presents an outline of a 2-year field experiment that evaluated the effect of IRWH on sunflower x cowpea production. It includes an analysis of tillage and cropping systems effects on seasonal crop water use, water use efficiency and precipiation use of sunflower and cowpea.

Chapter 5 presents a field rainfall simulation experiment. The effects of tillage and tillage by rainfall intensity interactions on runoff are presented.

Chapter 6 includes calibration and verification of the CYP-SA model in attempt to assess the risk associated with sunflower production using IRWH technique on the ecotope. Long-term climate data (1983-2010) and CMUL of PAW, DUL of PAW, LL of PAW, P, ET_o and θ_p were used as inputs to run the model.

Chapter 7 gives summary and general conclusions with recommendations.

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CHAPTER 2

SOIL HYDRAULIC PROPERTIES OF A SHORTLANDS SOIL

Abstract

The Shortlands soil is one of the most important agricultural soils of South Africa. However, there is little documented study with respect to the hydraulic properties of this particular soil type. The aim of this study was to characterize some of the most important soil hydraulic properties of a soil profile at the University of Venda Experimental Farm in Thohoyandou, Limpopo Province. The soil is earmarked for IRWH development. Hydraulic soil properties were characterized alongside pedological properties of the profiles. The relationship between soil water content (θ) and matric suction (h) or soil water release curve (SWRC) was obtained using the hanging water column ($h \leq 800$ mm water). The drainage patterns as well the relationship between θ and unsaturated hydraulic conductivity (K) for each diagnostic soil horizons were evaluated using the *in situ* method of Hillel. Values of suction head (h) (≤ 800 mm of water) were inferred from laboratory determined SWRC. Field saturated hydraulic conductivity (K_s) of each diagnostic soil horizon was determined using a double ring infiltrometer. The soil at the University of Venda was classified as Shortlands soil form belonging to the Tongaat family and consisting of two diagnostic horizons, namely, the orthic A and structured B-horizons. Results from this study indicated that soil hydraulic properties were unique for each diagnostic horizon. The saturated hydraulic conductivity in the orthic A and structured B-horizons was 30 mm h-1 and 12 mm h^{-1}, respectively. The difference was largely attributed to the crumb microstructure observed in the orthic A-horizon. The study indicated that the University of Venda-Shortlands ecotope has good water retention properties as 19% (average for the profile) of the water was released between saturation and 8 kPa. It was also concluded that the plant available water (PAW) (267 mm) in the root zone of was high, making the soil suitable for IRWH strategy.

Key words: hydraulic conductivity; in situ drainage; pedological properties; water release characteristic;

2.1 Introduction

Shortlands soils (Sd) belong to the oxidic soil group. They have an orthic A-horizon and red structured B-horizon that is uniformly coloured with red and/or yellow oxides of iron (Fey, 2010). The oxidic soil variants with apedal B-horizon belong to the Hutton form (Soil Classification Working group, 1991). The characteristic feature of the oxidic soils is the relatively free drainage and well aerated B horizon. The oxidic soils form an important part of South African landscape. A wide range in degree of weathering is possible and these soils exhibit a broad geographic distribution (Figure. 2.1). The soils belonging to the Shortlands form, typically occur in the warmer, somewhat drier zones of savanna and thicket biomes (Fey, 2010).

It may be generalized that the soils belonging to the oxidic group are easier to till and are less prone to erosion due to their micro-aggregating effect. Low cation exchange capacity (CEC) on mineral colloids makes the soils prone to soil fertility loss if organic matter is not managed well. Soil acidity and phosphate fixation is a potential limitation for crop cultivation for the more leached and weathered apedal variants found in higher rainfall areas. The problem of acidity and infertility is especially important among the dystrophic families. However, the Shortlands are highly productive when irrigated due to their relatively free drainage and structural stability.

The Limpopo Province covers 11.96 million ha of which 88.2% (10.5 million ha) constitute farmland. Of the farmland, 37.7% is suitable for arable farming, yet it was estimated that agriculture contributed only 4% to the gross geographical product (GGP) of Limpopo Province in 2002 (Oni *et al.*, 2003). The total area currently under irrigation constitutes 1.4% of the total farmland in Limpopo Province (Oni et al., 2003). This means a great proportion of food requirements are produced under dryland conditions. The potential for food production in the Limpopo Province is limited by low and erratic rainfall. The smallholder farmers reported to be 273 000 in the province in 2002 (Statistics South Africa, 2002) are the most vulnerable because they cannot afford irrigation systems. It is reported that the average yield of maize was low (about 250 to 600 kg ha^{-1}) in Vhembe District of the Limpopo Province leading to the recommendations that farmers need to adopt water management strategies to mitigate the effects of unpredictable weather (Simalenga & Manstha, 2003).

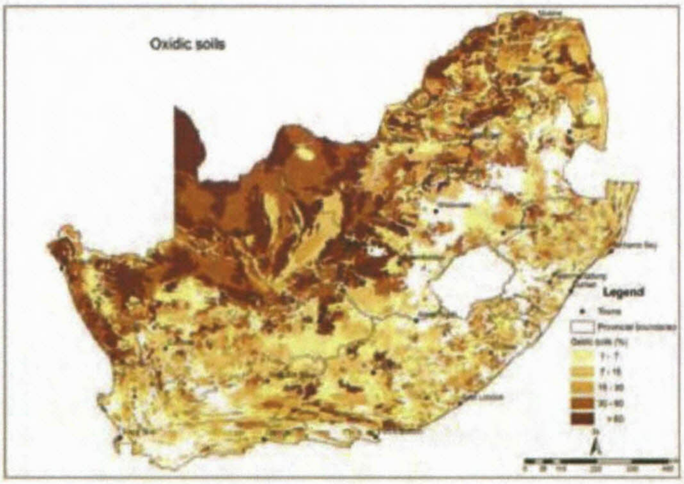


Figure 2.1 Oxidic soils in South Africa (abundance classes refer to estimated percentages within land types) (After Fey, 2010).

There has been increasing interest recently in South Africa of making crop production less risky and sustainable in semi-arid ecotopes through IRWH (Botha *et al.*, 2003). Botha & van Rensburg (2004) demonstrated from their study over six seasons that the IRWH crop production technique, when compared to CON practice (ploughing with mould board) increased maize and sunflower yields by as much as 50%. In order to implement the IRWH technique it is important to understand the soil hydraulic properties. Some work has been done on characterizing the hydraulic properties of some important soil types in South Africa. For example, Bothma (2009) on the Bloemdal and Sepane soils, Chimungu (2009) on the Tukulu and Bainsvlei, and Nhlabatsi (2011) on the Bonheim. However, there is hardly any study documenting the hydraulic properties of the Shortlands soil. Knowledge of soil hydraulic properties and the pattern of water movement within the profile are important for describing and predicting variables that may affect many agronomic, engineering and environmental projects (Hillel *et al.*, 1972; Zhang *et al.*, 2007). For example, understanding of soil hydraulic functions will help to solve problems related to irrigation, subsurface drainage contributions to groundwater, growth of saline seeps and water disposal, prediction of runoff and infiltration following precipitation. The basic soil hydraulic properties and characteristic functions that govern the flow of water in soil are (1) saturated hydraulic conductivity (K_s), (2) soil hydraulic conductivity as a function of soil water content $K(\theta)$ or $K(h)$, commonly called unsaturated hydraulic conductivity and (3) soil water content as a function of matric pressure head $\theta(h)$, commonly referred to as soil water retention curve and also known as the soil water characteristic curve (Hillel, 1998).

Hydraulic conductivity of a saturated soil is one of the most important soil properties controlling water infiltration and surface runoff, leaching of pesticides from agricultural lands and migration of pollutants from contaminated sites to the ground water. Saturated hydraulic conductivity depends strongly on soil structure (Dexter *et al.*, 2004; Bargarello et al., 2009), while unsaturated hydraulic conductivity is more related to the surface area of particles (texture). Unsaturated hydraulic conductivity varies over many orders of magnitude not only between different soils, but also for the same soil as a function of water content or suction. This makes the soil conductivity function one of the most important physical soil property, yet also one of the most difficult to measure accurately (Hillel, 1998). Soil water characteristic curve is a fundamental soil property employed to quantify plant available water and for modeling and managing water and solute movement in soils (Medina *et al.*, 2002). The $\theta(h)$ relationship is strongly dependent on soil pore geometry (Kutilek, 2004).

Mathematical models of hydrologic and agricultural systems require knowledge of the relationships between soil water content (θ), h and $K(\theta)$. Knowledge of these parameters at matric pressures between 0 and approximately 10 kPa where the flow of water is most significant, is particularly important for estimating drainage and as well as for the recharge of the ground water storage (Heathman *et al.* (2003). The water movements in the unsaturated zone, together with the water holding capacity of this zone, are important for the water demand of crops. However, data on hydraulic properties especially for these important soils of South Africa like the Shortlands is not readily available. It is envisaged that data emanating from the characterization of the soil hydraulic properties of the Shortlands will fill the knowledge gap and contribute to the understanding of the soil water balance of the IRWH system. A better understanding of the IRWH system could translate into more food and improved standard of living for South Africans in particular and for those people living in the semi-arid regions of the world in general. The data emanating from this study could also be used in irrigation designs and other environmental projects in the region. Therefore the objectives of this chapter were to:

(i) quantify soil hydraulic properties of the Shortlands soil , and

(ii) relate the measured hydraulic properties to the pedological features of the Shortlands soil.

2.2 Material and methods

2.2.1 Soil sampling

The soil samples were taken from a soil profile pit (Figure 2.2) at the University of Venda Experimental Farm in Thohoyandou, Limpopo Province of South Africa: (22° 58" 40' S /30° 26"25' E; 596 m). Disturbed soil samples were taken per diagnostic horizon and analyzed according to the standard methods described by the Non-affiliated Soil Analysis Work Committee (1990). Undisturbed soil core samples (6 per horizon) were taken from the profile pit under moist conditions at the depth of 300 mm (representing the A-horizon), 600 mm (representing B1-horizon) and 1200 mm (representing B2-horizon) using a core sampler whose dimensions were 50 mm (diameter) and 50 mm (height). Three cores per horizon were oven-dried for 24 hours at 105° C and the dry weight determined. Remainder cores samples were used for SWRC determination (section 2.2.6). Bulk density (D_b) was calculated by dividing the dry soil mass by the volume of the core (Blake & Hartge, 1986).

Figure 2.2 Soil profile of the University of Venda-Shortlands ecotope.

2.2.2 Determination of saturated hydraulic conductivity

To estimate saturated conductivity (K_s) a steady state infiltration rate was measured from a ponded double ring infiltrometer, with a 530 mm outer and 277 mm inner diameter cylinder inserted 100 mm into the soil (three replicates). The rings were carefully driven into each soil horizon which had a flat surface created prior to infiltration tests. Equal pressure head in both the outer and inner rings were maintained during the infiltration process. Initial soil water content was measured before each infiltration run. The criterion used for attaining steady-state infiltration was that the 5 minutes infiltration volume during a 30 minute record remained constant (Mertens *et al.*, 2002). Samples of saturated soil were taken to determine the saturated water content, θ_s. The gravimetric soil water content was converted to volumetric water content by multiplying it with D_b.

2.2.3 Internal drainage method

In this study, the internal drainage method of Hillel *et al.* (1972) was used to determine the $K(\theta)$ relationships. The main advantage is that it is non-destructive, and can be applied simultaneously at several soil depths under natural conditions that include swelling and shrinking, and normal field suction heads (Hillel *et al.*, 1972). The internal drainage is based on Darcian analysis of transient soil water content and hydraulic head profiles during vertical drainage following a thorough wetting by irrigation or rain. This method is also known as the instantaneous profile method. The method requires frequent and concurrent measurement of both soil water and matric suction head (h) over time during vertical drainage of a uniformly wet soil profile. Uniform, one dimensional flow, non-hysteric, and isothermal conditions are assumed, giving the general equation describing the flow of water in a vertical soil profile according to Hillel *et al.* (1972) as:

$$q = -K(\theta)\frac{\partial H}{\partial z} \qquad 2.1$$

Where:

q = soil water flux (LT^{-1})

z = the vertical depth (L) here taken as positive downward

$K(\theta)$ = the hydraulic conductivity ($L\ T^{-1}$) as a function of soil wetness

H = hydraulic head (L) = $h + z$

$\partial H/\partial z$ = hydraulic head gradient

An area of 4000 mm x 4000 mm was leveled and earthen dike made around the perimeter of the plot to prevent lateral movement of water. Three replicates were made. Two neutron water meter (NWM) access tubes (2000 mm long), spaced at 1000 mm from each other were installed in the centre of the area. Measurements were taken at depths coinciding with the soil horizons as follows: 300 mm (A-horizon), 600 mm (B1-horizon) and 1200 mm (B2-horizon). A hosepipe was connected to a nearby hydrant to fill the plots with water, and keep them full until continuous NWM readings showed that the wetting front had reached about 1500 mm. At this stage additional water was stopped. Time was recorded when the last surface water disappeared into the soil, and the water content of the whole profile was measured. This represented the water content at saturation (θ_s). The plots were carefully covered with a white plastic sheet. Care was taken to ensure that there was a good seal around the protruding access tubes to prevent wetting by rain. Readings were taken daily (08h00) in the beginning and staggered later until the decrease in soil water content of the root zone (θ_r) became negligible (Botha *et al.*, 2003). The experiment was monitored for 60 days. The drained upper limit (DUL) was considered to have been reached when $\Delta\theta_r$ became negligible at about 0.1 to 0.2% per day according to Ratliff *et al.*

(1983). The water content of the root zone (θ_r) plotted against time (days) after saturation describes the drainage curve.

2.2.4 Data processing for internal drainage method

Data processing was according to the method by Hillel et al. (1972). Firstly, the *in situ* θ values were plotted with time for each selected depth (Figure 2.3). Secondly, the flux (q) was calculated through each depth increment by integrating the θ-time curve, with respect depth. Thirdly, the hydraulic gradient $\partial H/\partial z$ was determined using SWRC obtained from laboratory measurements. Values of matric suction (h) corresponding to the *in situ* measured θ values were estimated from the SWRC (section 2.2.6). Gravitational head (z) was then added to h to obtain change in hydraulic gradient (ΔH). Fourthly, $K(\theta)$ was calculated at each depth and for the different θ values by dividing the flux (q) with the corresponding $\partial H/\partial z$ values. Finally, $K(\theta)$ was plotted against θ values and a curve was fitted. A similar approach has been followed by other researchers (Zhang *et al.*, 2007; Chimungu, 2009; Nhlabatsi, 2011).

2.2.5 Lower limit of plant available water (LL)

The lower limit of plant available water (LL) was determined during the course of the growing season. LL was taken as the lowest θ_r for each soil layer measured over the two growing seasons (Botha, 2006). LL is the lowest field- measured water content of a soil after plants have stopped extracting water and is at or near pre-mature death, or has become dormant as a result of water stress (Ratliff *et al.*, 1983).

2.2.6 Laboratory characterization of the water retention characteristics

2.2.6.1 Soil sampling

As described in section 2.2.1.

2.2.6.2 Sample saturation

The procedure followed was previously described by Chimungu (2009). The bulk density (D_b) was determined after drying the samples at 105°C for 24 hours. To determine the $\theta(h)$ using the undisturbed sample samples the first step was to saturate the soil cores using vacuum saturation chambers. Saturation chambers are vessels filled with water in which a soil sample in a retaining ring can be inundated for saturation. De-aired water was used for saturation. Water was de-aired by continual stirring in a container to a vacuum source ± 60 kPa. The deaired water was then let in gradually into a companion chamber where de-aired soil samples were placed, until the water level was just below the top of the samples. It was found that 24 hours was enough to reach saturation. The gravimetric water content of the samples was then determined by weighing the sample immediately after taking it out of the saturation chamber. The volumetric water content (θ_s) value was later calculated by multiplying the gravimetric water content by the D_b value.

2.2.6.3 Desorption measurements

The SWRC was measured using the hanging water column (h = 0-800 mm water ≈ 0- 8 kPa). The samples on the hanging water column were equilibrated until no more outflow occurred. After equilibration, the samples were weighed to determine the water content corresponding to the suction. The gravimetric water content was converted to volumetric water content by multiplying it by the relevant D_b value.

2.3 Results

2.3.1 Pedological properties

A detailed profile description is given in Table 2.1 Selected soil properties are shown in Table 2.2. The profile was deeply weathered to more than 1500 mm and derived from basalt rock of the Sibasa Formation. The orthic A-horizon was reddish brown (2.5YR 3/4 dry; 2.5YR 3/3 moist) over a uniform dark red structured B1 and B2-horizons (2.5 YR 4/6 moist; 2.5YR 3/6 moist) (Fig. 2.2). Soil structure was weak to moderate fine subangular blocky. Micro-aggregates were developed in the 0-400 mm depth or the orthic A-horizon and less developed in the structured B1 and B2-horizons. Common clay skins were also observed in the structured B-horizons. Boundaries between the orthic A and structured B1-horizons were clear and diffuse between the structured B1 and B2-horizons. The profile was well drained and had rapid permeability.

The soil profile was dominated by clay (average 60%) which changed slightly with depth. Relatively high silt content (>30%) throughout the profile was also a typical feature of the soil profile (Table 2.2).

Bulk density was low, ranging from 1.24 in the A-horizon to 1.33 g cm^{-3} in the B-horizons. The liquid limit was 47, 53 and 49 for the A, B1 and B2-horizons, respectively. The plastic limit was 30, 40 and 37 for the A, B1 and B2-horizons, respectively, giving the plasticity index (P_i) (liquid limit-plastic limit) of 17, 13 and 12 for the respective horizons (Table 2.2).

All horizons were acidic [pH (water) 5.4-5.5]. Organic carbon contents of the soils were 1.7% in the A-horizon and 0.6% (average) in the B1 and B2-horizons. Exchangeable bases were dominated by Ca followed by Mg, Na and K. The CEC was relatively high and ranges from 19 in the A-horizon to 15 $\mathrm{cmol_c\ kg^{-1}}$ (average) in the B1 and B2-horizons (Table 2.2).

In terms of classification the soil at the University of Venda has a weak to moderate soil structure. The soil structure is therefore borderline between apedal B and structured B-horizons. Under such circumstances the South African Soil Classification System defines the CEC in the B-horizon as the determining factor. The CEC of 11 $\mathrm{cmol_c\ kg^{-1}}$ soil is defined as the threshold for differentiating between apedal and structured B- horizon. Therefore because the CEC in the structured B-horizon was 15 $\mathrm{cmol_c\ kg^{-1}}$ (average) (Table 2.2) the soil was accordingly classified as Shortlands (Sd) form belonging to the Tongaat (1110) family; dystrophic, non-luvic, subangular structure (Soil Classification Working Group, 1991; Garry Paterson, ARC-ICSW, Pretoria, personal communication, 2011).

Clay mineralogy was dominated by kaolinte (99% in the orthic A-horizon) with some smectite (<30%) in the structured B-horizon (Table 2.3). The sub-soils contained some traces (<10%) of hematite.

Table 2.1 Profile description of the University of Venda-Shortlands ecotope

Location:	Univen Exp. farm	Soil form and family:	Shortlands *Tongaat*
Latitude:	22° 58" 40' S	Surface rockiness:	None
Longitude:	30° 26"25' E	Occurrence of flooding:	None
Altitude:	596 m	Wind erosion:	Slight
Land type:	Ab179	Water erosion:	None
Terrain unit:	Mid-slope	Vegetation/Land use:	Fallow
Slope:	8%	Water table:	None
Slope shape:	Straight	Described by:	J.Mzezewa / HP Nemakundani/
Aspect:	South	Date described	15/10/11
Microrelief:	None	Weathering of underlying material:	Moderate chemical
Parent material solum:	Basalt (Sibasa formation)		

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 400	Dry state; disturbed; clay; friable; sticky; slightly plastic; weak fine subangular blocky; crumb microstructure; reddish brown (2.YR 3/4 dry, 2.5YR 3/3 moist); rapid permeability; well drained; very fine roots; clear smooth transition to:	Orthic A
B1	400 - 760	Dry; undisturbed; clay; moderate fine subangular blocky, common cracks; friable; sticky; plastic; Red (2.5YR 4/6 dry); dark red (2.5YR 3/6 moist); good permeability; well drained; Diffuse transition to:	Red Structured B
B2	760 - 1300+	Dry; undisturbed; clay; moderate fine subangular blocky; common cracks; friable; sticky; very plastic; Red (2.5YR 4/6 dry); dark red (2.5YR 3/6 moist); few clay skins; good permeability; well drained.	Red Structured B

Table 2.2 Selected soil properties of the University of Venda-Shortlands ecotope

	Orthic A horizon 0 - 400 (mm)	Red structured B1 horizon 400 - 760 (mm)	Red structured B2 horizon 760 - 1300+ (mm)
	Physical properties		
Course sand (2-0.5 mm)	1.7	1.5	1.8
Medium sand (0.5-0.25 mm)	2.2	1.5	1.5
Fine sand (0.25-0.106 mm	4.1	2.8	3.0
Very fine sand (0.106-0.05 mm)	4.2	3.2	3.2
Course silt (0.05-0.02 mm)	4.0	9.4	9.2
Fine silt (0.02-0.002 mm)	26.3	20.7	21.1
Clay (<0.002 mm)	57.5	60.9	60.2
Texture class	Clay	Clay	Clay
Bulk density (g cm^{-3})	1.24	1.33	1.20
Plasticity Index (P_i)	17	13	12
	Chemical properties		
pH(H_2O)	5.4	5.4	5.5
Organic carbon (%)	1.71	0.72	0.52
	Exchangeable cations (c mol_c+ kg^{-1} soil)		
Sodium)	0.12	0.10	0.12
Potassium	0.09	0.04	0.03
Calcium	2.12	1.48	1.01
Magnesium	1.24	0.95	0.78
S- value	3.57	2.56	1.93
CEC	19.11	13.97	15.62

Table 2.3 Mineralogical analysis of the University of Venda-Shortlands ecotope

	Orthic A horizon 0 - 400 (mm)	Structured B1 horizon 400 - 760 (mm)	Structured B2 horizon 760 - 1300+ (mm)
	Minerals (%)		
Quartz (Qz)	0	0	0
Kaolinite (Kt)	99	80	64
Smectite (St)	1	20	29
Feldspar (Fs)	0	0	0
Hematite (Hm)	0	0	7

2.3.2 Drainage patterns of soil horizons.

Drainage data were obtained from the internal drainage experiment, which lasted 60 days. The change in water content with time is shown in Figure 2.3. The associated regression equations are summarized in Table 2.4. The internal water re-distribution in the profile is further depicted in Figure 2.4. The power function fitted the drainage data very well ($R^2 > 0.80$) for all horizons. It is clear from Figure 2.3 and also from regression equations that drainage pattern in the A-horizon was unique, whilst the pattern in the B1 and B2-horizons were similar. The water re-distribution pattern shown in Figure 2.4 revealed that there was a sharp decline in SWC between saturation (day 0) and subsequent days after saturation. Thereafter the change in SWC was gradual to almost insignificant after 14 days after saturation. Profile water re-distribution diagram revealed two distinct patterns. One pattern of water distribution occurred in the orthic A-horizon, whilst a different pattern was observed in the structured B1 and B2-horizons.

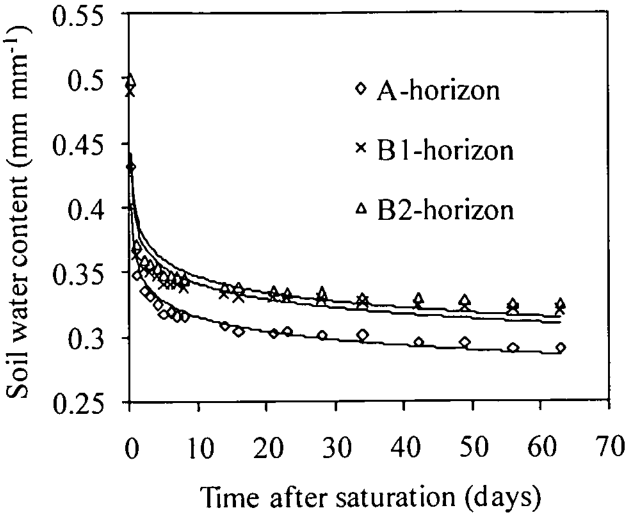


Figure 2.3 Drainage curves of three soil horizons from initially saturated soil.

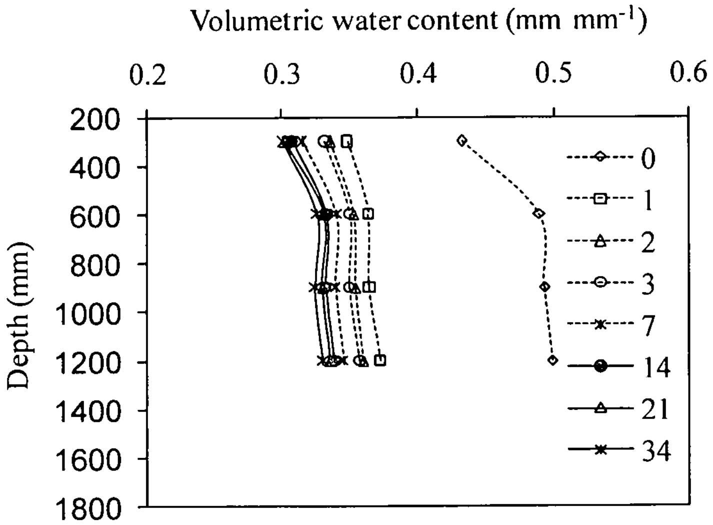


Figure 2.4 Soil water re-distribution during drainage from initially saturated uniform profile.

The numbers indicate duration of the process (days).

Table 2.4 Regression functions describing drainage patterns over 60-day period for the horizons of the University of Venda-Shortlands ecotope

Horizon	Soil depth (mm)	Regression function	R^2
A	300	$\theta = 0.356t^{-0.05}$	0.93
B1	600	$\theta = 0.384t^{-0.05}$	0.81
B2	1200	$\theta = 0.392t^{-0.05}$	0.83

θ is the soil water content in mm mm^{-1} and t is time after field saturation in days.

The DUL corresponding to the drainage rate of between 0.1 and 0.2% per day according to Ratliff *et al.* (1983) method was reached after 14 days for A-horizon at SWC of 0.31 mm mm^{-1}, 14 days for B1-horizon at SWC of 0.33 mm mm^{-1} and 21 days in B2 at SWC of 0.34 mm mm^{-1}. The corresponding DUL (depth equivalent of water) in the A, B1 and B2-horizons was 119, 124 and 214 mm, respectively, with profile total of 457 mm. Basing on SWRC (Figure 2.7), the suctions corresponding the DUL in A, B1 and B2-horizons were 200, 200 and 600 mm of water.

2.3.3 Hydraulic conductivity of horizons

The K_s for the orthic A-horizon was 30 mm h^{-1}, whilst the K_s for the structured B1 and B2-horizons were identical at 12 mm h^{-1} . Field saturated (θ_{sf},) and laboratory saturated (θ_{sl}) water contents and saturated hydraulic conductivity (K_s) of three horizons are depicted in Figure 2.5. The field and laboratory determined water content at saturation differed for all horizons differed marginally. The θ_{sf} for the A, B1 and B2-horizons were 0.43, 0.49 and 0.50 mm mm^{-1}, respectively. The θ_{sl} for the same horizons were 0.48, 0.51 and 0.55 mm mm^{-1}, respectively.

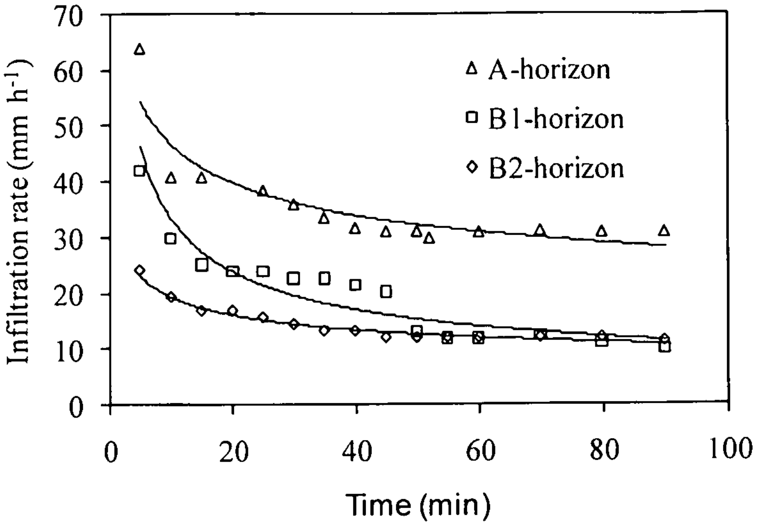


Figure 2.5 Steady-state mean infiltration rate for the three soil horizons.

Table 2.5 Field saturated hydraulic conductivity (K_s), field-saturated water content (θ_{sf}) and laboratory saturated water content (θ_{sl}) for the University of Venda-Shortlands ecotope

Horizon	Soil depth (mm)	K_s (mm h^{-1})	θ_{sf} (mm mm^{-1})	θ_{sl} (mm mm^{-1})
A	300	30	0.43	0.48
B1	600	12	0.49	0.51
B2	1200	12	0.50	0.55

The K(θ) curves for the University of Venda-Shortlands ecotopel is presented in Figure 2.6 and results of regression functions for each of the three horizons are given Table 2.6. The relationship between unsaturated hydraulic conductivity (K) (mm h^{-1}) and soil water content (θ) (mm mm^{-1}) was best described by the exponential equations. The R^2 values were > 0.80 for the A and B2-horizons and > 0.70 for the B1-horizon, indicating a strong relationship. The hydraulic functions are unique for the orthic A-horizon and generally similar for the structured B1 and B2-horizons. It seems the vertical flow in the profile is controlled by the B horizons when volumetric water content is above 0.38 mm mm^{-1}, and controlled by the A-horizon when volumetric water content is between 0.32 - 0.36 mm mm^{-1}.

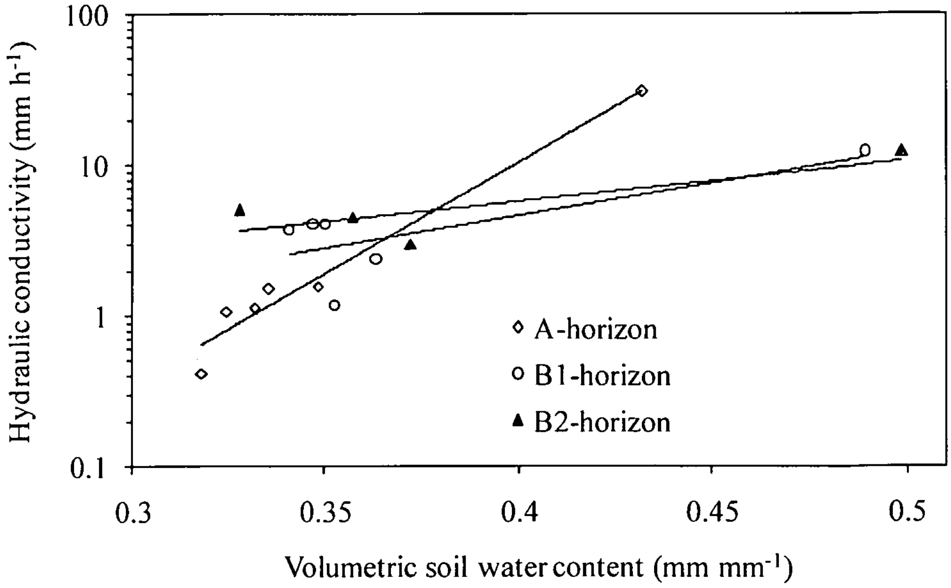


Figure 2.6 Relationships between the hydraulic conductivity (K) and volumetric water content (θ) for three horizons. Values of suction head (h) (≤800 mm of water) were inferred from laboratory determined θ(h) relationships.

Table 2.6 Regression functions describing K(θ) relationships ($h \leq 800$ mm of water)

Horizon	Soil depth (mm)	Regression functions	R^2
A	300	$K = 1 \times 10^{-5}e^{33.86(\theta)}$	0.97
B1	600	$K = 0.05e^{11.33(\theta)}$	0.71
B2	1200	$K = 0.218e^{8.079(\theta)}$	0.95

2.3.4 Characterization of θ(h) relationships of horizons

The relationships between volumetric soil water content (θ) versus matric suction (h) for the different soil horizons are shown in Figure 2.7. Zero suction ($h = 0$) was taken as 0.1 in this study. In the wet zone, near saturation, the B1 and B2-horizons gave higher water retention than A. For suctions greater than 100 mm of water the curves seemed generally similar for all the horizons.

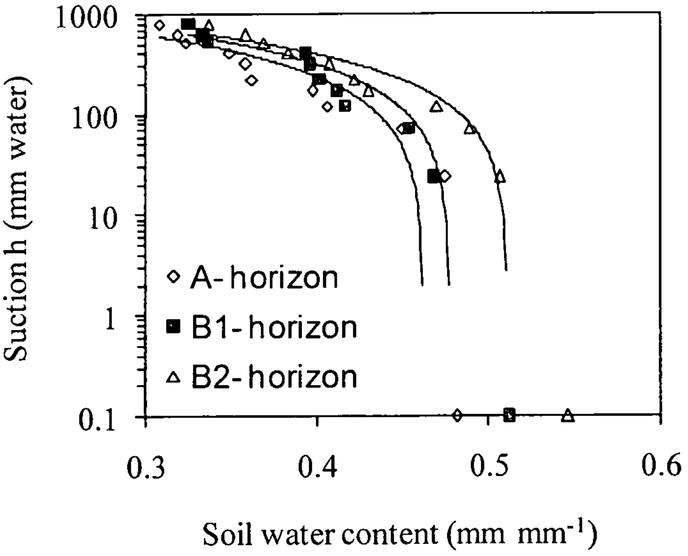


Figure 2.7 Soil water release curves ($h \leq 800$ mm) for three horizons of the University of Venda-Shortlands cotope.

2.4 Discussion

Saturated hydraulic conductivity is a function of total soil pores available for conducting water, and, therefore will relate to the structure of the soil (Chimungu, 2009). The laboratory measured θ_s was slightly exaggerated compared to the field measured θ_s for all three horizons, as expected, because under field conditions a certain amount of air is usually entrapped in the soil (Mertens *et al.*, 2002). The laboratory determined θ_s is an indicator of total soil pores available for transmitting water. Based on the laboratory measured θ_s, 48%, 51% and 55% porosity is available for conducting water in A, B1 and B2-horizons, respectively. Although the total horizon porosities do not differ much, K_s in the A-horizon was 2.5 times higher than that measured in the B1 and B2-horizons (Table 2.5). The differences may be due to the presence of macro-pores or larger pores associated with a crumb micro-structure (or micro-aggregates) common in the orthic A-horizon. Soil micro-aggregation has been linked to higher K_s in similar soils (Medina *et al.*, 2002; Balbino *et al.*, 2004). Macro-pores or structural pores are found between soil aggregates and are responsible for water flow between 0 - 10 kPa (Kutilek, 2004). Higher organic carbon in the A-horizon compared to the B horizon (Table 2.2) may have contributed to the aggregation of the orthic A-horizon and thereby creating larger pores compared to the structured B-horizons with less organic carbon concentration. In addition to micro-aggregation, low saturated conductivity in the B-horizons may be attributed to the slightly higher bulk density (2.7 g cm^{-3} on average) compared to the A-horizon (Table 2.2). Slightly elevated bulk density in the B-horizons was probably due to compaction pressures exerted by the bottoms of tillage implements, as previously reported by Dexter *et al.* (2004).

The fall in hydraulic conductivity from the wet end of SWRC or θ_s to the drier end (8 kPa) is steeper in A-horizon compared to the other two horizons which showed a similar pattern (Figure 2.8). This could suggest that the A-horizon contains larger pores that empty quickly compared to the other two horizons. The change in pore space between saturation and 8 kPa suction represents the amount of water released. For example, the change in pore space was 17%, 18% and 21% for the A, B1 and B2- horizons. This could indicate that only large pores were emptied between saturation and 8 kPa suctions, similar to the findings of Nhlabatsi (2011) who reported that 19% pore space was associated with suctions between 0 and 1.1 kPa in a Bonhein soil.

The Shortlands soil has a high plant available water (PAW) (DUL-LL) for the sunflower crop. This can be seen from the percentage PAW for the A (20%) and B (21%) horizons in Table 2.7. When the Shortlands soil is compared with the Bonheim soil with high clay content and slightly high D_b, it can be derived that the difference between PAW in the A-horizon is 6%, and 8% in the B- horizon. For 300 mm depth of horizon A, for example, the Shortlands will have 18 mm of water more than the Bonheim soil. Similarly, for a 900 mm layer of B-horizon, the Shortlands will supply 72 mm for crop growth. This gives a Shortlands soil a total of 90 mm of PAW advantage over the Bonheim soil. A similar comparison between the Shortlands and the agriculturally important soil such as the Hutton soil (from Bethal), reveals that difference in the PAW of the A- horizons is 6% and that of the B-horizons is 14%. Using a similar argument as above, the Shortlands will have 18 mm of PAW in the A horizon more than the Hutton soil, and 126 mm more in the B-horizon. This gives an advantage of 144 mm of PAW in total for the Shortlands soil. The relationship between the PAW and the clay content (using data in Table 2.7) revealed that clay content or soil texture accounted for 69% variation in PAW in the A-horizon, and 72% in the B-horizons. Thus the high PAW in the Shortlands soil could partly be attributed to the high clay content (60% on average).

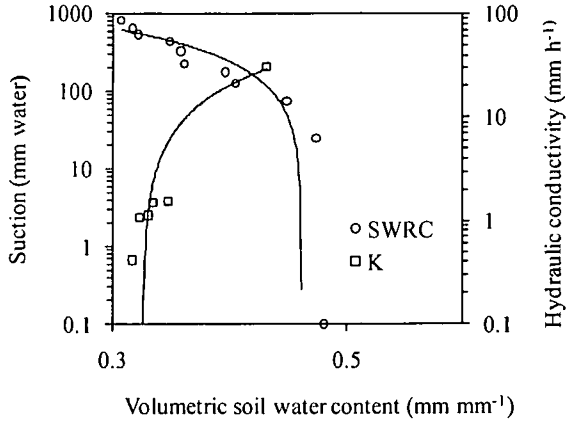
The IRWH technique aims to mange rainfall and runoff and it requires fairly deep soils (>700 mm) with a high water storage capacity (Hensley *et al.*, 2011). With a total profile PAW of 267 mm and a profile depth of >1500 mm, the Shortlands soil has huge advantages compared with common agricultural soils in South Africa. High DUL implies that the soil has high water holding capacity and therefore water loss by deep drainage is minimized. Water loss by evaporation is also minimized because water is stored deep in the profile. Large pores due to the micro-structure in the A-horizon favours water entry by the process of infiltration. The value of K_s may indicate good water transmission into the profile. Therefore the results suggest that the Shortlands soil is highly suitable for the IRWH strategy.

Table 2.7 Comparison of the University of Venda-Shortlands ecotope with other ecotopes (data reworked from Hensley, 1997)

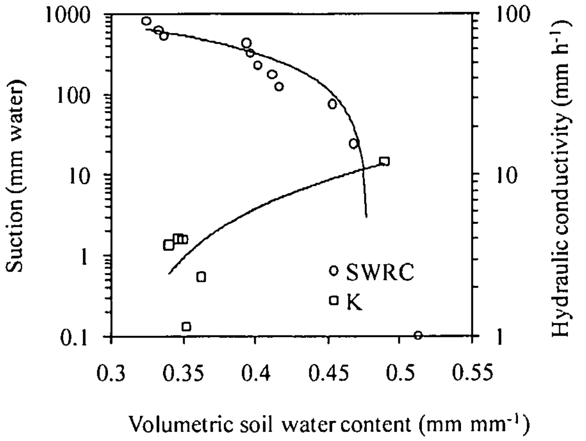
Ecotope	Diagnostic horizon	Structure	Clay%	Db (g cm^{-3})	Depth (mm)	DUL (mm)	LL# (mm)	PAW (mm)	PAW (mm mm^{-1})	K_s (mm h^{-1})
University of Venda-Shortlands	orthic	*wk sab	58	1.24	400	119	40	79	0.20	30
	red structured	mod. sab	60	1.27	900	338	150	188	0.21	12
Glen-Bonheim	melanic	st. sab	44	1.58	300	70	28	42	0.14	20
	pedo-cutanic	st. ab	42	1.45	600	210	133	77	0.13	22
Setlagole-Clovelly	orthic	apedal massive	6	1.6	300	30	12	18	0.06	143
	yellow-brown apedal	apedal	10	1.6	1500	194	127	67	0.04	419
Bethal-Hutton	orthic	apedal massive	21	1.3	300	56	15	41	0.14	214
	red apedal	apedal massive	28	1.6	1500	267	156	111	0.07	214
Bethal-Avalon	orthic	apedal massive	13	1.7	400	71	27	44	0.11	-
	yellow brown apedal	apedal massive	24	1.6	400	54	26	28	0.07	87
Petrusburg-Bloemdal	orthic	apedal massive	8	1.7	230	39	8	31	0.13	101
	red apedal	apedal massive	18	1.7	1100	232	93	139	0.13	128

*wk = weak; mod. = moderate; ab = anguar blocky; sab = subangular blocky; st. = strong; # Sunflower

(a) A-horizon



(b) B1-horizon



(c) B2-horizon

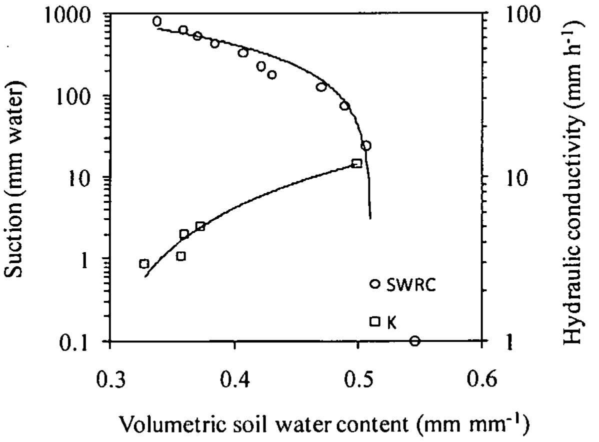


Figure 2.8 Relationships between SWRC and hydraulic conductivity for the A, B1 and B2-horizons.

2.5 Conclusions

The drainage patterns, hydraulic conductivity and water retention properties of the Shortlands soil were unique for each diagnostic horizon. It was concluded that (1) the saturated hydraulic conductivity in the orthic A-horizon was 2.5-fold higher than the structured B-horizon and the difference was largely attributed to the crumb microstructure observed in the orthic A-horizon, (2) the Shortlands soil has good water retention properties as 19% (average for the profile) of the water was released between saturation and 8 kPa (3) the PAW of 267 mm in the root zone is high and surpasses some of the soils tested for IRWH, making the soil suitable for IRWH production strategy.

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CHAPTER 3

RAINFALL AND CLIMATE ANALYSIS

Abstract

Detailed knowledge of the rainfall regime is an important prerequisite for agricultural planning. Despite the importance of rain-fed agriculture to food security in the semi-arid regions of South Africa, studies to understand the spatial and temporal variability of rainfall are not widely documented. Twenty-three years (1983 - 2005) of rainfall data was analyzed in order to study the basic statistical rainfall characteristics at University of Venda- Shortlands ecotope. Data from rainfall analysis would give insight into the feasibility of IRWH development on the ecotope. Annual and monthly rainfall was fitted to theoretical probability distributions. Anderson-Darling goodness-of-fit test was used to evaluate best fit models. Probability of receiving annual and monthly rainfall was predicted using the appropriate probability distribution functions. The chance of experiencing dry spells of different durations was determined. Cumulative frequency analysis of daily rainfall amounts was characterized. It was found that the distribution of daily rainfall was highly skewed with high frequency of occurrence of low-rainfall events. A comparatively small proportion of rainy days supplying a high proportion of the rainfall. High coefficient of variation (CV) of 315% for annual rainfall was reported for the eotope. Further analysis of the rainfall record indicated that 50% of the monthly rainfall patterns during the cropping season (October to March) were best described by the lognormal theoretical distribution model.

Keywords: dry spells, ecotope, , Limpopo, semi-arid, temporal rainfall analysis

3.1 Introduction

Climate plays an important role in biomass production. Extreme climatic conditions and high inter-annual/ seasonal variability of climatic parameters could adversely affect productivity (Li *et al.*, 2006) because rainfall governs the crop yields and determines the choice of the crops that can be grown. The pattern and amount of rainfall are among the most important factors that affect agricultural systems. The analysis of rainfall records for long periods provides information about rainfall patterns and variability (Lazaro *et al.*, 2001).

Drought mitigation can be planned by understanding daily rainfall behaviour (Aghajani, 2007). Dry spell analysis assists in estimating the probability of intra-season drought and management practices can be adjusted accordingly (Tesfaye & Walker, 2004; Kumar & Rao, 2005). It is of importance to know how long a wet spell is likely to persist, and what the probabilities are of experiencing dry spells of various durations at critical times during the growing season (Dennet, 1987; Sivakumar, 1992)

Probability distributions are widely used in understanding the rainfall pattern and computation of probabilities (Abdullah & Al-Mazroui, 1998). It is believed that naturally events follow certain types of distributions (Tilahun, 2006). The normal distribution is one of the most important and widely used in rainfall analysis (Kwaku & Duke, 2007). Despite the wide applicability of the normal distribution there remain many instances when observed distributions are neither normal nor symmetrical. It is observed that rainfall is not necessarily normally distributed (Stephens, 1974) except in wet regions

(Edwards *et al.*, 1983). Jackson (1977) has emphasized that annual rainfall distributions are markedly skew in semi-arid areas and the assumption of normal frequency distribution for such areas is inappropriate. Research elsewhere has shown that rainfall can also be described by other distributions, e.g. Gamma distribution (Abdullah & Al-Mazroui, 1998; Aksoy, 2000; Garcia *et al.*, 2007), the log-Pearson type III distribution (Chin-Yu, 2005), the Weibull and Gumbel distributions (Tilahun, 2006).

One of the reasons for the low crop production in semi-arid areas is marginal and erratic rainfall, exacerbated by high runoff and evaporation losses. The IRWH technique as proposed by Hensley *et al.* (2000) has been shown to improve the yield of maize and sunflower on some benchmark ecotopes in South Africa. There has been increasing interest recently in South Africa of making crop production less risky and sustainable in semi-arid ecotopes through in-field rainwater water harvesting (Botha *et al.*, 2003). The University of Venda–Shortlands ecotope in Thohoyandou is one of the areas where such studies have not been carried out. An ecotope is defined as a homogenous piece of land with unique combination of climate, topographic and soil characteristics (MacVicar *et al.*, 1974). In order to understand the feasibility of establishing a water harvesting system, rainfall analysis and the identification of prevailing rainfall patterns is required (Dennet, 1987; Rappold, 2005). The main objective of this chapter was to analyse the 1983 - 2005 rainfall records from the weather station in Thohoyandou (Limpopo Province, South Africa) as a basis for future studies on sustainability of crop production in general and IRWH in particular. The approach to data analysis was largely similar to those of other authors such as Belachew (2002) and Tilahun (2006). The latter served as the main reference for this study.

3.2 Materials and methods

3.2.1 Data

Daily rainfall data were obtained from the South African Weather Service. Daily reference potential evapotranspiration records were provided by the Agricultural Research Council of South Africa (ARC). Missing data were obtained from neighbouring stations. Annual and monthly totals were calculated from daily rainfall records. Years with missing data were not included in the calculations of averages. Where consecutive months had no recorded rain, these records were considered to indicate missing records and were not included in calculations of averages. This was so for 1982, 2006 and 2007 and 23 year-old rainfall record (1983 - 2005) was analyzed.

A standard method of analysing of rainfall data for agricultural purposes that involved first summarising the daily data to give monthly and then annual totals (Abeyasekera *et al.*, 1983) was followed. The main reason for totalling the daily data has been that the volume of data to be handled subsequently is greatly reduced and data normality would be assumed.

3.2.2 Methods of data analysis

3.2.2.1 Probability distributions of annual and monthly rainfall

In order to determine the underlying distribution, the observed distribution were fitted to theoretical probability distribution by comparing the frequencies observed in the data with the expected frequencies of the theoretical distribution. Preliminary data normality was tested using skewness and kurtosis coefficients. Probability distributions were evaluated by constructing probability plots and curve fitting in Minitab 14 statistical software. Goodness-of-fit test were based on the Anderson-Darling test (D-statistic) (Stephens, 1974). The D-statistic was used to measure how well the data followed a particular distribution. The smaller D-statistic value indicated a better fit. The corresponding p-value was used to test if the data come from a chosen distribution. If the p-value was less than 0.05, the null hypothesis that the data come from that distribution was rejected. The p-value with the greatest magnitude was considered to be the best fit. If the p-value was the same, the smallest D-statistic value was then used to decide the best fit. Rainfall data from October to March were considered in fitting distributions. The rest of the monthly rainfall data were not considered due to limited non-zero values. The normal distribution, lognormal distribution, Gamma and Weibull distributions were tested (Table 3. 1).

Table 3.1 Probability distribution models used for the University of Venda-Shortlands ecotope

Distribution	Probability density function	Parameter description
Normal	$f_{(x)} = n(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\Pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] for -\infty \leq x \leq \infty$	μ= mean of the population x σ= standard deviation of the population x
Lognormal	$y = \frac{1}{\sigma_y\sqrt{2\Pi}} \exp\left[-\frac{1}{2}\left(\frac{y-\mu_y}{\sigma_y}\right)^2\right] 0 \leq x \leq \infty$	y = ln x σ_y = the standard deviation of ln x μ_y = the mean of ln x
Gamma	$f_{(x)} = \frac{1}{\beta^\alpha \Gamma_{(\alpha)}} \alpha^{x-1} e^{-x/\beta}$ for $0 \leq x \leq \infty$	α = the scale parameter β = the shape parameter of the distribution $\Gamma_{(\alpha)}$ = the normalising factor
Weibull	$f_{(x)} = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left(-\left[\frac{x}{\beta}\right]^\alpha\right)$ for $0 \leq x \leq \infty$	α = the scale parameter β = the shape parameter of the distribution

3.2.2.2 Aridity index (AI)

AI represents climatic aridity and is used to determine the adequacy of rainfall in satisfying the water needs of the crop (Tsiros *et al.*, 2008). The agro-climatic zonation of the meteorological study area was determined using UNESCO (1979) AI given as:

$$AI = P/ET_o \tag{3.1}$$

Where:

P = mean annual rainfall (mm)

ET_o = mean annual reference evapotranspiration (mm)

According to this classification, $AI < 0.03$ is hyper-arid zone, $0.03 < AI < 0.20$ is an arid zone, and $0.20 < AI < 0.50$ is semi-arid zone, and > 0.5 is sub-humid. Mean annual rainfall P and ET_o was calculated from meteorological stations used in this study.

3.2.2.3 Exceedance probability of annual and monthly rainfall

This is the probability that a given amount of rainfall is exceeded. The probability of exceedance of annual and monthly rainfall was calculated from the respective rainfall distributions. This information is important regarding choice of crops because each crop has a specific water requirement to take it through the growth cycle (Rappold, 2005). The information is also vital for designing appropriate water storage facilities for supplementary irrigation.

3.2.2.4 Probability of dry spells

In this study, a dry day is a day with rainfall less than 1 mm. A dry spell is a sequence of dry days bracketed by wet days on both sides (Kumar & Rao, 2005). A method for frequency analysis of dry spells in this study was adapted from Belachew (2002) as follows: in the years (Y) of records, the number of times (I) that a dry spell of duration (t) days occurs was counted on a monthly basis. Then the number of times (I) that a dry spell of duration longer than or equal to t occurs was computed through accumulation. The consecutive dry days (d) (1 d, 2 d, 3 d ...) were prepared from historical data. The probabilities of occurrence of consecutive dry days were estimated by taking into account the number of days in a given month (n). The total possible number of days (N) for that month over the analysis period was computed as $N = n*Y$. Subsequently the probability (p) that a dry spell equal or longer than t days was given by:

$$p = I/N \qquad 3.2$$

3.2.2.5 Cumulative frequency of daily rainfall

Cumulative frequency analysis is the analysis of the frequency of occurrence of values of a phenomenon less than a reference value. The distribution of daily rainfall totals by amount and frequency was obtained by using frequency analysis of historic daily rainfall data.

3.3 Results and discussion

3.3.1 Long-term climatic trends

Rainfall was highly seasonal with 85% occurring between October and March (summer) (Table 3.2). The mean maximum temperature (T_{max}) was around 30°C, while the mean minimum temperature (T_{min}) was about 20°C during the growing period. The highest evaporative demand also occurred from October to March. Average was about 781 mm.

The aridity index calculated using Equation 3.1 was 0.52. Based on the UNESCO classification criteria, the study area is on borderline between semi-arid and sub-humid. The area received low-rainfall amount and experienced high evapotranspiration. The relationship between potential evapotranspiration (ET_o) and mean monthly rainfall is shown in Figure 3.1. ET_o was always higher than rainfall throughout the year. This meant that rainfall was not effective at the study site. Research results worldwide show that approximately 70% of annual rainfall is lost due to evaporation from the soil in semi-arid regions (Jalota & Prihar, 1990). Similar results were obtained in South Africa (Hoffman, 1990; Botha *et al.*, 2003). Therefore, in order to maximise the utilisation of rainfall, some more effective practices are necessary to be adopted to reduce unproductive evaporation loss (Li *et al.*, 2006).

Table 3.2 Long-term (23 years) monthly rainfall for the University of Venda-Shortlands ecotope

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year Average
T_{max} (^{o}C)	30.8	30	29.6	27.6	26.2	23.6	23.7	25.4	27.2	27.5	28.9	30	27.6
Tmin (^{o}C)	19.9	19.7	18.9	16.4	12.7	9.9	9.8	11.7	14.2	16.3	17.6	19.4	15.5
T_{mean} (^{o}C)	25.3	24.8	24.2	22.0	19.4	16.8	16.8	18.6	20.7	21.9	23.3	24.7	21.5
Rainfall (mm)	135	134	92	40	18	12	8	8	25	64	98	140	781
ET_o (mm)	158	157	149	104	96	74	85	111	126	143	127	177	1507
Aridity index	0.85	0.85	0.62	0.38	0.19	0.16	0.10	0.10	0.20	0.44	0.77	0.79	0.52

3.3.2 Annual and monthly rainfall statistics

The statistical parameters for both the annual rainfall and monthly rainfall data is summarised in Table 3.3, where the mean, standard deviation, coefficient of variation, skewness, kurtosis are given. The skewness and kurtosis coefficients for a normal distribution are zero or near zero. Skewness and kurtosis coefficients indicated that annual rainfall approximated a normal distribution. This was further confirmed by the p-value (0.468) of the Anderson-Darling test (Table 3.4). The data indicated that monthly rainfall was strongly skewed to the right (high positive values of skewness coefficients) and highly leptokurtic, a phenomenon common in semi-arid regions.

The yearly rainfall analysis indicated that the mean annual rainfall at the University of Venda was about 781 mm with the standard deviation of 248 mm. Coefficient of variation (CV) of annual rainfall was high (315%). This showed a very high variability of rainfall from year to year typical of a semi-arid environment.

Monthly rainfall analysis indicated that the site received about 80% of annual rainfall during the months of October to March (Figure 3.1). This result is similar to the findings of Tyson (1986) who reported similar rainfall pattern in the interior regions of South Africa. December was the wettest month with an average of about 140 mm rainfall. July and August were the driest months with average of about 8 mm rainfall. During the rainy season (October-March), there was pronounced variability in rainfall from one month to another as shown in Table 3.3. The coefficient of variation and standard deviation for the analysis period ranged from 114 to 156 %, and 56.41 mm to 117.07 mm, respectively, confirming the great variability in mean monthly rainfall on the ecotope.

High coefficients of variation are not uncommon in semi-arid environments. FAO (2009) reported coefficient of variation of annual rainfall of 40% in the Limpopo River basin of Zimbabwe and Mozambique. At Kranskop in the Limpopo Province (SA), Kosgei (2009) reported coefficient of variation of annual rainfall of 25%. Lynch *et al.* (2001) reported high annual rainfall variability at Potchefstroom (North West Province, SA) with coefficient of variation of 26% for rainfall recorded over 74 years.

Table 3.3 Statistical parameters for mean monthly and annual rainfall data (1983-2005)

Parameter	Mean	^{a}SD	CV	Min	Max	C_s	C_k
Oct	64.38	56.41	1.14	3.5	243.8	1.64	3.31
Nov	97.89	77.14	1.27	7.3	296.5	1.4	1.2
Dec	139.95	89.59	1.56	31.3	331.69	0.78	-0.68
Jan	134.96	100.24	1.35	12	420	1.02	1.29
Feb	133.87	117.07	1.14	5.3	420.7	0.87	-0.02
Mar	91.63	79.5	1.15	5.7	361.2	1.87	5.146
Apr	39.87	53.94	0.74	0.1	249.2	2.57	8.55
May	17.74	35.35	0.50	0	162.7	3.53	13.74
Jun	12.41	14.1	0.88	0	45.9	1.00	-0.16
Jul	8	15.29	0.52	0	67.3	3.01	10.37
Aug	7.87	10.87	0.72	0	48.5	2.67	8.6
Sept	25.29	38.11	0.66	0	162.5	2.58	7.35
Annual	781.47	248.07	3.15	281.2	1239.32	-0.15	-0.14

^{a}SD = Standard deviation; CV = Coefficient of variation; C_s = skewness coefficient; C_k = kurtosis coefficient.

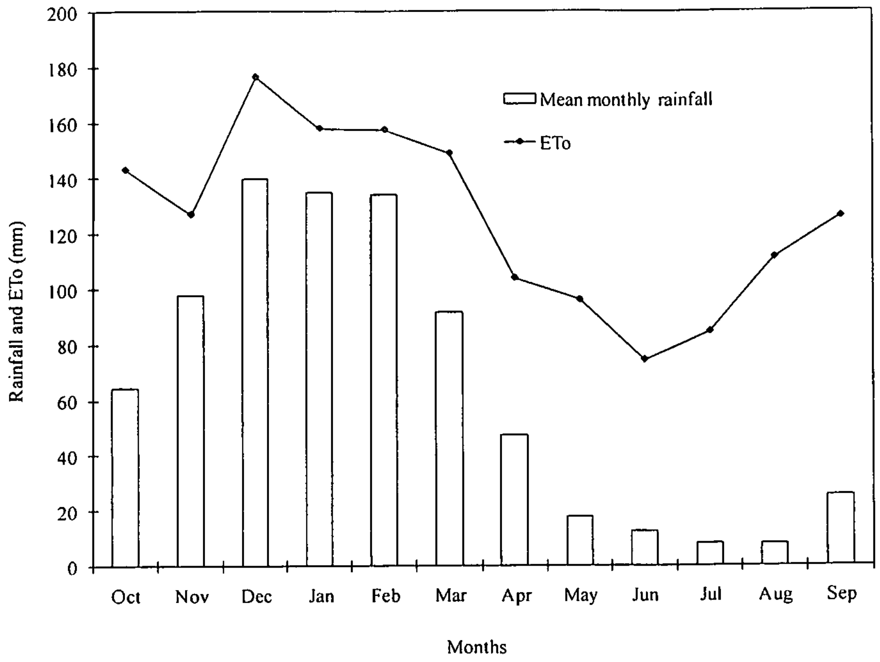

Figure 3.1 Comparison of mean monthly rainfall and reference evapotranspiration for the University of Venda-Shortlands ecotope.

3.3.3 Probability distributions of annual and monthly rainfall

Annual and monthly rainfall data were fitted to four probability distribution functions, i.e. the normal, lognormal, Gamma and the Weibull distributions. The respective parameters of the distribution functions were determined and presented in Table 3.4. The values of the D-static and associated p-values are also presented in the table. Based on the D-statistic and p-values, annual rainfall was best described by the normal distribution. Using the same criteria monthly rainfall was best described by the theoretical distributions as indicated in parenthesis as follows: October (lognormal), November (lognormal), December (lognormal), January (Weibull), February (Weibull), March (Gamma). Out of the considered six months of the rain season, half of them were best described by the lognormal distribution. In his study in Ethiopia, Tilahun (2006) found that most of the monthly rainfall was best described by the lognormal distribution and annual rainfall by the Weibull, Gumbel and Gamma distribution. In semi-arid Kenya annual rainfall approximated to a normal distribution (Rowntree, 1989). Fitted CPF graphs are presented in Mzezewa *et al.* (2010).

Table 3.4 Goodness-of-fit values and parameters of theoretical probability distributions fitted to annual and monthly rainfall data for the University of Venda-Shortlands ecotope

	Normal				Lognormal				Gamma				Weibull			
Month	D[a]	μ	σ	p-value	D	μ	σ	p-value	D	α	β	p-value	D	α	β	p-value
Oct	1.168	64.38	56.41	<0.005	0.308	3.775	0.9904	0.533	0.250	45.14	1.42	>0.250	0.269	68.86	1.216	>0.250
Nov	1.529	97.89	77.14	<0.005	0.370	4.292	0.8297	0.397	0.466	52.59	1.861	>0.250	0.555	107.8	1.385	0.154
Dec	0.912	140.0	89.59	0.017	0.289	4.735	0.6718	0.584	0.419	54.17	2.583	>0.250	0.474	157.8	1.695	0.232
Jan	0.595	135.0	100.2	0.109	0.489	4.578	0.9126	0.200	0.341	80.48	1.677	>0.250	0.316	147.9	1.384	>0.250
Feb	0.905	133.9	117.1	0.017	0.539	4.375	1.206	0.149	0.389	122.3	1.094	>0.250	0.404	137.7	1.078	>0.250
Mar	0.958	91.63	79.50	0.013	0.995	4.086	1.091	0.010	0.519	70.57	1.298	0.218	0.478	97.06	1.185	0.228
Annual	0.339	781.5	248.1	0.468	0.818	6.603	0.3711	0.029	0.586	89.43	8.738	0.144	0.361	867.3	3.634	>0.250

[a] D = D-statistic; u, α, β as defined in Table 3.1; p = probability.

3.3.4 Exceedance probability of annual and monthly rainfall

Probability of receiving rainfall exceeding various amounts was calculated from the respective distribution curves. Table 3.5 summarises probability of receiving annual rainfall at the University of Venda. It can be observed that the probability of exceeding various amounts of annual rainfall diminished as the threshold rainfall amount increased. For example, there was a 94% chance of receiving annual rainfall greater than 400 mm, whilst the chance of having more than 1 500 mm was zero. There was 47% probability of exceeding 800 mm of annual rainfall. This result means that almost 50% of the recorded rainfall was below average. Table 3.6 summarises the probability of receiving monthly rainfall greater than certain threshold amounts. Probability was computed from best fit CPF of respective months as follows: October (lognormal), November (lognormal), December (lognormal), January (Weibull), February (Weibull), March (Gamma). There were almost equal chances of receiving rainfall equal or greater than 5 mm from October to March, save the month of February with 72% chance. The probability decreased as the monthly rainfall threshold increased. The probability of receiving high rainfall (>100 mm) was greatest in December (58%) and lowest in the month of October (20%). This again reaffirms that December is the wettest month at the University of Venda-Shortlands ecotope. Thirty five percent chance of receiving rainfall amount equal or greater than 100 mm was recorded in March. This confirms earlier reports that summer rainfall in South Africa occurs between October and March (Landman & Klopper, 1998). The chance of receiving rainfall amount equal or exceeding 200 mm increased from October to February and then decreased to low of 9% in March. There was very little chance (0 - 2%) chance of receiving rainfall amounts equal or exceeding 500 and 600 mm from

October to March. A study in Kenya by Rowntree (1989) defined reliable rainfall as that annual rainfall with an exceedance probability of 80% for upland cultivators. According to this definition, high rainfall (>100 mm) is not reliable at this site.

Table 3.5 Probability of receiving annual rainfall greater than 400, 600, 800, 1 000, 1 200 and 1 500 mm

Annual rainfall (mm)	Probability of exceedance (%)
400	94
600	77
800	47
1 000	19
1 200	5
1 500	0

Table 3.6 Probability (%) of receiving monthly rainfall greater than 5, 50, 100, 200, 500 and 600 mm

Month	Monthly rainfall (mm)					
	5	50	100	200	500	600
Oct	99	44	20	6	1	0
Nov	100	68	35	11	1	1
Dec	100	89	58	20	1	1
Jan	99	80	56	22	0	0
Feb	72	71	49	22	2	0
Mar	97	63	35	9	0	0

3.3.5 Frequency and probability of dry periods

The occurrence of dry spells has particular relevance to rain-fed agriculture, as rainfall water is one of the major requirements for plant life in rain-fed agriculture (Belachew, 2002; Rockstrom *et al.*, 2002). The occurrence of dry spells is summarised in Figure 3.2.

The probability of occurrence of dry spells of various durations varied from month to month. It can be observed that lowest probabilities of occurrence of dry spells of all durations were recorded in the month of December. Generally the occurrence of dry spells of all durations decreased from October to March. This period coincides with the rainy season in the summer rainfall area of South Africa (Lynch *et al.*, 2001; Kosgei, 2009). The probability of having a dry spell increases with the shorter periods (i.e. more chance of having a 3-day dry spell than a 10 or 21-day dry spell). For example in December, there was 20% probability of having a dry spell duration of 5 days and 0% chance of having a dry spell duration of 21 days. This trend is similar to that reported by several workers, e.g. Kosgei (2009) at Kranskop (SA); Aghajani (2007) in Iran and Sivakumar (1992) in West Africa.

3.3.6 Cumulative frequency of daily rainfall

In this study it was observed that 97% of the daily rainfall events had values equal or less than 20 mm (data not shown), but accounting for only 54 % of the total rainfall (Table 3.7). Though infrequent, heavier rainfall (>20 mm) forms a significant percentage of the total rainfall. Adequate water storage during these storms is therefore essential for reasonable crop yields (Botha, 2006). Frequency distribution was highly skewed with storms of less than 5 mm accounting for the greatest proportion of rainy events. Clearly a large proportion of the events were smaller storms. A comparatively small proportion of the rain-days also contributed a high proportion of the rainfall. Though infrequent, heavier rainfall events made up a significant percentage of the total rainfall. In South Africa, Harrison (1983) found that only 13% of all rain days in the eastern Free State are responsible for 50% of the rainfall and only 27% contributed 75% of the total rainfall, whereas the lowest 50% of all rainy days produce as little as 7% of the rainfall.

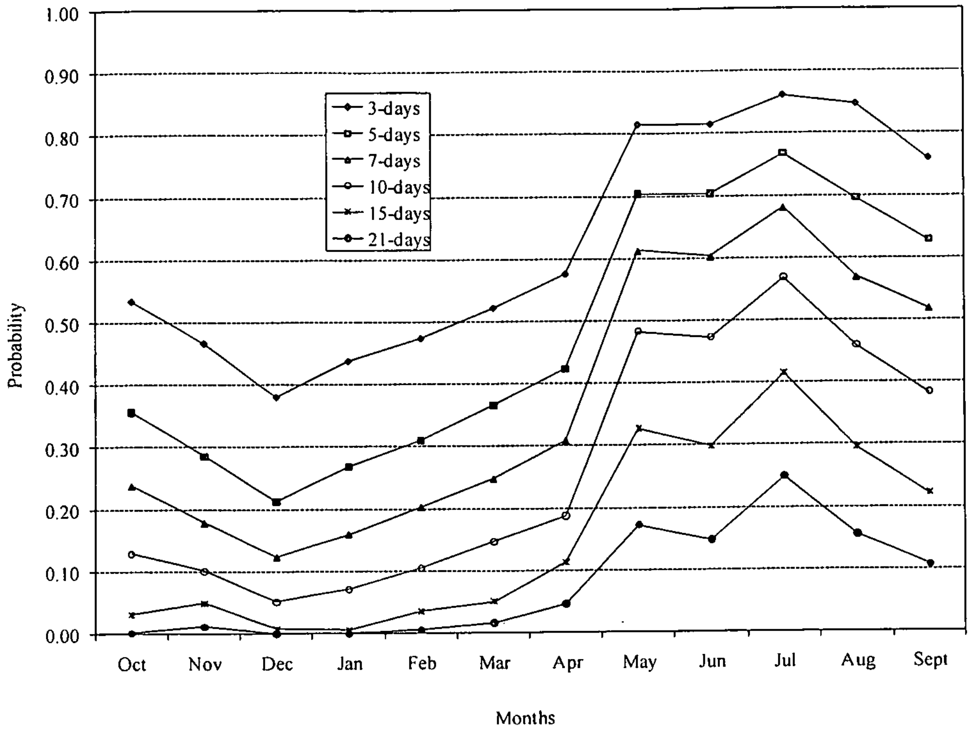

Figure 3.2: Probability of a dry spell of length ≥n days, for n=3, 5, 7, 15, 21, in each month, estimated using the raw data from 1983 – 2005, for the University of Venda-Shortlands ecotope.

Table 3.7 Characterization of the rainfall pattern at the University of Venda-Shortlands ecotope from January 1983 to December 2005

	Classes of rainfall amount per event (mm)					Total
Parameter	0 – 5	6 – 10	11 – 20	21 – 30	>30	
Amount of rainfall (mm)	7115	2639	4485	3166	8971	26376
% of total	27	10	17	12	34	100
Number of rainfall events	1423	263	230	101	145	2162
% of total	66	12	11	5	6	100
Mean no. of rain events per annum	62	11	10	4	6	93

3.3.7 Implications for crop production

Information on rainfall amount and variability is important for improved decisions concerning choice of crops and crop varieties to grow on the ecotope. Knowledge of month-wide distribution of rainfall is also important because it tells how much water is available for the biomass in rain-fed areas. Aghajani (2007), determined that the threshold of rain-fed agriculture is 250 mm rainfall. Monthly rainfall also showed a high variability. The amount of rain during the growing season is important for the crop to give the highest yield. For example, optimum rainfall for maize production is between 500 and 800 mm (Ovuka & Linqvist, 2000). However, the probability of exceeding 800 mm of rainfall is 47% (Table 3.5). This makes less drought-tolerant crops like maize (Sivakumar, 1992) risky to produce unless water harvesting measures are taken.

There is a 50% chance of receiving 50 mm of rainfall in October such that water harvesting can be practiced to capture the rainfall and store it in the soil profile to be later used for early planting. Benefits of doing this could however fail to be realised due to excessive water losses from the soil profile by evaporation (Hensley *et al.*, 2000)

Information on probability of exceedance of rainfall is important in designing water conservation and/ or harvesting structures. In order to be efficient, water harvesting structures should be constructed in proportion to the amount of water that can be expected during a rainfall event (Schiettecatte *et al.*, 2005).

High evaporative demand as indicated by the AI of 0.52 at this site means that most of the rain is not available for crop use and rainfall cannot meet demands of evaporation and deficit prevails throughout the rainy season, as observed elsewhere (Li *et al.*, 2006). Water harvesting, based on the collection of runoff from prepared catchment surface and stored in the crop rooting zone could be used to increase rain water use efficiency, as demonstrated by Botha *et al.* (2003). Various mulches can be employed to minimise further losses from soil evaporation (Hensley et al., 2000; Botha *et al.*, 2003; Li *et al.*, 2006). In the arid and semi-arid regions, where water is available for a relatively short period during the year, it is essential to match the crop phenology with dry-spell lengths to meet the crop water requirements at the sensitive stages of crop growth (Sivakumar, 1992).

Information on the length of dry-spells could be used as a guide for planning supplementary irrigation, because high water demand periods can be predicted. Choice of a crop or crop variety can be made based on the length of dry spells. For example, the probability of dry spells longer than 15 days is very low during the rainy season at this site. Crops can be selected based on their degree of tolerance to drought (Sivakumar, 1992). However, decisions can be better made if probability of dry spells is computed after effective (successful) planting dates (Sivakumar, 1992; Belachew, 2002). Bridging dry spells through *in situ* rainwater harvesting is a viable option in rain-fed crops (Rockstrom *et al.*, 2002; Schiettecatte et al., 2005; Li *et al.*, 2006). Barron & Okwach (2005) noted that it is the natural occurrence of dry spells due to high variation in rainfall distribution and amounts during season that limits crop development and result in yield reductions.

3. 4 Conclusions

The statistical analysis of rainfall at the study site has revealed that the rainfall was highly variable (CV of 315% for annual rainfall). Further analysis revealed that the probability of receiving high rainfall amounts was low with small storms (<20 mm) accounting for a large proportion of rainfall received.

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CHAPTER 4

EFFECTS OF IN-FIELD RAINWATER HARVESTING ON SUNFLOWER X COWPEA INTERCROP PRODUCTION

Abstract

Sustainable food production in semi-arid tropical countries can be achieved through efficient utilization of rainwater. A field experiment to assess the grain yield, seasonal water use (WU), water use efficiency (WUE) and precipitation use efficiency (PUE) of sunflower (*Helianthus annuus* L.) and cowpea (*Vigna unguiculata* L.) intercrop on two tillage systems was conducted during the 2007/2008 and 2008/2009 cropping seasons at the University of Venda-Shortlands ecotope (22^o 58' S, 30^o 26' E at 596 m above sea level). The experiment was configured as a split plot with four replications. Two tillage systems (TS) were assigned to main plots. The tillage treatments were CON (control) and IRWH system. Cropping systems (CRS) were assigned to sub-plots. The IRWH is a special crop production technique that promotes runoff on a 2.0 m wide no-till strip between crop rows and collects the runoff water in basins where it infiltrates into the soil profile (*Hensley et al.*, 2000). The treatments in the CRS consisted of a sole crop (sunflower or cowpea) and an intercrop (sunflower x cowpea). Results of the experiment revealed that IRWH led to a significant ($P<0.05$) increase in sunflower grain yield in the second season, but cowpea grain yield was not influenced by TS. IRWH resulted in significantly higher WU, WUE and PUE of both crops compared to CON system in the second season. The CRS had significant effects on sunflower grain yield in both seasons, but none on the cowpea grain yield. WU was significantly higher in intercrops than in sole cowpea and sole sunflower in the first and second season, respectively. WUE and PUE were significantly greater in sole sunflower than in the intercrops but less in the sole cowpea than in the intercrops.

Key words: cowpea; dryland; precipitation use; sunflower; tillage; water harvesting.

4.1 Introduction

Constraints to food production in semi-arid tropical countries often result from water loss by runoff and evaporation (Mando, 1997). Maximizing precipitation use efficiency (PUE) is therefore important in the semi-arid regions to stabilize or improve food production. Two primary sources of water loss are runoff (R) and soil evaporation (E_s) (Botha, 2006). E_s is more important than runoff in contributing to inefficient precipitation use in dryland crop production (Beukes *et al.*, 1999). Bennie and Hensley (2001) reported that in arid and semi-arid areas between 60 and 85% of the rainfall evaporates from the soil surface before making any contribution to crop production. Runoff losses range from 6 to 30% of annual rainfall on various soil types under CON (Botha, 2006). The IRWH technique, developed by Hensley *et al.* (2000), can stabilize yields.

The IRWH system promotes rainfall runoff on a 2.0 m wide no-till strip between crop rows and collects the runoff water in basins where it infiltrates into the soil profile (Figure 1.1). Two distinct areas, namely a 2.0 m catchment area or runoff strip and a 1.0 m collection basin are created. In order for the runoff strip to direct surface water into the collection basins, a slope towards the basins is created. The runoff created in this way is called in-field, which differs substantially from ex-field runoff that occurs in the CON system. In-field runoff can be captured and used to enhance WU and PUE, stabilizing or increasing crop yields. Rain drop impact on the runoff strip causes surface compaction and therefore contributes to the formation of soil crusts, which stimulate in-field runoff. No-till is practiced on the runoff strip so that a smooth surface can be maintained (Hensley *et al.*, 2000). The IRWH system is synonymous with the mini-catchment runoff farming and is a special form of no-till system. IRWH has been proven to contain runoff from the soil surface, increasing plant available water and crop yields on smallholder farms in Thaba Nchu, South Africa (Botha *et al.*, 2003). The IRWH increased maize and sunflower yields by as much as 50% compared to conventional production systems on duplex soils (soils that have an abrupt textural change) in the Free State Province of South Africa (Hensley *et al.*, 2000). However, despite the increase in crop yields, the researchers recorded high evaporation losses of water from the fields. For example, 79% of annual rainfall was lost from IRWH maize plots treated with organic mulches (Botha *et al.*, 2003). Experiments at the Glen-Bonheim and Glen-Swartland ecotopes documented that improving PUE above 7.4 and 4.8 kg ha^{-1} mm^{-1} for maize (*Zea mays* L.) and sunflower, respectively, Thus E_s must be reduced to improve yield stability. A continuing constraint for successful utilization of IRWH is excessive loss of soil water from the soil profile by evaporation (Hensley *et al.*, 2000; Botha *et al.*, 2003). In a study designed to examine the effect of a combination of ridge and furrow with gravel mulch, the bare furrow treatment resulted in less maize grain yield compared to the film-covered surface ridges and gravel-mulched furrows (Li *et al.*, 2000). The yield advantage was attributed to suppression of evaporation losses. Previous research efforts in South Africa focused on suppressing evaporative soil water losses from IRWH plots with organic or stone mulches (Botha *et al.*, 2003). Despite these efforts, results to date indicate that water loss by evaporation remains problematic. Living soil cover between crop plants (live or green mulches) has been proposed as an environmentally viable option to suppress water loss from the soil surface. This is a sound option if living mulches are integrated in an intercropping design in order to derive other benefits of intercropping such as increased yield under conditions of water stress, protection against risks of drought and pests as well as provision of more balanced human diet and weed suppression (Aladesanwa & Adigun, 2008).

The influence of cowpea (*Vigna unguiculata* (L.) Walp.) living mulch on soil evaporation has not been tested within the IRWH systems. Information on the effects of tillage practices and intercropping on the performance of crops remains scarce and inconclusive. In particular, interaction between the IRWH technique and sunflower x cowpea intercrops has not received attention in South Africa. Knowledge on how cowpea affects water utilization and yield of sunflower under IRWH would be important in forming a scientific basis for recommending this practice to smallholder farmers who produce this legume usually in intercrop systems. Therefore, this study was designed to assess the grain yield, WU, WUE and PUE of sunflower intercropped with cowpea under IRWH and CON practices on Shortlands soil that crust readily. The crusted no-till runoff strip can increase runoff into the basins resulting in rainfall storage (Figure 1.1). It was hypothesized that IRWH will increase crop yields in Shortlands soil compared to the CON system. It was further hypothesized that cowpea intercropped as living mulches with sunflower will increase water use (WU), water use efficiency (WUE), PUE and grain yield of sunflower.

4.2 Materials and methods

4.2.1 Experimental site

Site characteristics are described in Chapters 2 and 3 in this document. During the two seasons meteorological weather variables were recorded by an automatic weather station belonging to the Agricultural Research Council located within 100 m of the experimental blocks. Rainfall was also recorded within the experimental plots using three rain gauges. This data is averaged and summed (rainfall) for the growing months.

4.2.2 Agronomic details

Soil samples were taken for fertility tests prior to each cropping season. The soil samples were obtained from 0 - 200 mm depth. The fertilizer applications were based on potential yield of 2500 kg ha^{-1} and 1000 kg ha^{-1} for sunflower and cowpea, respectively. Planting material consisted of a short season hybrid of sunflower (cv. AFG 5551) and a local cowpea landrace sourced from farmers. The landrace was previously selected for its spreading growth habit. Both species required 120 days to reach physiological maturity. The intercrop components were sown simultaneously using row replacement series (1:1) in both seasons. Planting was done on 22 December 2007 and 28 December 2008 when the average soil profile water content was 500 mm and 450 mm, respectively. Plant density for sole sunflower and sole cowpea were 30000 and 66666 plants ha^{-1} respectively. In the intercrop, the plant density was 48333 plants ha^{-1}.

Fertilizers, including lime, were applied uniformly in all plots per soil analysis recommendations. Prior to the 2007/2008 cropping season, a commercial fertilizer (at a rate of 530 kg ha^{-1} 2:3:2 (22) NPK giving 33 kg P ha^{-1}, 50 kg P ha^{-1} and 33 kg K ha^{-1}) was applied and incorporated into the soil in the experimental plots. Similarly, in the second season, the same fertilizer was applied with an additional 178 kg ha^{-1} limestone ammonium nitrate (LAN) (28) as top dressing five weeks after planting to sunflower plots. No top dressing was applied on the cowpea crop. During the season, weeds were controlled manually in both CON and IRWH plots. Glysphosphate (360 g ae. l^{-1} in x l water ha^{-1}), was used to control weeds during the fallow periods. Aphids and beetles were controlled with Malathion 50% EC (ae. 0,0 dimethyl-phosphorodithioate of diethyl mercaptosuccinate) as necessary. Crop harvesting was done by hand and stover removed from the field thereafter.

4.2.3 The tillage systems

Two tillage systems were used in the study. The first tillage system, termed the CON, consisted of disk plough, disk harrow and roller at the beginning of the experiment and followed later by manual digging (in order to protect access tubes for measuring soil water content) to a depth of about 200 mm. The second tillage system, termed IRWH consisted of a no-till area and collection basins (Figure 1.1). Initially, the entire experimental block was ploughed and then disked to obtain a fairly level surface. The IRWH plots were created manually (using spades and rakes to make the basins and runoff area). The use of a 2:1 surface area ratio between the runoff and basin area is based on field experience with crops in a semi-arid environment in which crops are planted in tramlines (1.0 m wide) along the basins or collection area. Tramline planting is also based on standard maize practices in the eastern Free State region of South Africa. The role of the basin area is to (i) stop ex-field runoff, (ii) maximize infiltration, and (iii) store the harvested water in the soil surface beneath the basin (Hensley *et al.*, 2000). The basin facilitates surface storage until the infiltration process is completed. The infiltrated water is stored in the rooting zone where it remains available for crop uptake. Its loss through evaporation is decreased (Hensley *et al.*, 2000).

4.2.4 Experimental design and layout

The experiment was configured as split plot design with four replications. Two tillage systems (TS) were assigned to main plots (27 m x 10 mm) and cropping systems (CRS) to subplots (9 m x 10 m). The tillage treatments were CON and IRWH. CRS consisted of two treatments which were either a sole crop (sunflower or cowpea) or intercrop (sunflower x cowpea). The experiment was conducted over two consecutive cropping seasons (CS) starting with the 2007/2008 season. All treatments were randomized within each block. The experimental unit (plot) consisted of six rows with tramline row spacing measuring 1 m x 2 m. The measurements for each response variable were obtained from the two middle rows of each experimental unit.

Field layout is shown in Table 4.1

Table 4.1 Layout of the experimental plots

Block A	Bock B	Block C	Bock D	Bock E	Block F	Block G	Block H
IRWH	CON	IRWH	CON	IRWH	CON	IRWH	CON
SS	SC	ISC	SC	SS	ISC	SC	SS
SC	ISC	SS	SS	ISC	SC	SS	ISC
ISC	SS	SC	ISC	SC	SS	ISC	SC

Main plot treatment = Tillage systems: CON and IRWH; Subplot treatment = CRS: sole sunflower (SS); sole cowpeas (SC); intercrop (sunflower x cowpea) (ISC)

4.2.5 Grain yield

In order to minimize damage by birds, sunflower was harvested at 106 and 90 days after planting for the 2007/2008 and 2008/2009 seasons, respectively and air-dried to a constant weight thereafter. The sunflower grain yield was determined by harvesting 6.0 m portions of the two central rows. Similarly, cowpea was harvested at 150 and 140 days after planting during the 2007/2008 and 2008/2009 cropping seasons, respectively. The net plot was determined by means of a wooden frame measuring 500 mm x 2000 mm. Three samples were randomly taken from the middle rows of each plot. Grain was separated from stover before drying in the oven at 70°C for 24 h and adjusting the grain yield to 13% moisture content.

4.2.6 Seasonal crop water use

In field research, WU has commonly been defined as the evapotranspiration (ET) component of a water balance (Sinclair *et al.*, 1983). The crop WU (or ET) was calculated for both crops at various stages during crop growth according to Oluwasemire *et al.* (2002), as follows:

$$ET = SAW_a + P - D - R - SAW_b \qquad 4.1$$

Where:

ET = evapotranspiration (mm)

P = precipitation during the cropping season (mm)

D = deep drainage (mm)

R = is the run-off (mm)

SAW_a = initial soil profile water content at planting (mm)

SAW_b = final soil profile water content at harvest (mm)

The sum of periodical crop WU of the component crops gives the seasonal crop WU. In this study the assumption was made that D was negligible as the water contents were consistently lower than the DUL value obtained in Chapter 2. Net R in the IRWH technique was zero and R in CON treatment was also negligible since there were no high intensity storms during the experimental period. Generally the study area receives low intensity storms of less than 20 mm h^{-1} (Mzezewa *et al.*, 2010).

4.2.7 Precipitation use efficiency

The PUE for the cropping season (PUE_g) was calculated using the following equation (Hensley *et al.*, 2000):

$$PUE_g = \frac{GY}{P_g + \left(\theta_{p(n)} - \theta_{h(n)}\right)} \qquad 4.2$$

Where:

PUE_g = precipitation use efficiency for the cropping season plus fallow season, based on the grain yield (kg ha mm^{-1})

GY = grain yield (kg ha^{-1})

Pg = precipitation during the cropping season (mm)

$\theta_{p(n)}$ = water content of the root zone at planting for the current season (mm)

$\theta_{h(n)}$ = water content of the root zone at harvest for the current season (mm)

Intercrop PUE was calculated on the basis of total grain yield of sunflower and cowpea (Tsubo *et al.*, 2003).

4. 2.8 Water use efficiency

The water balance equation was used to estimate water use. Water use efficiency (WUE) was calculated using the water balance equation, assuming no drainage and runoff water, as follows:

$$WUE = GY/ET \qquad 4.3$$

Where :

WUE = water use efficiency (kg ha^{-1} mm^{-1})

GY = grain yield (kg ha^{-1})

ET = total evapotranspiration over the whole cropping season (mm).

Similarly, intercrop WUE was calculated on the basis of total grain yield of sunflower and cowpea.

4.2.9 Soil water content

Measurements of the volumetric water content of the soil profile were conducted once a week during the cropping season and once every fortnight during the fallow period using a neutron water meter (NWM) (model 503DR, Campbell Pacific Nuclear International) to a depth of 1500 mm. The frequency of measurements was increased after each rain event and subsequently staggered. Before each measurement, the standard count (C_s) of the NWM was determined in five replicates. Four NWM access tubes were inserted to a depth of 2000 mm. Two of these tubes were inserted in the basin for the IRWH technique while the remaining two were inserted in the centre of the 2000 mm area between crop rows in each IRWH and CON plot. Five readings were taken from each tube at the following depths: 0 – 300 mm, 300 – 600 mm, 600 – 900 mm, 900 – 1200 mm, and 1200 - 1500 mm. Summation of the results gave the water content of the root zone (θ_r).

4.2.10 Data analysis

In order to test the main effects of each of the three factors and their interactions on the response variables, data sets were subjected to analysis of variance (ANOVA) procedures using SPSS version 18. Levels of significance were reported at $P \leq 0.05$ unless otherwise stated. Because of the high variability (315%) of the agro-ecological conditions particularly in terms of the rainfall pattern (Mzezewa *et al.*, 2010), further analysis of the effects of only two of the factors (namely TS and CRS) and their interactions per cropping season was performed. Mean separation was done using Tukey's honest significant difference (HSD) procedures.

4.3 Results

4.3.1 Climatic conditions during the experimental period

The mean monthly temperatures at the experimental location ranged from 23°C to 25°C during 2007/2008 and 2008/2009, respectively, which compared favorably with the long-term average of 24.8°C over the same period (Table 4.2). In the 2007/2008 season, the onset of the rainy season occurred in mid-December. The total rainfall (405 mm) received during the 2008/2009 cropping season was slightly higher and more evenly distributed than during the 2007/2008 season (391 mm) in which dry spells were experienced during February. The onset of rainfall during 2008/2009 occurred towards the end of December.

Table 4.2 Mean temperature and rainfall during the experimental period compared with long-term averages

Month	Mean temperature (°C)			Rainfall (mm)		
	2007/08	2008/09	Long-term average	2007/08	2008/09	Long-term average
Dec	22.7	25.3	24.7	33.4[a]	16.6[a]	22.1
Jan	23.4	25.6	25.3	264.3	197.9	135
Feb	24.9	24.8	24.8	79.1	43.3	134
Mar	22.7	22.6	24.2	14.1	147.6	92

[a] Rainfall received on or after planting

In both seasons, more than normal rainfall was received during January in comparison with the long-term average (135 mm).

4.3.2 Effects of tillage systems

4.3.2.1 Grain yield

The grain yield of sunflower was influenced significantly ($P < 0.001$) by TS, CS and CRS, but in cowpea, both TS and CRS had no significant influence on the grain yield (Table 4.3). When, TS was compared between the two seasons, it influenced the sunflower grain yield only in the second season (Table 4.4). The grain yield under IRWH treatment was 56% higher than under CON treatment during the 2008/2009 season. In contrast, similar grain yields between the two tillage systems were obtained for cowpea in both cropping seasons (Table 4.4).

4.3.2.2 Seasonal WU, WUE and PUE

The mean WU of each crop over the two cropping seasons was >350 mm, but the mean WUE of sunflower (3.33 kg ha^{-1} mm^{-1}) was approximately double that observed for cowpea (1.67 kg ha^{-1} mm^{-1}) (Table 4.3). During the 2008/2009 cropping season, the WUE of sunflower under IRWH (4.65 kg ha^{-1} mm^{-1}) and CON (2.81 kg ha^{-1} mm^{-1}) increased compared to the previous season. The effect of the TS resulted in significantly higher PUE in IRWH (3.86 kg ha^{-1} mm^{-1}) compared to CON (2.65 kg ha^{-1} mm^{-1}) during the 2008/2009 season (Table 4.4). This represented a 31% difference in favour of IRWH.

In cowpea, CRS significantly ($P < 0.001$) influenced the WUE in both seasons (Table 4.3). In addition, there were significant ($P < 0.05$) interactions between the three factors on the WUE of cowpea (Figures 4.1 and 4.2). The PUE was significantly ($P < 0.001$) influenced by all the three factors in both sunflower and cowpea. The WUE of cowpea under IRWH was significantly higher than that under CON treatment during 2008/2009 season. In addition, the WUE of cowpea increased 14-fold in an intercrop compared with the sole crop (Table 4.5). A significantly ($P < 0.05$) high PUE of cowpea was observed under IRWH compared to CON during 2008/2009 season. The PUE for cowpea in the intercrop was at least 15-fold higher than in the sole crop.

4.3.3 Effects of cropping systems

4.3.3.1 Grain yield

Sunflower sole cropping resulted in significantly higher grain yield than intercrop sunflower in both seasons (Table 4.4). The grain yield of sole sunflower was more than double that in the intercrop during the 2007/2008 season. In the second season, the sole sunflower crop produced 49% higher grain than in the intercrop (Table 4.4). On the other hand, the grain yields of cowpea were similar in both seasons irrespective of the cropping system (Table 4.5).

Table 4.3 Effect of tillage system, cropping season and cropping system on grain yield (GY), water use (WU), water use efficiency (WUE) and precipitation use efficiency (PUE) in sunflower and cowpea evaluated during the 2007/2008 and 2008/2009 cropping seasons

	Sunflower				Cowpea			
Factor	GY	WU	WUE	PUE	GY	WU	WUE	PUE
Tillage System (TS)	0.0007**	0.3043 ns	0.0219 *	0.0024 *	0.4502 ns	0.1327 ns	0.0674 ns	0.0031 *
Cropping Season (CS)	0.0001**	0.0001 **	0.0672 ns	0.0001 **	0.0001 **	0.0001 **	0.8930 ns	0.0001 **
Cropping System(CRS)	0.0001 *	0.8867 ns	0.0314 *	0.0024 *	0.8287 ns	0.0001*	0.0001 **	0.0001 **
TS x CS	0.0288 *	0.0015 *	0.0622 ns	0.1178 ns	0.1516 ns	0.0092 *	0.0254 *	0.0009 **
TS x CRS	0.4662 ns	0.3695 ns	0.1863 ns	0.7261 ns	0.0214 *	0.7584 ns	0.0361 *	0.0001 **
CS x CRS	0.6363 ns	0.0844 ns	0.5996 ns	0.2319 ns	0.3247 ns	0.0051 *	0.0002 **	0.5824 ns
TS x CS x CRS	0.4948 ns	0.9136 ns	0.3364 ns	0.3648 ns	0.7263 ns	0.5681 ns	0.0421 *	0.0001 **
Mean	1.15	375.57	3.33	2.42	0.18	353.36	1.67	1.54

** = significant at $P < 0.001$; * = significant at $P < 0.05$; ns = not significant at $P < 0.05$.

Table 4.4 Means for sunflower grain yield (GY), water use (WU), water use efficiency (WUE) and precipitation use efficiency (PUE) as influenced by tillage system and cropping system

CS	Treatment	GY (kg ha^{-1})	WU (mm)	WUE (kg ha^{-1} mm^{-1})	PUE (kg ha^{-1} mm^{-1})
2007/	Tillage System (TS)				
08	CON	558a	274.5a	2.49a	1.36a
	IRWH	754a	309.9b	3.04a	1.81a
	Cropping System (CRS)				
	Sole sunflower	928a	286.1a	3.30a	1.86a
	Intercrop sunflower	384b	298.4a	2.23a	1.32a
	TS x CRS	ns	ns	ns	ns
2008/	Tillage System (TS)				
09	CON	1282a	440.6a	2.81a	2.65a
	IRWH	2002b	466.2b	4.65b	3.86b
	Cropping System (CRS)				
	Sole sunflower	1966a	437.8a	4.32a	3.81a
	Intercrop sunflower	1318b	469.0b	3.14b	2.69b
	TS x CRS	ns	ns	ns	ns

Means within each column followed by the same letter are not significantly different at the 5% probability level; ns = not significant at the 5% probability level.

Table 4.5 Means for cowpea grain yield (GY), water use (WU), water use efficiency (WUE) and precipitation use efficiency (PUE) as influenced by tillage system and cropping system

CS	Treatment	GY (kg ha^{-1})	WU (mm)	WUE (kg ha^{-1} mm^{-1})	PUE (kg ha^{-1} mm^{-1})
2007/	Tillage System (TS)				
08	CON	238.8a	247.1a	1.61a	0.85a
	IRWH	276.4a	281.6b	1.70a	0.92a
	Cropping System (CRS)				
	Sole cowpea	251.0a	230.4a	1.08a	0.46a
	Intercrop cowpea	264.2a	298.4b	2.23b	1.32b
	TS x CRS	ns	ns	ns	ns
2008/	Tillage System (TS)				
09	CON	96.3a	437.2a	1.26a	1.10a
	IRWH	108.3a	447.6a	2.10b	1.75b
	Cropping System (CRS)				
	Sole cowpea	112.5a	433.0a	0.22a	0.16a
	Intercrop cowpea	92.1a	469.8a	3.14b	2.69b
	TS x CRS	ns	ns	***	***

Means within each column followed by the same letter are not significantly different at the 5% probability level; ns = not significant at the 5% probability level.

4.3.3.2 Seasonal WU, WUE and PUE

The WU for sunflower was similar between sole and intercrop during the 2007/2008 season but there was a significant difference between the two cropping systems during the 2008/2009 season (Table 4.4). However, WUE in sole sunflower was 48% higher than that for the intercrop. In the 2008/2009 season, the WUE of sole sunflower and intercropped sunflower increased by 30% and 40% respectively (Table 4.4). In cowpea, the WU in the intercrop was 30% higher than in the sole crop during the 2007/2008 season (Table 4.5). In contrast, the WUE in the intercropped cowpea was significantly greater than in the sole cowpea in both cropping seasons. In the 2008/2009 season, there was a 14-fold higher WUE in intercropped cowpea than in the sole crop. There was a significant difference in the PUE between sole and intercropped cowpea in both seasons suggesting that selection of the CRS at the location would be useful for crop growers in the area.

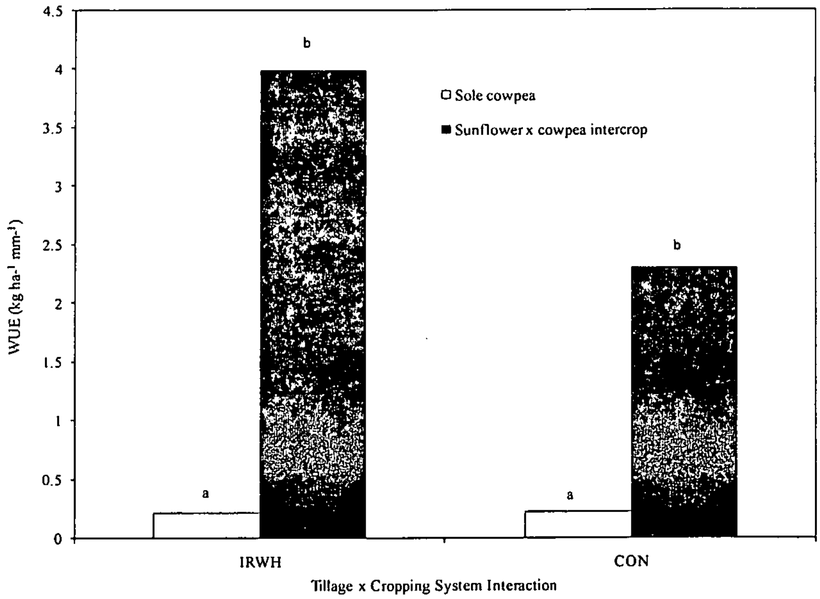

Figure 4.1 Water use efficiency (WUE) as a function of tillage and cropping system.

Means followed by different letters indicate significant difference at $P < 0.05$.

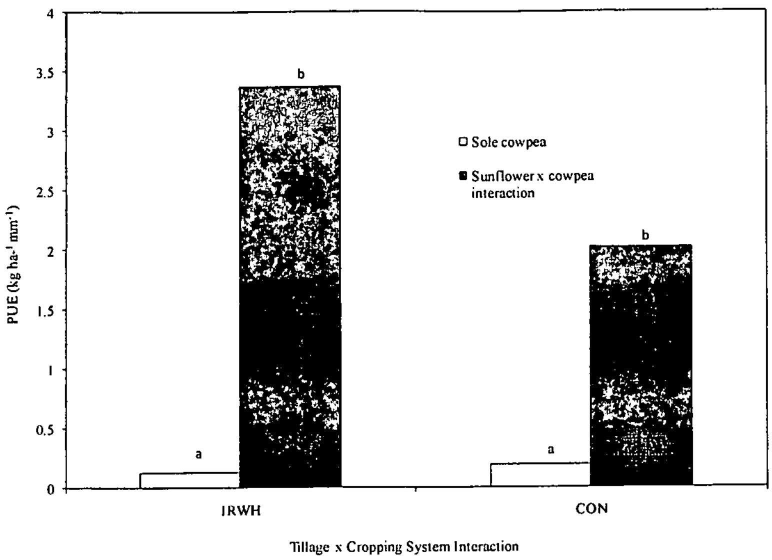

Figure 4.2 Precipitation use efficiency (PUE) as a function of tillage and cropping system

Means followed by different letters indicate significant difference at $P < 0.05$.

4.4 Discussion

4.4.1 The cropping season effect

The cropping season had a highly significant effect on both crops. The dry spells coincided with the flowering stage of sunflower crop and pod formation in the cowpea crop. Likely, this mid-season water stress affected sunflower performance. However, in spite of the lower rainfall received during the 2007/2008 cropping season (391 mm), the cowpea yield was higher than during the second season. This could be attributed to drought tolerance associated with cowpea (Akinyemi *et al.*, 2003).

In 2008/2009, the increased grain yield observed in sunflower could be attributed probably to the somewhat more uniform distribution of the rainfall throughout the cropping season compared with the first cropping season. In addition, legumes such as cowpea increase soil fertility through biological nitrogen fixation that benefits subsequent field crops that are planted in rotation with the legumes (Martins, *et al.*, 2006). The seasonal differences in the grain yield of sunflower could be accounted for, at least in part, by the differences in fertilizer application (in the form of topdressing) between the two cropping seasons. Although there was no drought period experienced during 2008/2009, the lower cowpea yield was probably due to its sensitivity to nutrient mining following the repeated cropping of cowpea in two consecutive seasons in the same field plots. The results reported in this study suggested that cowpea performs well under moisture stress, which is in agreement with the observations by Simpson and Gumbs (1992) cited by Akinyemi *et al.* (2003). The results also indicated that the rainfall distribution pattern was more important than the total amount received *per se*, in determining the potential crop production in a season, which is consistent with the observation reported by Leihner *et al.* (1993).

4.4.2 Tillage effects on crop yield

The grain yields of sunflower that were consistently higher in IRWH compared to CON system in both seasons were attributed to the tillage method which is known to improve crop yields. The results were consistent with Hensley *et al.* (2000) who obtained a sunflower yield of 1612 kg ha^{-1} under a total soil tillage system (equivalent to conventional tillage) and 1853 kg ha^{-1} under a water harvesting technique (equivalent to IRWH) during 1996/1997 season at Glen/Bonheim-Onrus ecotope near Bloemfontein in South Africa. The similarity in grain yield response between the CON and IRWH systems in the first cropping season was most likely due to the short-term implementation of IRWH. The short duration of the experiment could have resulted in insufficient development of the soil crust in IRWH plots that would enhance runoff into the basins which would influence the grain yield significantly. The runoff is often generated as a result of the crust development on the soil surface (Carmi and Berliner, 2008). The more pronounced effects of the IRWH in the second season could be due to extra harvested water available for transpiration.

Unlike sunflower, cowpea yield was not significantly affected by the tillage system in both seasons. Nevertheless, IRWH treatment consistently gave higher yields compared to the CON system. The weak response to TS observed for cowpea in this study was in agreement with the findings reported elsewhere. For instance, Simpson and Gumbs (1985) reported that there were no significant differences in cowpea yield between tilled and untilled plots. However, conflicting results have been reported by other researchers. In a similar study aimed at evaluating the grain yield of maize and cowpea under different tillage systems in the Savanna region in Ghana, Kombiok *et al.* (2005) reported that the yields of both crops were higher under conventional and bullock plough systems compared with hand hoeing and zero tillage systems. In Nigeria, Akinyemi *et al.* (2003) investigated the effects of three tillage systems (zero, ridge and flat) on cowpea performance on Oxic Paleustalf soil and concluded that the ridge tillage system produced the highest yield. This concurred with the findings by Leihner *et al.* (1993) who reported that ridging increased cowpea grain yield in the West African Sahel region. It is therefore reasonable to conclude that the response of cowpea to the tillage method is variable and depends on soil type and tillage practices. Nonetheless, there is merit in conducting further investigation using the IRWH for cowpea at similar testing locations since this tillage system consistently produced higher grain yields.

4.4.3 Tillage effects on WU, WUE and PUE

Improved water and precipitation use efficiencies in crop production are key factors for dryland cropping systems (Hatfield *et al.*, 2001). The results indicated that tillage systems influenced sunflower water use significantly in both seasons. Water use under IRWH was consistently higher than in the CON system but varied between the cropping seasons. The results are comparable to those reported by Hensley *et al.* (2000). The pronounced response in water use due to tillage was attributed to the ability of IRWH plots to concentrate water for crop use, as previously reported (Hensley *et al.*, 2000; Botha *et al.*, 2003). In contrast, Aboudrare *et al.* (2006) reported that sunflower seasonal water use was not significantly affected by soil tillage provided that the plant population was uniform and weed control was adequate in reduced tillage systems under semi-arid Mediterranean climate. Runoff harvesting benefits have been documented in other in-situ water harvesting systems (Li *et al.*, 2000; Schiettecatte *et al.*, 2005). Higher WUE and PUE under IRWH system compared to CT treatment were expected. This might be a result of extra harvested water in the basins, compared to the CT system which contributed huge ex-field water losses. Sinclair *et al.* (1983) noted that all management practices that minimize surface runoff tended to increase WUE. Hensley *et al.* (2000) reported that sunflower WUE and PUE under IRWH was higher than under the CON system. The researchers also observed that the sunflower WUE tended to increase with seasonal precipitation. However, the difference in rainfall amount between the two seasons in this study was small. This is contrary to the view of Zoebl (2006) who argued that higher rainfall decreases the water use efficiency. This view is further supported by Fuchs (1975), cited in Zoebl (2006), who maintained that plant canopies show a higher water use efficiency if water stressed. However, WUE varies from one crop genotype to the other. Compared to the results of Hensley *et al.* (2000), WUE and PUE values in this study were slightly lower. WUE and PUE values in this study were also lower than those reported by Botha *et al.* (2003) in which stone and organic mulches were applied on the runoff strip and basins. This underscores the importance of adequate groundcover in order to improve water and precipitation use efficiency.

In this study, the WU in cowpea was consistently higher in IRWH treatment compared to CON system although the difference between tillage systems was non-significant in the second season. This was true also for WUE and PUE although similarities between treatments were observed in the first season. The response to water and precipitation utilization was attributed to tillage effects. These results concur with those reported by Adekalu *et al.* (2009) who found that runoff harvesting with supplemental irrigation increased WUE in cowpea planted in a reduced tillage system. Although this study was rainfed, their results are applicable to this case in that they emphasize the importance of runoff harvesting in improving WUE.

4. 4.4 Effect of cropping system on crop yield

Higher productivity of sole sunflower over its intercrop was attributed to lower population of sunflower in the intercrop. The results could also suggest intense competition for resources between crop species in the crop mixture. Wang *et al.* (2004) reported that some cowpea genotypes can suppress the growth of sunflower. The results from this study are in agreement with the findings of other researchers working with other cropping systems. Khan *et al.* (1999) reported that sunflower gave the maximum grain yield when sown alone and minimum when intercropped with soybean. Differences between sole and intercropped sunflower yield were attributed to competition for resources such as nutrients and soil water. The results also confirm the findings reported by other researchers that sole crops produce higher yield than their intercrops (Kendel *et al.*, 1977; Aladesanwa & Adigun, 2008; Awe & Abegunrin, 2009). Lower yield under intercropping system might be attributed to both inter- and intra-species competition for resources, as reported in maize-amaranthus intercrops (Awe & Abegunrin, 2009). However, the values of the land equivalent ratio (LER) across both tillage systems were >1, indicating that the intercrop was more productive than the pure stands of sunflower and cowpea (Mead & Willey, 1980). In contrast, the grain yield of cowpea showed no differential response to the cropping system probably because cowpea was able to out-compete sunflower in acquiring nutrients and other resources. The cowpea yield in the intercrops was expected to be substantially less than in the sole cropping since cowpea is an under-storey which can be limited by light (Kombiok *et al.*, 2005). Probably the tramline row spacing between component crops was wide enough to avoid a shading effect on the cowpea.

4. 4.5 Effect of cropping systems on WU, WUE and PUE

The observed greater WU in intercrops compared with the sole crops could probably be attributed to the differences in plant population. Apart from the differences in plant density, this higher WU in intercrops could have been due to the relatively higher water use of sunflower compared to cowpea (Moroke *et al.*, 2002). When the two crops were combined in an intercrop, their combined water use became higher than in the sole cowpea (Moroke *et al.*, 2002). The results indicated that WUE and PUE of sole sunflower were consistently higher than their intercrops. However, the opposite was observed in cowpea in which the intercrop WU and PUE were higher in intercrops than in sole crops. Conflicting results on WU and WUE of intercrops have been reported by other researchers. Tsubo *et al.* (2003) reported that WUE of maize-bean intercropping were equivalent to or higher than corn sole cropping, and higher than bean sole cropping. Soetedjo *et al.* (1998) reported that the WUE of the early sown intercrop was significantly greater than that of early sown pure stands of field pea and canola but the WUE of the intercrop sown late was not significantly different from those of the pure stands that were also sown late. In north east Nigeria, Grema and Hess (1994) reported that intercropping cowpea with millet did not increase the WU rate over sole millet as transpiration by cowpea was probably substituting for E_s.

4.5 Conclusions

The TS effect on sunflower grain yield and water use parameters was more evident in the second cropping season. The IRWH tillage system increased sunflower grain yield by 56% compared to the CON during the 2008/2009 seasons. Similarly, WUE of sunflower under IRWH increased by 40% and PUE by 31% compared to the CON during the same period. The CRS had a significant effect on sunflower grain yield. Sole sunflower had higher productivity than intercropped sunflower. The CRS resulted in 60% and 33% more grain yield in sole sunflower compared to the intercropped sunflower during 2007/2008 and 2008/2009 seasons, respectively. WU was 1.1-fold higher in the intercrop sunflower than sole sunflower during 2008/2009 season. WUE was 1.4 times higher in the sole sunflower than the intercrop during 2008/2009 season.

TS had no effect on cowpea grain yield but led to significant increase on water use parameters. WU of cowpea under IRWH increased by more than 10% compared to CON during 2007/2008 season. The WUE of cowpea under IRWH was 1.7-fold higher whilst PUE was 31% higher than CON during 2008/2009. CRS effects were not significant on cowpea grain yield but had a significant influence on water use parameters. The WU in the cowpea intercrop was 1.3-fold higher than the sole crop during 2007/2008 season.

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CHAPTER 5

EFFECTS OF IN-FIELD RAINWATER HARVESTING ON RUNOFF

Abstract

Runoff is an important water balance component in the semi-arid areas. The purpose of this chapter was to quantify runoff under IRWH using simulated rainfall, and compare with annually tilled CON (control). IRWH is a special type of no-till (NT) that promotes runoff water from crusted runoff strip into basins where it infiltrates beyond evaporation but is available for crop use. Runoff was related to time to runoff, total runoff, final runoff rate and runoff coefficient. The results showed that time to runoff was significantly shorter ($P<0.05$) whilst final runoff rate and runoff coefficients were significantly higher in IRWH compared to CON. Total runoff was higher in IRWH compared to CON, yet the differences were non-significant. This experiment demonstrated that by adopting IRWH production technique smallholder farmers could harness an additional 45.5 m^3 ha^{-1} of water compared to the CON system. The extra water harvested could be enough to meet 1% of maize water requirements. It was concluded that IRWH was an effective water harvesting technique on the University of Venda-Shortlands ecotope.

Key words: Limpopo Province; no-till; runoff; rainfall simulation; water harvesting

5.1 Introduction

Water availability is a major constraint in semi-arid areas, leading to a natural focus on water conservation (Jensen *et al.*, 2003). Runoff constitutes one of the major water losses in semi-arid areas, causing the loss of valuable water, soil and nutrients (Schiettecatte *et al.*, 2005; Vahabi & Mahdian, 2008). Research results from semi-arid regions have shown that runoff losses can be as high as 50% of the rainfall on bare untilled lands (Stroosnijder, 2003). Excessive runoff not only limits the water available for crop production but also constitutes an erosion hazard (Rao *et al.*, 1998). However, the goal of water harvesting is to convert runoff water “loss” into productive use by storing it in basins where it can infiltrate and becomes available for crop use (Hensley *et al.*, 2000). Water harvesting based on the collection of runoff from a prepared catchment surface and its storage in the adjacent crop area has been used successfully for crop and tree improvement in other parts of the world (Li *et al.*, 2000; Li & Gong, 2002; Schiettecatte *et al.*, 2005). Among the various water harvesting technologies available, IRWH has shown to be an efficient water conservation crop production technique especially appropriate for rural poor households (Botha *et al.*, 2003). It has therefore been selected for this study.

The IRWH system is regarded as a special form of water harvesting. It is also known as mini-catchment runoff farming (Oweis *et al.*, 1999). IRWH has been tested in South Africa on clay and duplex soils in semi-arid areas where it has given maize yield increases of between 25% and 50% compared to CON (Hensley *et al.*, 2000; Botha *et al.*, 2003). The technique illustrated in Figure 1.1 combines the advantages of water harvesting from the no-till, flat, crusted runoff strip, and decreased evaporation from the deeply infiltrating runoff water which accumulates in the basin (Hensley *et al.*, 2000). Thus the IRWH partitions rainfall into runoff (on the no-till runoff strip) and run-on (in the basin).

Runoff is an important water balance component in the semi-arid environments (Bennie & Hensley, 2001). Zere *et al.* (2005) used runoff data to simulate the long-term crop yields planted on CON and IRWH on Glen-Tukulu ecotope. It was concluded that the PutuRun Model can be used with reasonable confidence after calibration to simulate long-term runoff on conventionally tilled, and bare untilled plots on the Glen/Tukulu ecotopes using daily rainfall data. In Ethiopia Welderufael *et al.* (2008) used 2-year runoff data to predict maize yield increase of between 25% and 35% under IRWH compared with conventional tillage. Some rainfall-runoff relationships from semi-arid ecotopes are summarized in Table 5.1.

The research results presented in Table 5.1 clearly indicate that IRWH technique is a promising soil management technology under certain soil conditions and that it needs to be explored further to promote crop production in marginal areas.

Results obtained with water harvesting techniques are not always transferable from one set of conditions (i.e. from a particular ecotope) to another because of the differences in local characteristics (Ojasvi *et al.*, 1999). Considerable IRWH research has been done on specific ecotopes in the Free State Province of South Africa. It is, however, uncertain how the technique will perform on a Shortlands soil in the Limpopo Province. The majority of smallholder farmers in the province depend on these type of soils for crop production, yet yields continue to be low due to erratic and low rainfall, exacerbated by high runoff and evaporation losses.

The hypothesis is that the IRWH technique will increase crop yield on the University of Venda-Shortlands ecotope, compared to conventional tillage. This is due to the fact that enhanced runoff on the flat, crusted no-till runoff strip shown in Figure 1.1 will result in a large fraction of the rainfall being stored in the basins, resulting in higher rainfall use efficiency than with CON. It is predicted that CON will have ex-field runoff losses as well as higher water losses due to surface evaporation.

The purpose of this chapter was to quantify the effect of IRWH technique on runoff from Shortlands soil using simulated rainfall of various intensities, and to compare these results to those results obtained with annually tilled CON. The study will improve our understanding of rainfall-runoff processes on two tillage practices and thereby provide insight into the constraints and potential of IRWH production technique on the University of Venda-Shortlands ecotope.

Table 5.1 Summarized measured rainfall-runoff relationships from annually tilled and bare crusted soils on semi-arid ecotopes

Site	Measured period (yrs)	Rainfall (mm) *1	Slope (%)	Description of the top soil	Tillage treatment	Runoff as percentage of rainfall	Reference
Glen (SA)	18	508	5.0	Orthic, red 11% clay	No-till, bare, flat crusted surface	29	Zere *et al.* (2005) *2
Glen (SA)	18	508	5.0	Orthic, red 11% clay	Annual maize, conventionally tilled	7	Zere *et al.* (2005) *3
Pretoria (SA)	27	721	3.8	Orthic, red sandy loam	Tilled and left bare	24	Bennie and Hensley (2001)
Pretoria (SA)	27	721	3.8	Orthic, red sandy loam	Continuous maize	27	Bennie and Hensley (2001)
Glen (SA)	6	500	1.0	Melanic, dark brown, 45% clay	No-till, bare flat crusted surface	29.2	Hensley *et al.* (2000) and et al. (2003)
Glen (SA)	3	501	1.0	Melanic, dark brown, 45% clay	Conventional-tilled and left bare	3.6	Hensley *et al.* (2000)
Glen (SA)	3	538	1.0	Melanic, dark brown, 45% clay	No-till, bare, stone mulch	25	Botha *et al.* (2003)
Glen (SA)	3	538	1.0	Melanic, dark brown, 45% clay	No-till, bare, organic mulch	6	Botha *et al.* (2003
Glen (SA)	6	500	1.0	Orthic, dark brown, 38% clay	No-till, bare, flat, crusted surface	29.9	Hensley *et al.* (2000) and et al. (2003)
Glen (SA)	3	501	1.0	Orthic, dark brown, 38% clay	Conventional tillage and left bare	3.9	Hensley *et al.* (2000)
Glen (SA)	3	533	1.0	Orthic, dark brown, 38% clay	No-till, bare, stone mulch	20	Botha *et al.* (2003)
Glen (SA)	3	533	1.0	Orthic, dark brown, 38% clay	No-till, bare, organic mulch	4	Botha *et al.* (2003)
Dera (Ethiopia)	2	-	-	-	No-till, bare, flat, crusted surface	46	Welderufael *et al.* (2008)
Dera (Ethiopia)	2	-	-	-	Conventional tillage and left bare	39	Welderufael et *al.* (2008)

*1 rainfall that occurred during the measurement period; *2 reporting re-worked original data of du Plessis and Mostert (1965);*3 reporting original

Data of Haylett (1960).

5.2 Materials and methods

5.2.1 Site description

The study was carried out at the University of Venda-Shortlands ecotope. Site characteristics are described in chapters 2 and 3 in this document.

5.2.2 Description of IRWH system

IRWH system is described in Chapter 4 in this document.

5.2.3 Soil surface state characterization

Surface (0 - 100 mm) soil water content was determined by gravimetric methods prior to rainfall simulation. The surface roughness index was determined in the 1 m x 1 m runoff plot with a 100 peg-board method (Zobeck & Onstad, 1987). Pegs of length 100 mm (pre-calibrated) with a diameter of 25 mm were evenly spaced on the 800 mm x 800 mm x 20 mm board, i.e. 10 x 10 holes with 60 mm intervals between rows and pegs. The holes in the board are made slightly wider than the pegs so that they can move freely. During measurements the board was placed at randomly selected sites on the soil surface and the vertical distance to the surface was then recorded for each peg. Three measurements were recorded for each plot. The mean value was taken as the roughness index of the surface.

The slope in the selected plots was determined following a simple method described in Bothma (2010). Two broomsticks, each 500 mm long were used for this purpose. One broomstick (A) was placed at the bottom slope with a cord attached 500 mm from the base of the broomstick. Another broomstick (B) was mounted at the top of the 2 m runoff area (Figure 1.1). The cord from broomstick (A) was then stretched level to broomstick (B) using a spirit level. The difference in height from the soil surface at A and B was then used to calculate the slope.

5.2.4 Tillage treatments and historical background

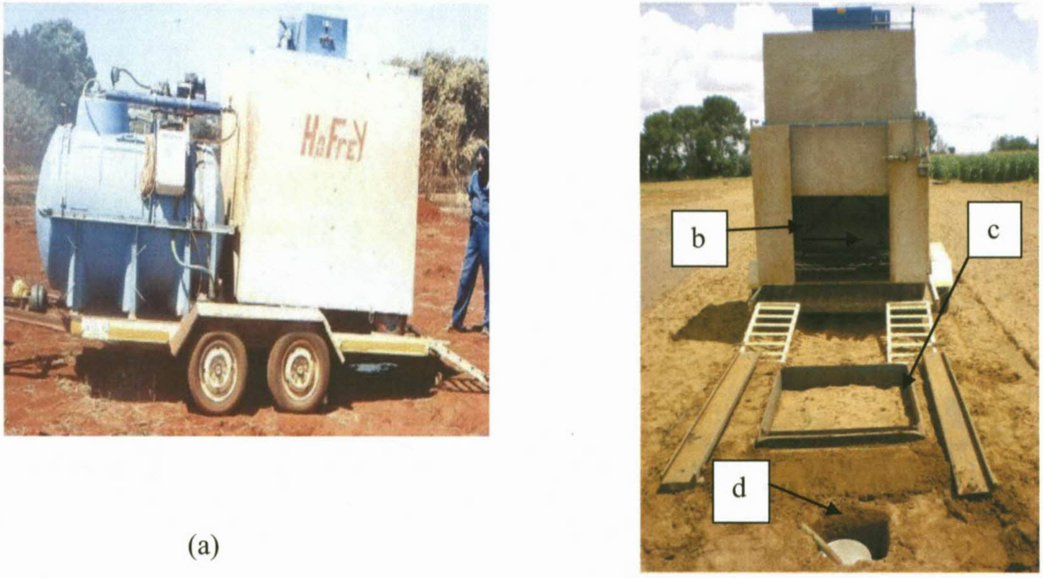
The study focused on plots subjected to artificial rainfall. Treatments were:

1. In-field rainwater harvesting (IRWH)
2. Annually tilled conventional tillage (CON)

The experimental site was established in 2005 in order to evaluate the effects of IRWH on sunflower-cowpea cropping systems. Details of the experimental design and treatments are described in Chapter 4. The following plot surface characteristics were recorded before the simulation experiment: (a) Slope: 8%; (b) mean surface roughness: IRWH (10 mm); CON (29 mm); mean surface soil water content was 4% (by mass) for all plots.

5.2.5 Rainfall simulation experiment

Simulated rainfall allows for a complete control of experimental conditions (Truman *et al.* 2007). Rain storms with specified intensities were simulated with the Hofrey rainfall simulator (Figure 5.1). The design of the simulator was based on the oscillating overhead sprinkler type described by Classens and van der Walt (1993). This design produces a reasonable distribution pattern of rain drop sizes under field conditions. The Hofrey simulator (Figure 5.1a) has a closed compartment (Figure 5.1b) with adjustable oscillating sprinkler nozzle. This simulator is equipped with pressure gauges and timer control for the oscillation of the sprinkler. In the closed compartment, a metal runoff frame (Figure 5.1c) of 1 m by 1m is inserted at 100 mm soil depth. On the downslope of this frame is a gutter into which a pipe is connected for the purposes of runoff collection (Figure 5.1d). The rainfall simulator fits on a trailer which can be towed by a vehicle.



(a)

Figure 5.1 Hofrey simulator (a) mounted on trailer, (b) showing closed compartment, (c) metal runoff frame, and (d) runoff collection.

The simulation experiment was conducted *in situ* on bare soil in September/October 2009 after crop harvesting in April. Two blocks of IRWH and CON were conveniently chosen from the eastern end of the experimental block because of their proximity to the source of electricity. Plots were randomly selected from IRWH and CON treatments. Gravimetric water content was measured in all plots earmarked for rainfall simulation at the beginning of the experiment. The plots were then covered in plastic sheets. The plastic sheets were removed on the day of the experiment. It was assumed that the plastic sheeting would keep away any rain and maintain soil moisture at the same level in the control and IRWH plots during the experiment. The experiment was completed in the best shortest time so as to minimize any moisture variation. The 1 m^2 runoff plots were prepared in three replicates by forcing the frame to a depth of 100 mm into the soil and then installing both the gutter and container in which runoff was collected using a measuring cylinder. The sprinkler chamber was then pushed in position before the desired rain storm intensity was applied. Simulated rainfall was applied at constant intensity. Four rainfall intensities (RI) were applied (23, 33, 52 and 71 mm h^{-1}) for a duration of 60 minutes. Although lower rainfall intensities (5, 10 and 15 mm h^{-1}) close to the natural rainfall of the site were simulated during the calibration of the equipment (calibration curve not presented), simulation using these rainfall intensities under field conditions consistently gave erratic and inconsistent results. Using higher rainfall intensities than average intensities of the area was the rational thing to do under the circumstances. Although natural rainfall intensities at the study site are typically low (less than 20 mm h^{-1}), the use of higher rainfall intensities were justified because infrequent heavy rains do occur at the study site (Mzezewa *et al.*, 2010). Selection of rainfall intensities as to cover the whole possible range was especially important in semi-arid areas where rainfall often occurs as short high-intensive storms (Hamed *et al.*, 2002). Time to get the first runoff was recorded and samples were taken. Thereafter samples were taken every 5 minutes. Runoff was measured using measuring cylinders. Each rainfall event was replicated three times per plot. A total of 24 rainfall simulations were carried out (2 tillage systems x 4 rain intensities x 3 replicates).

5.2.6 Runoff parameters

Three indicators were used to study the runoff process, *viz*: time to runoff (minutes); total runoff (mm) during the simulation period of 60 minutes; final runoff rates (mm h^{-1}). The later was estimated as the average of nearly constant (steady) 5-minute readings with the smallest difference between them. Runoff coefficients were calculated as the ratio (%) of total runoff (mm) to total rainfall (mm) applied during the simulation period.

5.2.7 Statistical analyses

An analysis of variance (ANOVA) was conducted using SPSS version 17.0 (SPSS Inc., 2008). Mean separations were achieved by using Tukey's honestly significant difference (HSD). The probability level less than 0.05 was designated as significant. If there was a statistically significant interaction, then the interaction was presented. Otherwise only the main effects of tillage were reported.

5.3 Results and discussion

5.3.1 Tillage effects

Time to runoff was significantly influenced by tillage practice (Table 5.2). Mean time to runoff in IRWH treatment was less than CON treatment by about 6 minutes or 48%. Total runoff was 1.7-fold higher in IRWH plots compared to CON plots, but the differences were not significant (Table 5.2). Short runoff time is beneficial for water harvesting especially on the study site where most of the rainfall comes in light showers (Mzezewa *et al.*, 2010). A shorter runoff time and higher total runoff from IRWH strips compared to CON was expected. This could be attributed to the formation of surface crust on the runoff strip of IRWH plots. Surface crust is a major factor in runoff generation (Philippe *et al.*, 2001). No-till promotes surface soil sealing. Jin *et al.* (2008) reported that long-term application of no-till might lead to soil compaction and thereby increasing the runoff and decreasing infiltration. Higher total runoff on IRWH could also be attributed to low surface roughness (10 mm) on IRWH plots compared to CON (29 mm). The generation of runoff has been linked to soil-surface roughness (Carmi & Berliner, 2008). Guzha (2007) attributed higher runoff rates in NT compared with other tillage systems due to lack of surface depressional storage. Lack of significant difference in total runoff between the two treatments in the current experiment may be attributed to the higher rainfall intensities (23 – 71 mm h^{-1}) compared to the natural rainfall normally received on the study site. High intensity rainfall caused slacking and collapse of clods in CON plots leading to the formation of a surface seal similar to that in IRWH plots, akin to the observation of Welderufael *et al.* (2008). Previous study has shown that 54% of the rainfall received on the study site has intensity of less than 20 mm h^{-1} (Mzezewa *et al.*, 2010). The results are in agreement with the findings of Rao *et al.* (1998) who reported no significant difference in runoff between no-till with crusted surface and conventional tillage plots on an Alfisol. Lack of difference in runoff from the two tillage systems was attributed to structurally unstable crusting soils. In Ethiopia Welderufael *et al.* (2008) measured runoff from natural rain from flat, crusted NT plots (similar to IRWH) and CON plots on a Fluvic Regosol during the 2003 and 2004 seasons. They found no statistical difference between the runoff on the two treatments. They attributed this to high rainfall intensity that probably caused the clods on the CON plots to disperse and slake quickly, promoting faster crust formation, resulting in the soil surface having similar properties to that on the IRWH plots.

Final runoff rate was significantly affected by tillage systems (Table 5.2). By the end of the simulation period IRWH plots were discharging runoff at 26.2 mm h^{-1} compared to 20.5 mm h^{-1} in CON plots (Table 5.2). Runoff from IRWH plots is in-field and therefore is stored in the basins where it infiltrates for use by crops whilst runoff from CON plots is ex-field and ends up in river systems. The results indicate that IRWH technique offers advantages of water conservation over CON systems, as previously reported (Hensley *et al.*, 2000; Botha *et al.*, 2003).

Tillage system had a significant effect on runoff coefficients (Table 5.2). Runoff coefficient was 2.1-fold higher in IRWH compared to CON treatment, as expected. Runoff coefficients obtained in this study are higher compared to those reported for similar production practice on some South African ecotopes (Table 5.1). Surface seal is the dominant factor in reducing infiltration in most African soils. The work of Stern *et al.* (1991) in South African soils demonstrated that kaolinite-dominated soils have the most stable aggregates, but the presence of smectites in small quantities may affect dramatically the degree of dispersion. This observation was corroborated by Lado & Ben-Hur (2004). Contrary to findings reported in literature, soils at this ecotope which contain 99% kaolinite clay minerals produced higher runoff than those at Glen (38% and 45% clay) which contain high proportion of smectite clay mineralogy (Hensley *et al.*, 2000). The dispersion of soil colloids is also controlled by the nature and distribution of the exchangeable cations of which sodium is the most dispersive cation. However, exchangeable sodium is low at this ecotope (< 0.12 $\text{cmol}^+ \text{kg}^{-1}$) and therefore cannot be blamed for exacerbating collapse of soil aggregates. The differences between runoff generated at this site and Glen could largely be attributed to weak topsoil structure of Shortlands at this ecotope. The differences were also largely attributed to steeper slopes on this ecotope (8%) compared to flat slopes such as those reported in Table 5.1. The simulated high rainfall intensities could have resulted in heavy raindrop impact that led to the collapse of soil aggregates and therefore higher runoff than expected. However, the results of this study are comparable to those of Welderufael *et al.* (2008) who reported that the ratio of runoff to precipitation on NT plots and plots were 46 and 39%, respectively.

High runoff coefficient means high rate of runoff and therefore high potential for in-field water harvesting. The results therefore indicated that IRWH production technique is a viable water harvesting practice on this ecotope.

Table 5.2 Mean runoff, time to runoff and runoff coefficients as affected by tillage. Means not followed by the same letter in the same column are statistically different based upon Tukey's HSD means separation test at $P < 0.05$

	Parameters			
Tillage treatment	Time to runoff (min)	Total runoff (mm)	Final runoff rate (mm h^{-1})	Runoff coefficient (%)
CON	13.1a	13.5a	20.5a	30a
IRWH	6.8b	22.5a	26.2b	50b
*SEM	0.9	3.3	0.7	5.7

*SEM =standard error of mean; Rainfall averaged across all RI's over the simulation period was 45 mm.

5.3.2 Tillage x rain intensity interaction

A significant tillage x rain interaction was observed on runoff time (Table 5.3 and Figure 5.2). At rainfall intensity of 23 mm h^{-1}, time to runoff was significantly shorter in IRWH compared to CON treatment. Runoff started after 7 minutes on IRWH plots compared to 25 minutes on CON treatment. The difference in runoff time could translate into huge additional volume of water on IRWH system compared to CON on this type of soil. For example in this case, on a 1 ha of IRWH with 2 m runoff strips and 1 m basins (i.e. 66% runoff strips) a difference of 18 minutes before runoff is initiated (25-7) at a rainfall intensity of 23 mm h^{-1} it would result in additional 45 540 l ha^{-1} or 45.54 m^3 ha^{-1}. This would meet about 1% of irrigation water requirements of maize, assuming maize water consumption of 5840 m^3 ha^{-1} as determined at nearby Thabina smallholder irrigation scheme (Yokwe, 2009). However, as the rain intensity increased, the differences between the treatments were not statistically significant. This could suggest that at higher rainfall intensities tillage system had less influence on time to runoff although time to runoff was consistently shorter in IRWH plots compared to CON plots throughout the simulation period (Figure 5.2). The results suggested that under the experimental conditions, the time to runoff was always shorter on the IRWH treatment compared to the CON treatment regardless of the rain intensity applied. This could also suggest that runoff was induced more easily under IRWH compared CON treatment.

A significant tillage x rain intensity interaction effect on final runoff rate was observed (Table 5.3). Final runoff rate was significantly higher in IRWH compared to CON treatment at rain intensity of 33 and 51 mm h^{-1} (Figure 5.3). No significant differences in final runoff rates were observed between tillage treatments at rain intensities of 23 and 71 mm h^{-1} (Table 5.3; Figure 5.3). A possible explanation for lack of significant difference between the treatments at high rainfall intensity could be the effect of high kinetic energy of rain drops that could have destroyed the soil structure. It is clear from Figure 5.3 that the final runoff rate increased as rainfall intensity increased, as expected. The observations were similar to the findings of Arnaez *et al.* (2007). It is also clear that the final runoff from IRWH treatment was consistently higher compared to CON treatment across all rain intensities. The results suggested that at any given rain intensity, IRWH technique harnesses more runoff compared to the CON treatment. The tillage x rain intensity results indicated that differences in hydrological response in the two tillage systems can be explained, in part, by differences in how the two tillage systems react to various rain intensities.

Table 5.3 Effects of tillage and rainfall intensity, and their interactions on time to runoff, total runoff, final runoff rate and runoff coefficients

Sources of variation	Time to runoff (min)	Total runoff (mm)	Final runoff rate (mm h^{-1})	Runoff coefficient (%)
Tillage (T)	0.001*	0.092	0.000*	0.020*
Rain intensity (RI)	0.000*.	0.003*	0.000*	0.042*
T x RI	0.006*	0.894	0.000*	0.537

* indicate the effects are significant ($p<0.05$).

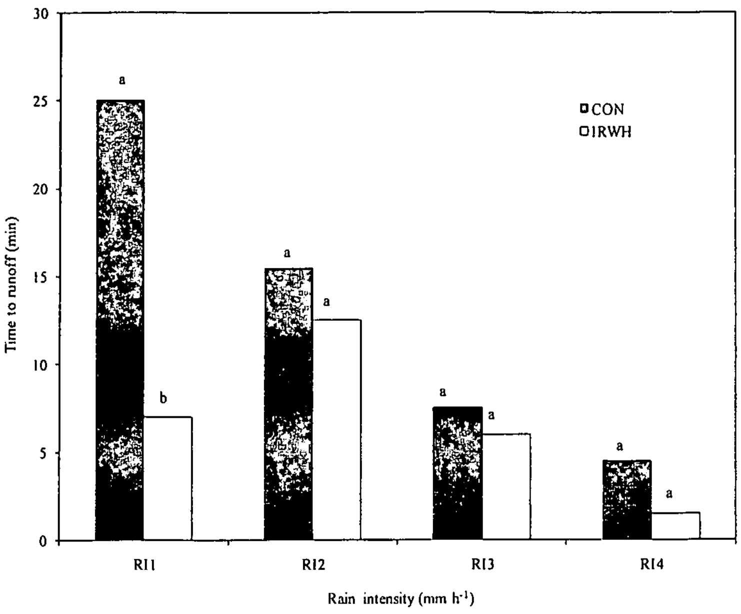


Figure 5.2 Time to runoff as a function of rain intensity and tillage treatment (RI= rain intensity 23, RI2= rain intensity 33, RI3= rain intensity52, and RI4= rain intensity 71 mm h^{-1}). Means followed by different letters indicates significant difference at $P < 0.05$.

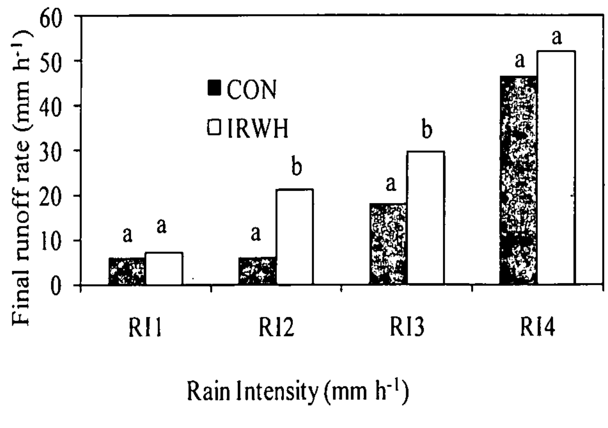


Figure 5.3 Final runoff rate as a function of rain intensity and tillage treatment (RI= rain intensity 23, RI2= rain intensity 33, RI3= rain intensity52, and RI4= rain intensity 71 mm h^{-1}). Means by different letters indicates significant difference at $P < 0.05$.

5.4 Conclusions

IRWH production technique harvested 45.5 m^3 ha^{-1} of water compared to the CON during the simulation experiemnt. The harvested water could be enough to meet 1% of maize water requirements during the growing season. Based on the results of this study, IRWH could be used to improve crop water availability on the University of Venda-Shortlands ecotope.

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CHAPTER 6

RISK ASSESSMENT OF SUNFLOWER PRODUCTION USING IRWH TECHNIQUE ON A SEMI-ARID ECOTOPE IN THE LIMPOPO PROVINCE

Abstract

In order to make reliable recommendation concerning the best production techniques for a crop on a particular ecotope it is desirable to evaluate the technique using long-term yields. The use crop models with long-term climate data can achieve this objective. The aim of this study was to assess the risk associated with sunflower production using an empirical model developed for the semi-arid areas. The Crop Yield Prediction for Semi-arid Areas (CYP-SA) was used to simulate sunflower yield using 26 years (1984 - 2010) climatic data. Scenarios of crop yield simulation included production techniques associated with IRWH, and CON. Specific attention was given to study the effect of initial soil water content at planting *viz.* empty profile water content near the lower limit of plant available water (LL); half profile (water content between LL and the drained upper limit (DUL)); full profile (water content near DUL) and planting dates (November, December and January). The results indicated that simulated sunflower yield was significantly influenced by initial profile water content. Yield difference at 80% probability was 74% higher under IRWH compared to CON with empty initial soil water content at planting. The lower the initial water content at planting, the greater the yield difference between the IRWH and CON production systems. This showed that less production risk was associated with IRWH technique. It could be concluded that IRWH

in combination with low initial profile water could offer farmers some chance of a higher sunflower yield on the University of Venda-Shortlands ecotope.

Key words: cumulative probability functions; crop simulation; empirical model; production risk; rainwater harvesting

6.1 Introduction

In order to quantify risk for different production techniques, crop growth modeling can be used as an analytical tool (Hensley *et al.*, 2000; Singels *et al.*, 2010; Walker et al., 2005). According to Monteith (1996) a crop model is defined as a quantitative scheme for predicting the growth, development and yield of a crop, given a set of genetic coefficients and relevant environmental variables. Models can be used as research tools to conduct research faster and cost-effectively (Botha *et al.*, 2003). In addition, a valuable property of models is their ability to utilize long-term climate data to provide long-term yield simulations, which can serve to quantify risk (Botha *et al.*, 2003; Popova & Kercheva, 2005). By constructing cumulative probability functions (CPFs), risk associated with various production systems can be quantified (Hensley *et al.*, 2000; Botha, 2006; Walker *et al.*, 2005; Tsubo & Walker, 2007; Anderson, 2007; Zere *et al.*, 2007; Jagtap *et al.*, 1999; Diaz-Ambrona *et al.* 2005; Popova & Kercheva, 2005).

Models that employ long-term climatic data have been employed to assess the risk associated with water harvesting in South Africa in the last ten years. Walker *et al.* (2005) carried out a risk assessment of maize yield using a crop growth model combined with a deterministic runoff model and stochastic rainfall intensity model. Their simulation included production techniques such as IRWH and CON and initial soil water content at planting: empty (water content near LL of plant available water); half (water content between LL and DUL); full (water content near DUL). Their results showed that IRWH had a lower risk than CON under all the variations in agronomic practices such as planting date, plant population and cultivar type. Anderson *et al.* (2003) used the PUTU-Maize crop growth model for the long-term risk assessment of maize yields under IRWH. The CON and IRWH gave a 50% probability yield of 1715 and 2338 kg ha^{-1}, respectively, when PUTU-Maize was run with a full profile and 966 and 1832 kg ha^{-1} when starting with an empty profile, showing the superiority of the IRWH compared to CON. Zere *et al.* (2007) used an empirical yield prediction model to compare precipitation use efficiencies (PUE) over 80 seasons for four maize production practices. Based on the CPFs they concluded that PUE for IRWH was significantly better than PUE for CON.

Hensley *et al.* (2000) and later Botha *et al.* (2003) and Botha (2006) developed a model called Crop Yield Predictor for Semi-Arid Areas (CYP-SA). The model was applied for the long-term risk assessment for production of dry beans, maize and sunflower under CON and IRWH. The CYPSA model simulated reasonably well the long-term yield of maize and sunflower for CON and IRWH on Glen-Bonheim and Khumo-Swartland-Amandel ecotopes in the Free State Province of South Africa. The results of Botha et al. (2003) and Botha (2006) indicated that IRWH consistently had lower risk of production compared with CON. The CYP-SA model has potential to be applied for assessing risk for crop production in other ecotopes and therefore was chosen for this study to assist in decision making regarding the performance of IRWH and CON production techniques on this ecotope. Since the CYP-SA model was specifically developed for the IRWH crop production system, it is ideal for long-term yield predictions with this production technique. However, one of the disadvantages of the model is that runoff (R) is predicted using an empirical linear regression equation based on the relationship between R and daily rainfall. Runoff prediction may therefore be unreliable (Anderson, 2007).

In order to make reliable recommendation concerning the best production techniques for a crop on a particular ecotope it is desirable to have long-term yields. This is particularly important for ecotopes in semi-arid areas where rainfall is marginal, and also erratic with regard to amount, distribution and intensity (Hensley *et al.*, 2000). The aim of this study was to assess the risk associated with sunflower production using an empirical model (CYP-SA) developed for the semi-arid areas. Long-term (26 years) sunflower yield was simulated in order to quantify risk for two production techniques (IRWH and CON) on a clayey soil on a semi-arid ecotope in the Limpopo Province.

6.2 Materials and methods

6.2.1 Ecotope characteristics

These are described in Chapters 2 and 3

6.2.2 Model description

CYPA-SA is largely empirical and runs on daily time-step (Anderson, 2007). Details concerning the various processes and parameters are described in Botha (2006). The inputs required by the model are crop modified upper limit (CMUL) of plant available water (PAW); drained upper limit (DUL) of PAW; lower limit (LL) of PAW; rainfall (P); evaporative demand (ET_o) and soil water content at planting (θ_p). It was assumed that runoff (R) would be zero if the precipitation was less than 8 mm. Runoff from rainfall events of more than 8 mm can be calculated using Equations 6.1 and 6.2.

CON:

$P < 8: P_e = P$

$$P > 8: P = P - [\{0.473 \text{ x } P) - 2.168\} \text{ x } 0.4] \qquad r^2 = 0.60 \qquad 6.1$$

(after Hensley *et al.*, 2000)

Where:

P = rainfall for a particular day (mm)

P_e = effective rainfall for a particular day (mm)

IRWH:

$P < 8: P_e = P$

$$P > 8: Pe = P + [(0.474 \text{ x } P) - 0.8791] \qquad r^2 = 0.64 \qquad 6.2$$

(after Botha *et al.*, 2003)

6.2.3 Calibration and verification of the CYP-SA model

Calibration is a process of standardizing predicted values, using deviations from observed values for a particular area to derive correction factors that can be applied to generate predicted values that are consistent with the observed values. The calibration process can provide important insight into both local conditions and model performance (Muthukrishnan *et al.*, 2006). The original model algorithms rules were evaluated by combining available for ecotopes in the Free State Province (Hensley *et al.*, 2000; Botha, 2006). Modifications of the model were necessary in order to adapt to the soil conditions of this ecotope. Model calibration was achieved by inputting soil and climate data as detailed in section 6.2.2 above for the 2007/08 growing season. The original model runoff equations (6.1 and 6.2) were replaced with equations 6.3 and 6.4 which were developed for this ecotope in Chapter 5.

CON:

$$R = 0.421 \times P - 3.008 \qquad r^2 = 0.769 \tag{6.3}$$

IRWH:

$$R = 0.59x \times P - 2.203 \quad r^2 = 0.947 \tag{6.4}$$

Where:

R = runoff (mm)

P = precipitation (mm)

The predicted yield was compared with the measured sunflower yield for that season. The model parameters (stress factors) were adjusted stepwise until the predicted yield matched with the measured yield. This was repeated for all replications for that season. The averaged correction factors were then used for model verification. Separate calibrations were done for CON and IRWH treatments. Model verification test were designed to evaluate the model performance. After calibration of the model, it was verified using another set of field data. Data from 2008/09 growing season was used for model verification. The verified model was then used for simulation of long-term sunflower yield.

6.2.4 Statistical analyses for model verification

The model reliability tests were performed following the procedures proposed by Wilmott (1981). Wilmott (1982) recommended use of the index of agreement (D-index), root mean square error systematic ($RMSE_s$), root mean square error unsystematic ($RMSU_u$) and root mean square error (RMSE) for model evaluation. The following criteria according to Wilmott (1981) indicate model reliability: (1) $RMSE_s$ should be as small as possible, a large $RMSE_s$ indicates bias; (2) $RMSE_u$ should be as close as possible to RMSE, indicating that the deviations of predicted from measured values are random; (3) The D-index should be as close as close as possible to 1.

The Mean Absolute Error (MAE) and RMSE are among the best overall measures of model performance, and are calculated as follows:

$$MAE = n^{-1}\sum_{i=1}^{n} | \mathrm{P}i - \mathrm{O}i | \qquad 6.5$$

$$RMSE = \left[n^{-1}\sum_{i=1}^{n} (\mathrm{P}i - \mathrm{O}i)^{2} \right]^{0.5} \qquad 6.6$$

Where:

n = number of treatments

i = number of specific treatments.

These statistical parameters quantify the mean difference between observed (Oi) and predicted (Pi) values (Wilmott, 1982).The advantage of RMSEs that it indicates the bias (deviation of the actual slope from 1:1 line) in a particular model, compared with the random variation (RMSEu) that may occur. The RMSEs and RMSEu are calculated as follows:

$$RMSEs = \left[n^{-1} \sum_{i=1}^{n} \left(\hat{P}i - Oi \right)^2 \right]^{0.5} \qquad 6.7$$

$$RMSEu = \left[n^{-1} \sum_{i=1}^{n} \left(Pi - \hat{P}i \right)^2 \right]^{0.5} \qquad 6.8$$

Where:

$$\hat{P} = a + bO_i \qquad 6.9$$

a,b = parameters associated with an ordinary least squares (OLS) linear regression between O and P.

Wilmott (1982) proposed an index of agreement (D) of the form

$$D = 1 - \left[\sum_{i=1}^{n} (Pi - Oi)^2 / \sum_{i=1}^{n} (|P'i + |O')^2 \right] \qquad 6.10$$

Where:

$P'i = Pi - \overline{O}$

$\bar{O}$ = Average of the observed

$O'i = Oi - \overline{O}$

The index (D) is intended to be descriptive measure, and it is both a relative and bounded measure which can be widely applied in order to make cross-comparisons between models (Wilmott, 1982).

6.2.5 Model application

Meteorological data for both Thohoyandou and University of Venda meteorological stations were used for long-term (26 years) sunflower yield simulation. Meteorological record for the University of Venda only commenced in 2005. Since the rainfall pattern at Thohoyandou is similar to that experienced at the University of Venda it was decided to use the Thohoyandou data for the period 1984 - 2004. Rainfall and class A-pan evaporation data have been recorded for Thohoyandou meteorological station in the period 1984- 2004. The data was provided by the Agricultural Research Council-Institute for Soil, Climate and Water- Pretoria (Fritz, 2011; pers. comm.). Long-term evaluation of production techniques was achieved by comparing long-term cumulative probability functions (CPFs) of yield using the CYP-SA model and long-term climate data. The model together with long-term daily climate data was used to construct CPFs of crop yields in order to quantify the risk in the long-term associated with each production technique.

Long-term simulations have some limitations in that the water content at planting (θ_p) in each of the growing seasons is unknown. In addition, crop models generally do not simulate the water balance well during the fallow season (Hensley *et al.*, 2000; Botha, 2006; Tsubo & Walker, 2007). An approach that assumes different soil water content at planting each year was adopted. In this study, long-term crop model simulations were run with three different profiles of soil water content at planting each year (Tsubo & Walker, 2007). The following θ_p were used in the simulations: 0% (soil water content of the profile near empty, but enough in the top soil for germination of seeds, defined as the difference between DUL and LL), 50% (half full) and 100% (full). Total DUL and LL of the soil profile are 457 mm and 250 mm, respectively. The amount of plant-extractable soil water at planting in the effective rooting zone is 0 mm for empty profile, 99 mm for half full profile and 198 for full profile. The simulations were run for 26 seasons from 1984 - 2010 with different production techniques (CON and IRWH) and three planting dates: 1 November (early planting), 1 December (intermediate) and 1 January (late planting).

All statistical tests on cumulative probability functions were carried out using the Kolmogorov-Smirnov test for two samples ($P < 0.05$). This test is about the agreement between two empirical cumulative distributions (Tsubo & Walker, 2007). The null hypothesis is that the two groups are the same, and the test statistic D for two data sets x (the maximum distance between the two distributions) is defined as:

$$D = \max\left|S_{1(x)} - S_{2(x)}\right|, \qquad 6.11$$

Where:

$S_{1(x)}$, $S_{2(x)}$ = the cumulative distributions, S(x), for the two samples.

6.3 Results and discussion

6.3.1 Evaluation of the model performance

Results of model verification test using the procedure of Wilmott (1981) are presented in Table 6.1. The D-indices for both CON and IRWH were high (> 0.80), indicating good model performance. Furthermore, crop yield was correctly predicted (R^2 = 0.96) for IRWH and reasonably predicted for CON (R^2 = 0.68; Table 6.1), confirming a positive association and good agreement between measured and simulated yield. On the whole crop yield was underestimated by less than 25% in the CON whilst the model overestimated crop yield by less than 15% in the IRWH treatment (Figure 6.1; Table 6.1). The models for both CON and IRWH showed low $RMSE_u/RMSE$ values (<0.5), indicating that a high level of bias was associated with the models. The bias was also indicated by the large $RMSE_s$ relative to RMSE. Poor prediction of runoff could account for less satisfactory statistical indices in the model as previously reported (Anderson, 2007). Botha (2006) reported that IRWH system is a very complex to model. This could further be complicated by limited data availability in this study to run independent adjustment and verification.

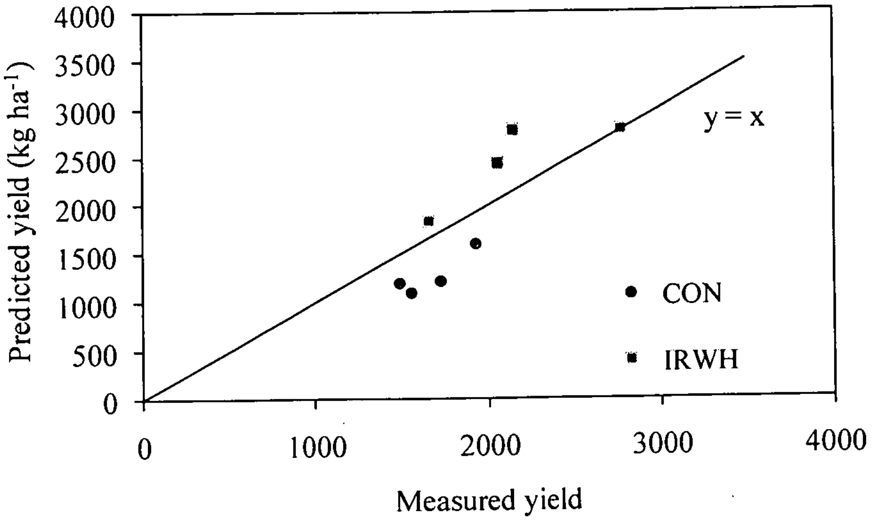


Figure 6.1 Predicted versus observed sunflower yield on the University of Venda-Shortlands ecotope.

Table 6.1 Statistical analysis of CYP-SA model performance predicting yields produced with conventional tillage (CON) and in-field rainwater harvesting (IRWH) (kg ha^{-1})

Treatment	MAE	RMSE	$RMSE_s$	$RMSE_u$	D-index	R^2	Measured mean yield	Predicted mean yield
CON	405	415	405	91	0.993	0.68	1685	1280
IRWH	370	403	384	121	0.994	0.96	1844	2062

6.3.2 Effects of initial soil water at planting and planting date

Yield variation over 26 years predicted under CON and IRWH management practices were compared using cumulative probability curves (Figure. 6.2; Table 6.2). The curves were constructed by averaging across all scenario factors. The curves were compared with for each scenario factor using the Kolmogorov-Smirnov test ($P \leq 0.05$). Sunflower yield was significantly higher in full initial water than in the other two water contents in the CON. Similarly, empty profile water gave the lowest yield compared to both half and full water contents in the IRWH (Table 6.2). At 80% probability the yield in the empty, half and full profile was 355, 691 and 1088 kg ha^{-1} for the CON, respectively. In the IRWH the yield was 1357, 1984 and 2601 kg ha^{-1} in the empty, half and full profile, respectively (Figure. 6.2). In general, the full profile water gave the greatest yield, followed by half profile and then the empty profile, illustrating the importance of adequate profile water content at planting in semi-arid environment. This is similar to the observation made in the Free State Province South Africa (Hensley et al. 2000; Botha, 2006; Walker *et al.*, 2005). Tsubo & Walker (2007) reported that sufficient soil water content at planting is important for a good harvest.

There were no effects of planting dates on yield in either production technique (Table 6.2; Figure 6.2). This may be attributed to high variability of rainfall on the ecotope. Mzezewa *et al.* (2010) reported that the coefficient of variation (CV) for November, December and January were 1.27, 1.56 and 1.35, respectively. Using the CYP-SA model Botha reported that late planting (January) was significantly better ($P \leq 0.01$) than December planting in the semi-arid Free State Province. Differences on the two ecotopes were probably due to climatic factors. For example, the climate at Glen in the Free State Province is drier (mean annual rainfall of 545 mm and AI of 0.24) compared to the conditions at the University of Venda-Shortlands ecotope (mean annual rainfall of 781 mm and AI of 0.52).

Table 6.2 The Kolmogorov–Smirnov (KS) test comparing tillage treatments (CON and IRWH) at different initial soil water levels and planting dates

Initial soil water	Tillage treatments		Planting date	Tillage treatments	
	CON	IRWH		CON	IRWH
Empty	a	a	November	a	a
Half	a	ab	December	a	a
Full	b	b	January	a	a

The same letter within columns indicates not significant difference at $P \leq 0.05$.

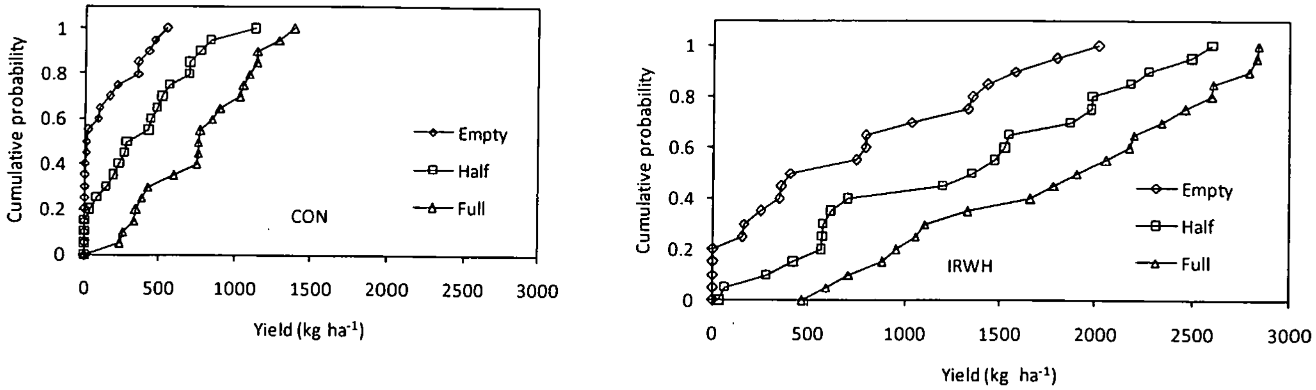
Further comparison of cumulative probability curves for scenario across different techniques was carried using the Kolmogorov-Smirnov test. No further analysis was done on scenarios involving planting dates due to lack of significance. There were significant yield difference between CON and IRWH production at all levels of initial profile water content (Table 6.3; Figure. 6.3). This confirms the superiority of the IRWH over CON. At 80% probability the yield difference between CON and IRWH was 74%, 65% and 58% in empty, half and full profile, respectively. This is in agreement with Walker *et al.* (2005) who reported that the lower the initial water content at planting, the greater the yield difference between the IRWH and CON. Similar results were reported by Anderson *et al.* (2003). The results strongly suggest that a farmer who adopts IRWH and plants on empty profile water content is likely to get higher yields than who uses CON production technique. The findings could be important in semi-arid environments where water for agriculture is a constraint. The results support the findings of other researchers who reported similar findings from semi-arid environments. Walker et al. (2005) reported that for all scenarios with empty initial soil water, the curves for IRWH were significantly different from those for CON while the difference was not significant under half and full initial soil water contents when they simulated maize yield in the Free State Province. In his experiments Botha (2006) concluded that simulated sunflower production risk was significantly less under IRWH compared to CON when CYP-SA was run between ¾ full and full profile water content.

Table 6.3 The Kolmogorov–Smirnov (KS) test for cumulated sunflower yield with CON and IRWH production techniques produced at different initial soil water content.

Initial soil water content	D-statistic	Probability level
Empty	0.48	0.011*
Half	0.57	0.001**
Full	0.62	0.000**

** = significant at $P < 0.001$; * = significant at $P < 0.05$.

(a) Initial soil water content



(b) Planting dates

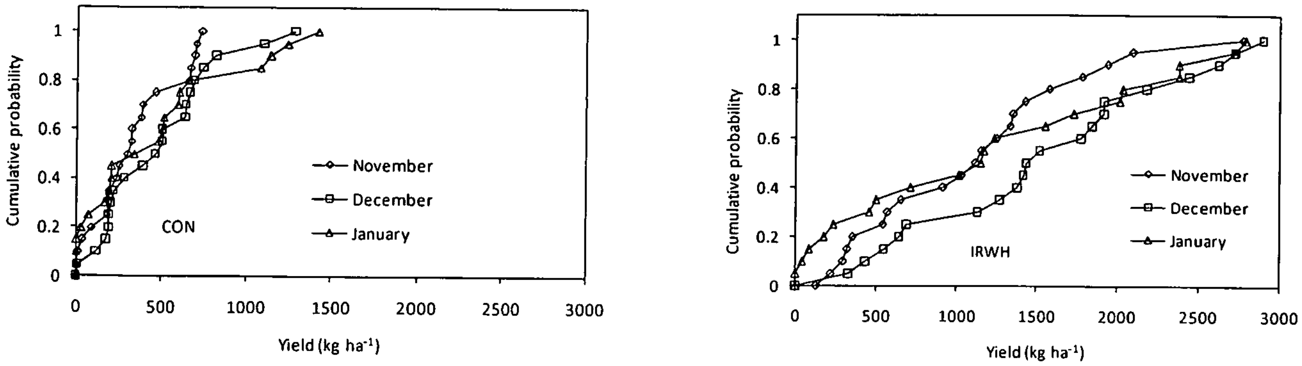


Figure 6.2 Cumulative probability of simulated long-term (1984 - 2010) sunflower for conventional (CON) and in-field rainwater harvesting (IRWH): (a) different profiles of initial soil water content (averaged over three planting dates) and (b) different planting dates (averaged over three water contents).

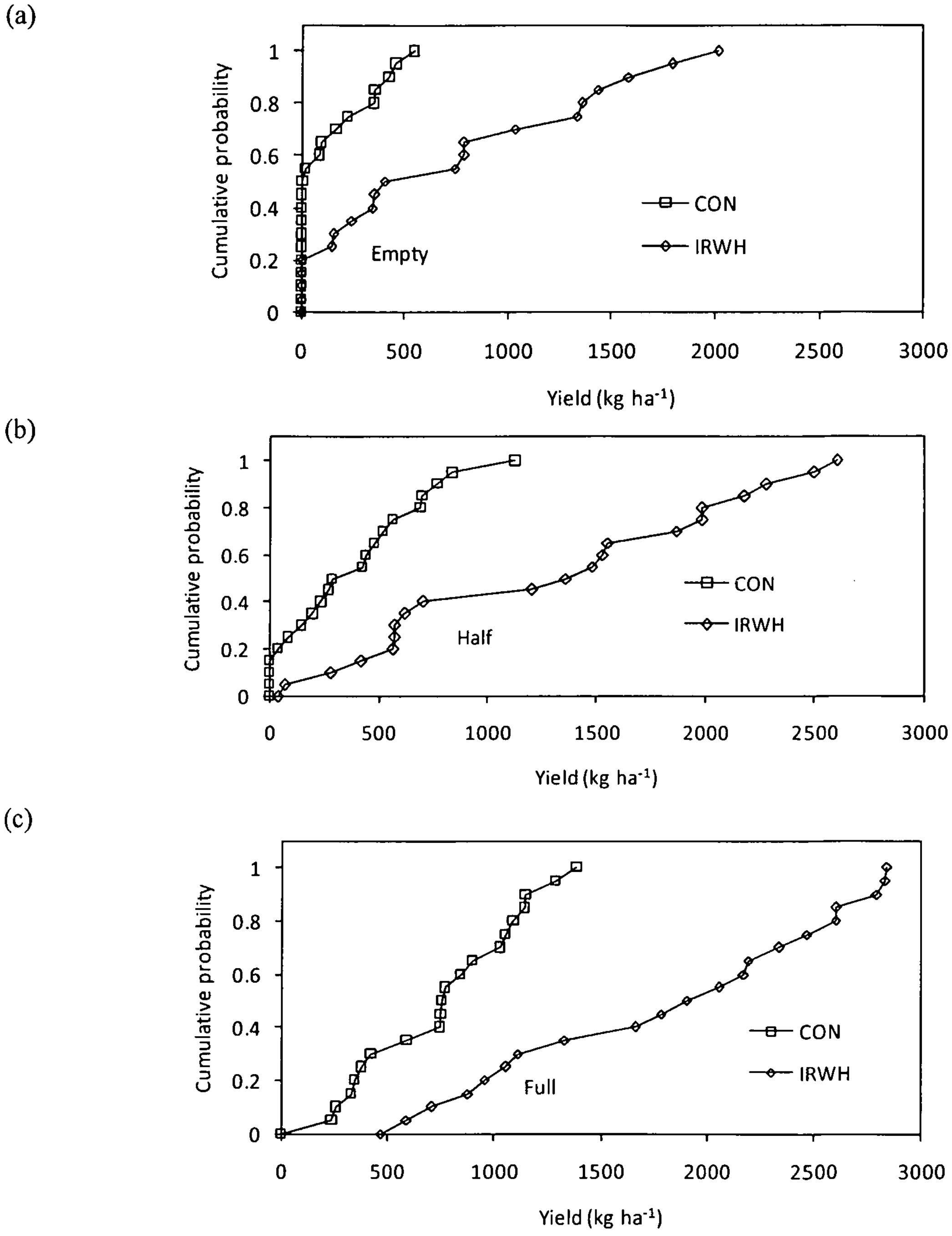


Figure 6.3 Cumulative probabilities of simulated long-term (1984 - 2010) sunflower yield with conventional (CON) and in-field rainwater harvesting (IRWH) for three water contents (averaged over three planting dates); (a) empty, (b) half and (c) full.

6.4 Conclusions

In this chapter the CYP-SA model was applied to simulate long-term sunflower yields in order to quantify the risk of crop production at the ecotope. The CON was compared with the IRWH production technique. Results from this study indicated that farmers who may adopt the IRWH technique and when profile water content is empty and can probably manage to get higher yields compared to those who choose the CON technique. The results from the simulation study supported results from field experiments carried out on this ecotope. Mzezewa *et al.* (2011) reported that IRWH out yielded CON system by 1.4 and 1.6 times in 2007/08 and 2008/09 seasons, respectively. In addition, Mzezewa and van Rensburg (2011) reported from their rainfall simulation experiment that by adopting IRWH production technique on the ecotope, farmers could harness an additional 46 m^3 $ha^{-1}$of water compared to the CON system. The harvested water could be enough to meet nearly 1% of maize water requirements per growing season.

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CHAPTER 7

SUMMARY AND RECOMMENDATIONS

7.1 Summary

The primary objective of this study was to evaluate in-field rainwater harvesting (IRWH) with a sunflower x cowpea intercrop. The study was carried out at the University of Venda in the Limpopo Province of South Africa, on soils with 60% clay content belonging to the Shortlands soil form, hence the name University of Venda-Shortlands ecotope was adopted. The soil profile has a generic orthic A horizon over a structured B horizon. The soils are deeply weathered to more than 1500 mm with no depth limiting material. The soils of the ecotope have relatively high CEC, high organic carbon in the surface horizon, low bulk density and very well drained making them highly productive. The University of Venda-Shortlands ecotope is characterized by a semi-arid climate with average annual rainfall of 781 mm. The rainfall has large variability (315%). Most of the rainfall comes in the summer months (October to March). Mid-summer drought is a common phenomenon in the area making crop production risky. Despite the climatic limitations to agriculture, a large population of smallholder farmers continues to rely on dryland agriculture for their subsistence. Maize yields in the smallholder sector are typically low (<1 t ha^{-1}) resulting in poor food security. Adoption of water conservation strategies by smallholder farmers could improve food production in the region and avert starvation.

Previous research has shown that the constraints to food production in semi-arid tropical countries often result from water loss by runoff and evaporation. Maximizing precipitation use efficiency (PUE) is therefore important in the semi-arid regions to stabilize or improve food production. Two primary sources of water loss are runoff and soil evaporation (E_s). E_s is more important than runoff in contributing to inefficient precipitation use in dryland crop production. The IRWH technique has a proven ability to reduce E_s and to stop ex-field runoff. The IRWH system promotes rainfall runoff on a 2 m wide no-till strip between crop rows and collects the runoff water in basins where it infiltrates into the soil profile. IRWH has been proven to contain runoff from the soil surface, increasing plant available water and crop yields on smallholder farms in Thaba Nchu in the Free State Province of South Africa. The IRWH increased maize and sunflower yields by as much as 50% compared to conventional production systems on duplex soils (soils that have an abrupt textural change) in the Free State province of South Africa. However, despite the increase in crop yields, the researchers recorded high evaporation losses of water from the fields. Experiments at Glen in the Free State Province documented that improving PUE for maize and sunflower E_s must be reduced to improve yield stability. A continuing constraint for successful utilization of IRWH is excessive loss of soil water from the soil profile by evaporation. The influence of cowpea living mulch on soil evaporation has not been tested within IRWH systems. Interaction between IRWH technique and sunflower x cowpea intercrops has not received attention in South Africa. Knowledge on how cowpea affects water utilization and yield of sunflower under IRWH would be important in forming a scientific basis for recommending this practice to smallholder farmers who produce this legume usually in intercrop systems. It was hypothesized that (i) IRWH will increase crop yields compared to the conventional tillage (CON) system, and (ii) cowpea intercropped as living mulches with sunflower will increase water use (WU), water use efficiency (WUE), PUE and grain yield of sunflower. A number of separate studies were carried in order to test the hypotheses. The studies are presented in the form of chapters.

The relationships between soil water content (θ) and unsaturated hydraulic conductivity (K), commonly called K(θ) relationships, was determined using the internal drainage method (IDM) of Hillel et al. (1972). Soil water release curve (SWRC) ($h \leq 800$ mm water) was determined in the laboratory. Characterization of the field saturated (K_s) hydraulic conductivity as well as the unsaturated hydraulic conductivity of the University of Venda-Shortlands ecotope confirmed the existence of two diagnostic horizons, namely, the orthic A and structured B-horizon. Results from this study indicated that soil hydraulic properties were unique for each diagnostic horizon. The saturated hydraulic conductivity in the orthic A and structured B- horizons was 30 mm h^{-1} and 12 mm h^{-1}, respectively. The difference was largely attributed to the crumb microstructure observed in the orthic A-horizon. The results also showed that the University of Venda-Shortlands ecotope has good water retention properties as 19% of the water was released between saturation and 8 kPa. The study further indicated that the plant available water (PAW) in the root zone of 267 mm is very high and surpasses most of the soils tested for IRWH, making the University of Venda-Shortlands ecotope suitable for this production strategy.

An analysis of a long-term rainfall and climate data is important in assessing the feasibility of implementing water harvesting strategies on the ecotope. A long-term (1983-2005) rainfall record was analyzed (Chapter 3) in order to understand the rainfall pattern on the ecotope. The statistical analysis of rainfall data revealed that the annual rainfall was highly unreliable with a CV of 315%, thus making crop production risky. Soil water which is available for crop growth only for limited periods at the location can be lost by evaporation. Therefore, this pointed to the need for adopting water conservation techniques such as the IRWH. Further analysis of the rainfall record indicated that 50% of the monthly rainfall patterns during the cropping season (October to March) were best described by the lognormal theoretical distribution model, as observed in other semi-arid environments.

A field experiment was conducted to evaluate the performance of IRW technique using sunflower x cowpea intercrop (Chapter 4). The experiment was conducted during 2007/08 and 2008/09 cropping seasons. The experiment was configured as a split plot design with tillage treatments (IRWH and CON) as main plots and cropping system (sole sunflower, sole cowpea and sunflower x cowpea intercrop) as subplots. Results of this experiment indicated that that IRWH led to a significant sunflower grain yield in the second season. IRWH resulted in significantly higher water use (WU), water use efficiency (WUE) and precipitation use efficiency (PUE) of both crops compared to CON system in the second season. The results highlighted the importance of having a long-term tillage experiment in order to derive meaningful conclusions.

Runoff is an important water balance component in the semi-arid environment. The

IRWH partitions rainfall into runoff (on the no-till runoff strip) and run-on (in the basin). An experiment was conducted to determine rainfall-runoff relationships on the University of Venda-Shortlands ecotope using simulated rainfall (Chapter 5). Simulated rainfall is less time-consuming, less expensive and allowed for complete control of experimental conditions. This experiment demonstrated that IRWH production technique could harness an additional 45.5 m^3 ha^{-1} of water compared to the CON system. The extra water harvested could meet nearly 1% of maize water requirements.

In order to make reliable recommendation concerning the best production techniques for a crop on a particular ecotope it is desirable to have long-term yields. The crop models with long-term climate data achieve this objective. The last chapter (Chapter 6) combined data obtained from various chapters of this study in a simulation model in order to quantify long-term risk of IRWH production on the ecotope. The Crop Yield Prediction for Semi-arid Areas (CYP-SA) model was applied to simulate long-term (26 years) sunflower yield. Simulation scenarios included initial profile soil water content at planting: empty (0%), half (50%) and full (100%) of PAW. Planting dates (November, December and January) were the second scenario factor. Cumulated probability functions (CPF's) of long-term simulated yield have showed that IRWH was significantly better than CON at all levels of initial profile water contents. Results from this study further indicated that farmers who may use the IRWH technique when profile water content is empty can probably manage to get higher yields compared to those who choose the CON technique. The results from the simulation study confirmed results obtained from field experiments carried out on this ecotope during 2007/2008 and 2008/2009 cropping seasons.

7.2 Recommendations

The IRWH productivity was improved by using living mulches in an intercropping design. This study therefore formed a strong basis for the implementation of the IRWH production technique on this ecotopes. Future studies on IRWH systems on this ecotope may focus on the following:

- Long-term evaluation of IRWH system using different living mulches.
- Strict monitoring of E_s within the IRWH systems.
- More accurate DUL determination involving measurement of the SWRC up to 15 bar tension and then applying a statistical procedure to characterize the pore-size distribution of the Shortlands soil, thus filling the knowledge gap. The statistical procedure has been applied successfully on Bonhein soil (Nhlabatsi, 2010).
- Smallholder farmer participation from the project inception stages may help to instill some interest in the technology.

APPENDIX

Appendix Table 1 Calibration equations for the soil water meter for different soil layers at the University of Venda-Shortlands ecotope. Equations are in terms of volumetric water content (θv, $m^3\ m^{-3}$) and count ratio (C_R)

Depth (mm)	Equation	N	RMSE	R^2
0-300	$\Theta v = 0.48991(C_R) - 0.3262$	30	0.009	0.9976
300-1200	$\Theta v = 0.2842(C_R) - 0.0401$	90	0.032	0.9212
1200-1500	$\Theta v = 0.6331\ (C_R) - 0.5077$	30	0.0180.018	0.9562

RMSE is root mean square error; N is the number of samples in the regression analysis