ENHANCING WATER USE EFFICIENCY OF CASSAVA AND SORGHUM BASED CROPPING SYSTEMS IN EASTERN UGANDA

ROBERT MULEBEKE

A thesis submitted in partial fulfilment of the requirements for award of Doctor of Philosophy Degree in Dryland Resources Management of University of Nairobi

Faculty of Agriculture
University of Nairobi

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DECLARATION

I hereby certify that, to the best of my knowledge and belief, the material presented in this thesis entitled "*enhancing water use efficiency of cassava and sorghum based cropping systems in eastern Uganda*" is my original work and has never been submitted to any university or institution for award of a degree or diploma, except where due reference has been indicated to such published works.

22/11/11

Robert Mulebeke

APPROVAL SHEET

This thesis entitled "***Enhancing water use efficiency of cassava and sorghum based cropping systems in eastern Uganda***" has been submitted with our approval as academic supervisors.

Sign________________ Date 22/11/11

Dr G. Kironchi
Department of Land Resource Management and Agricultural Technology,
University of Nairobi,
P.O. Box 29053-00625, Nairobi, Kenya.
Email: goekironchi@uonbi.ac.ke

Sign ________________ Date 22/Nov/2011

Prof. M.M. Tenywa
Department of Agricultural Production,
Makerere University
P.O. Box 7062, Kampala, Uganda.
Email: tenywamakooma@yahoo.com

DEDICATION

To the intellectual giants who offered their shoulders to prop me so that I could see this far.

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"Nothing succeeds like success" (Sir Arthur Helps, 1868)

This achievement is built on the successes of persons and organizations I interfaced with during this academic journey. The Rockefeller Foundation offered me the scholarship, through the Regional Universities Forum on Agricultural Resource Husbandry (RUFORUM) to pursue a doctoral programme at the University of Nairobi. The competitive research grant (W/4652-1) from the International Foundation for Science (IFS) kick started this study and I appreciate the additional exposure to the scientific tenets of water resource management.

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Finally, I am conscious of the priceless time I denied my family during the study.

May the Lord God who has blessed me with this wisdom bless all of you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

A/DAO	Assistant District Agricultural Officer
CA	Conservation Agriculture
CAADP	Comprehensive Africa Agricultural Development Programme
CLL	Crop Lower Limit
DAO	District Agricultural Officer
DUL	Drained Upper Limit
ET	Evapotranspiration
ETa	Actual Evapotranspiration
ETc	Reference Crop Evapotranspiration
FAO	Food and Agricultural Organization of the United Nations
FC	Field Capacity
IFPRI	International Food Policy and Research Institute
IWRM	Integrated Water Resource Management
MDGs	Millennium Development Goals
NARO	National Agricultural Organization of Uganda
NaSARRI	National Semi-Arid Resources Research Institute of Uganda
NEPAD	New Partnership for Africa's Development
PAW	Plant Available Water
PSE	Precipitation Storage Efficiency
PUE	Precipitation Use Efficiency
PWP	Permanent Wilting Point
SOM	Soil Organic Matter
SSR	Soil Surface Roughness
SWM	Soil Water Management
WAP	Weeks After Planting
WOCAT	World Overview of Conservation Approaches and Technologies
WUE	Water Use Efficiency

ABSTRACT

Water flow and storage within the root zone constrains water availability and use in rain-fed crop production, especially in the dryland cropping systems, where farmers are resource-strained and are not motivated to practice soil and water management. A study was carried out in eastern Uganda (34^0 0' E and 1^0 40' N) to: a) evaluate the effect of tillage and cropping systems on soil water storage, b) establish the water use efficiency in cassava-sorghum based cropping systems, c) examine the farmers' perceptions and understanding of soil moisture availability and establish whether knowledge/competences on soil moisture availability is used in planning cropping cycles in the cassava-sorghum cropping systems.

A field experiment was laid out in a randomised complete block design (RCBD) consisting of two tillage practices (mouldboard ploughing and ripping) and six cropping systems; i.e. i) sole cassava, ii) sole sorghum, iii) sole cowpea, iv) cassava + sorghum, v) cassava +cowpea, vi) sorghum + cowpea comprised the treatments and were replicated three times. Soil surface roughness was measured immediately after ploughing and two months later. Soil moisture content was measured fortnightly at 0-10 and 20-40cm depths. Evapotranspiration (ET) was estimated using the soil water balance approach. Yield of each crop was recorded at the end of each growing period. Water use efficiency (WUE) (kg ha^{-1} mm^{-1}) was calculated as a ratio of yield (kg ha^{-1}) to ET (mm). A household-level survey was designed to collect responses on household, production and field management characteristics and, knowledge on soil and water management in the cassava-sorghum cropping systems.

Soil moisture content was higher under ripping than mouldboard ploughing but, the upper (0-10cm) layer had more moisture under mouldboard ploughing, while ripping accumulated more moisture in the lower (20-40cm) layer of the root zone. Soil surface roughness did not differ two months after mouldboard ploughing giving rise to a relatively negligible surface runoff. Water use efficiency (WUE) varied significantly (α= 0.05) between cropping systems with the highest observed in cassava (34.38kg ha^{-1} mm^{-1}) while the lowest was 3.76kg ha^{-1} mm^{-1} for sorghum. In both tillage practices WUE did not differ appreciably. Also, ET varied (α= 0.05) between cropping systems but was similar in both mouldboard and ripper ploughed plots. Cassava + cowpea intercrop under mouldboard ploughing gave the best cassava yield (20,023 kg ha^{-1}), however tillage practice did not significantly (α = 0.05) affect the yield in sole cassava treatments. Cowpea yield was higher (8,397 kg ha^{-1}) under mouldboard ploughing than ripper ploughing (5,771 kg ha^{-1}). Sorghum yield was highest (1679 kg ha^{-1}) under ripper ploughing while the lowest was observed in sorghum + cowpea intercrop under mouldboard ploughing. The change in soil moisture content was more negative in the mouldboard ploughed plots than in ripped plots specifically for sole cassava (-4.215 mm) cassava + cowpea (-4.736 mm). The household is a major source of labour for the cassava and sorghum farms with 53.8 % of the households offering 4-6 persons to work on the farms. Up to 28% of the households did not offer any one for off-farm labour. Labour and knowledge at household level was used to manage the land and most households derived their livelihood from exploiting land. Up to 65 and 59% of the farmers allocated a quarter of their land to sorghum and cassava respectively. Farmers viewed soil and water management to have long term benefits, reduce soil erosion, and likely to increase yields on the farm. Farmers' positively exploited their competence in using crop rotation plans, selecting the right seed and evaluating the soil fertility status on field. However, the competence in detecting water stress in crops and altering crop spacing to manage soil moisture was not utilized when planning cassava-sorghum cropping cycles.

CHAPTER ONE

GENERAL INTRODUCTION

1.1 BACKGROUND TO THE STUDY

Soil moisture is a major limiting factor in agricultural production affecting crop growth, development and productivity, especially in the water-scarce regions (Ali and Talukder, 2008; Bossio *et al.*, 2008). Water use efficiency as a tool for integrated water resource management in rain-fed agriculture takes into account the soil water balance and yield components (bio-physical) but, also greatly relies on the farmers' perception (social) of soil and water management in dryland cropping systems. The food and livelihood security condition in the drylands of sub Saharan Africa is under threat with a food energy deficiency occurrence ranging between 37 % in Uganda and 76% in Ethiopia (IFPRI, 2009). This food insecurity condition is heavily blamed on low productivity related to rainfall regimes (climate factor) which drive the soil moisture deficits (Boko *et al.*, 2007). Over all, sustainable water resource management is unlikely as the region is projected to experience less and even more erratic rainfall (Rijsberman, 2006) and even reach water scarcity conditions (< 1000 m^3 per capita per annum) by 2025 (Inocencio *et al.*, 2003; Ngigi, 2009) which, directly degrades the soil moisture status.

Much as agricultural water use efficiency can improve from 0.6 kg per m^3 in rainfed crops to 1 kg per m^3 in irrigated crops (FAO, 2003), irrigation agriculture is projected to increase the demand for fresh water in the region by 14%. (FAO-NEPAD/CAADP, 2004). On the contrary, IFPRI, (2002) reported that a meagre 4% increase will be achieved in the developing world as water sources are affected by climate change and variability. Therefore, if the capacity to manage the available rain and water in the soil system is enhanced then the harmful effects of low rainfall can be greatly minimised.

Under such circumstances, rain-fed agriculture remains the most plausible option for improving food production as well as meet the Millennium Development Goals (MDGs) in sub Saharan Africa (Cooper *et al.*, 2008). Indeed there is a campaign to: increase water use efficiency and land productivity; continue efforts to explore ways to "*grow more food with fewer drops*" under sustainable conditions through research and development, capacity building and spread of technology (ICID, 2005). Specifically, over 60% of cereals are reported to be produced under rain-fed crop production systems (Boko *et al.*, 2007). It is also estimated that improvements in rain-fed production systems can provide up to 50% more produce than improvements done in irrigated systems. Farmers in the drylands are constrained not only by biophysical factors but also, socio-economic factors like; being resource-poor and lacking the incentive to improve water use efficiency in agricultural production (Abbate *et al.*, 2004) as well as the motivation to conserve water (Hsiao *et al.*, 2007). Therefore efforts by national and international programmes to introduce, adopt, and adapt integrated water resource management concepts (Snellen and Schrevel, 2004) in agriculture for both household and watershed development impracticable. Additionally, vulnerability and/or resistance of households to climate change and variability challenges depend on their understanding and perception of the problem, which is a theory in social and ecological resilience (Rockström, 2003). These farmers' livelihoods are intricate and dynamic in nature mostly due to differences in production decisions they make which are dependent on the household characteristics (Shiferaw *et al.*, 2007) and level of knowledge available to them (Salam *et al.*, 2005). Much as several biotic, abiotic, and social factors affect crop production, greater value is placed on local knowledge systems. Farmers are the ultimate users of soil and water resources, their understanding and perception of the soil moisture phenomenon is critical in agricultural production decision processes, shaping farmers' behavior, and determining sustainability of the system.

Therefore there is need to have a good understanding of the effects of tillage and cropping systems on water use efficiency and reflect on how variations in climate are likely to affect the soil moisture regime in dryland cropping systems. Figure 1.1 describes the conceptual framework for contributing to food and livelihood security as well as sustainable water resource management through enhancing water use efficiency in the cassava-sorghum based cropping systems of eastern Uganda.

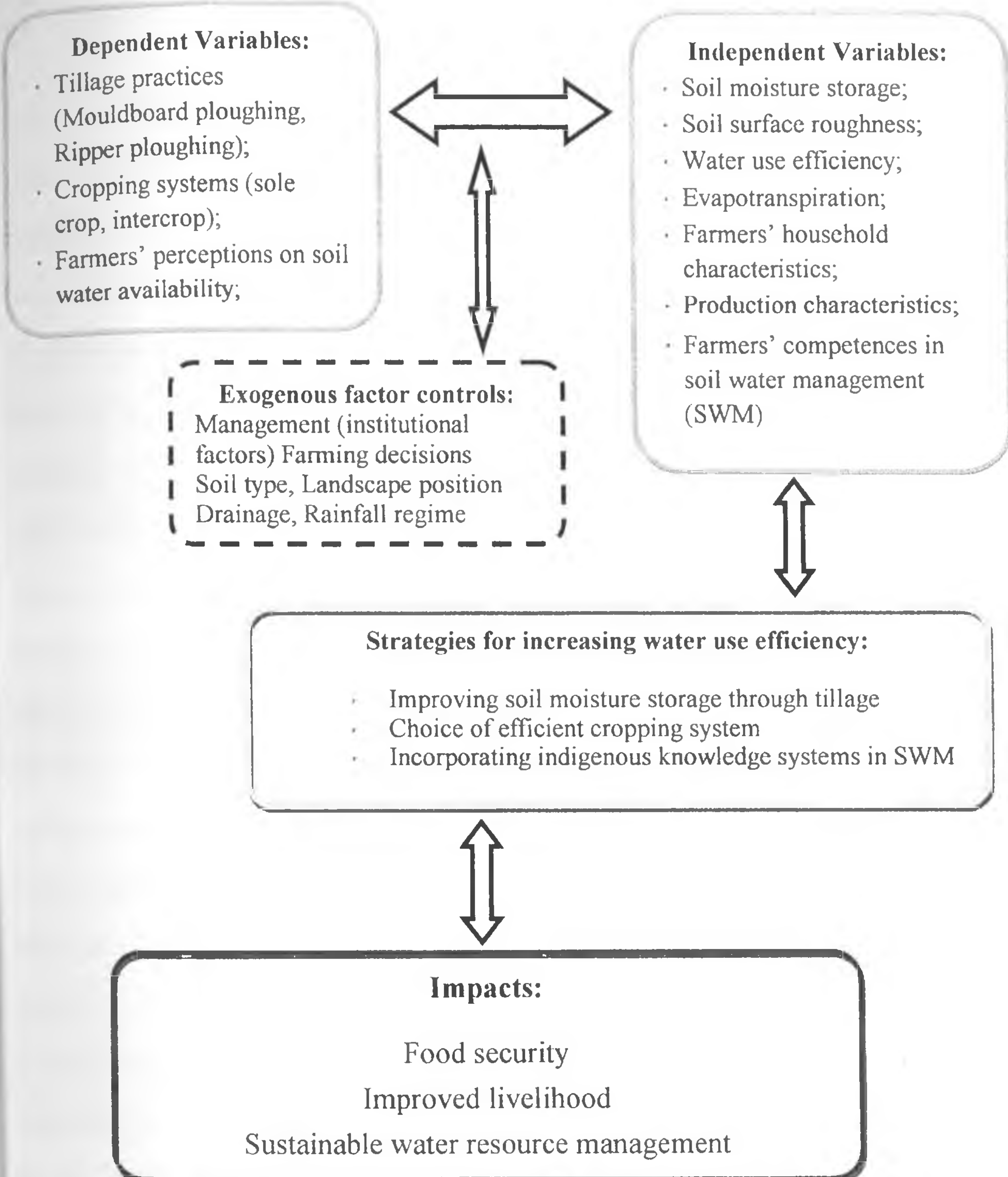


Figure 1.1 Conceptualising the agricultural water resource management problem for the cassava-sorghum based cropping systems in the drylands of eastern Uganda.

1.2 DEFINITIONS AND CONCEPTS

1.2.1 Water availability for agriculture

Water availability, a concept involving the flow of water through an agricultural system, is dependent on the biophysical characteristics as well as institutional and economic factors that control its use. Also, water availability is directly proportional to agricultural production, which is a function of soil moisture storage capacity (Bouman, 2007) especially for rainfed agricultural systems in sub Saharan Africa. The spatial and temporal variation in soil moisture storage across agroecological zones is further complicated by climate variability in terms of droughts, floods (IPCC, 2007) and the unsuitable agricultural water management practices. Much as several scholars have defined water productivity and water use as a ratio of agricultural produce to water used in the production process (Rockström *et al.*, 2003; Bouman, 2007; Ali and Talukuder, 2008; Ngigi, 2009), strategies to improve agricultural productivity will have to consider new technologies, water use efficiency, change in institutional structures and economic feasibility of available water for agriculture. Agriculture, by far the world's number one user of water, defines water availability in terms of two intricately related phenomena i.e. 1) meteorological drought- when the rainfall amount is below the minimum required to generate fundamental ecosystem services, 2) agricultural drought- when the soil moisture available in the root zone is not enough to support plant growth (Dracup, *et al.*, 1980) These phenomena impact on the soil-plant-atmosphere inter-relationships that are responsible for food production and human wellbeing (Cooley, 2006). Generally, drought is a balance between rainfall (amount and distribution), evapotranspiration (actual and potential) and soil moisture characteristics (retention, hydraulic conductivity). Since water used for agriculture primarily originates from rainfall, it is partitioned, processed then, made available to the plants through the soil system.

1.2.2 *Rainwater partitioning*

Dryland ecosystems are known to strongly depend on the water cycle for their functioning. Rainfall received at any site is processed and partitioned (Figure 1.2) into; 1) "green water" (water stored in the soil and/or used by plants for growth then lost through evapotranspiration) found in rain-fed agriculture and natural ecosystems, 2) "blue water" (water that runs off or drains through the soil) which constitutes the renewable water supply for downstream and/or groundwater users including domestic, irrigation, livestock, wildlife, industry and aquatic ecosystems (Rockström, *et al.*, 1999; UNESCO-WWAP, 2003; Rijsberman and Manning, 2006), but may be lost through flooding. In a sorghum crop grown in modified lysimeters in north-eastern Uganda, evapotranspiration was reported to be over 60% of the rainfall received more so, losses of up to 100 and 200% of the soil moisture to evapotranspiration were observed during the crops' vegetative and flowering stages respectively (Kizito, 2004). This indicates that it is the moisture stored in the root zone before the particular crop stage that can satisfy the crop water requirement during through the crop growth cycle. Therefore it is envisaged that synchronising the critical crop growth stages and crop water requirement to soil moisture availability will enhance the crop water use efficiency of the cassava and sorghum cropping systems in the drylands of eastern Uganda.

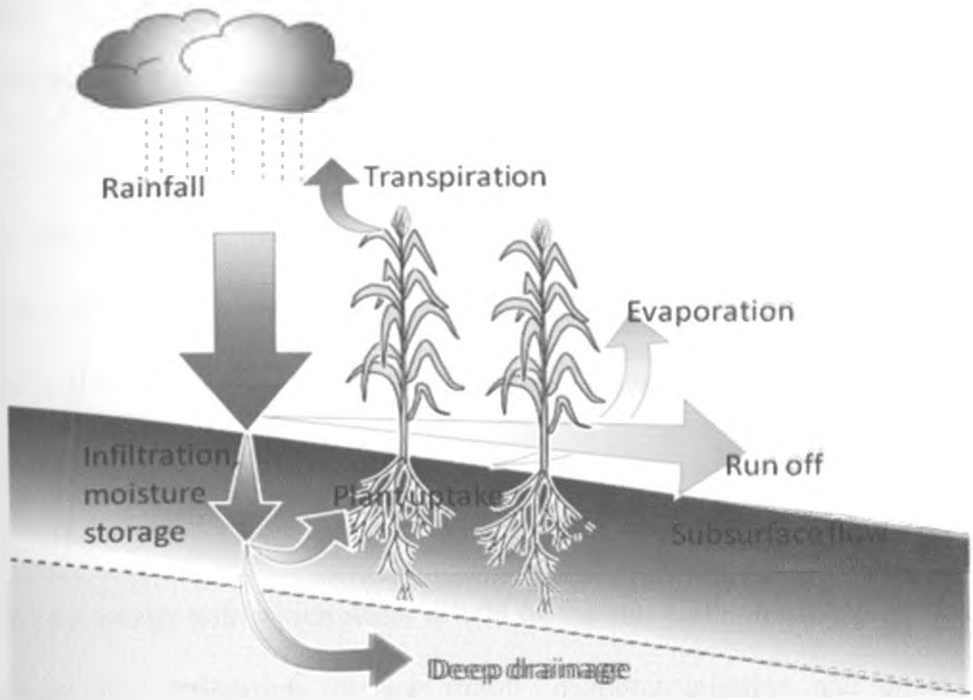


Figure 1.2 Schematic representation of rainfall partitioning in agricultural ecosystems (adapted from Rockström *et al.*, 2003)

1.2.3 Soil water content and potential

The soil system (void space) offers the reservoir in which water is made available for use by the crops. Soil water (moisture) content has been defined as the amount of water in a unit volume of soil, often expressed as volumetric water content (θ) i.e. the depth ratio of soil water;

$$\theta = \frac{V_w}{V_s} \qquad (1.1)$$

where; V_w = volume of water

V_s = volume of soil (Hillel, 1980).

This soil moisture content (θ) is intricately related to the basic physical parameters of the soil i.e., matric potential (ψ_m) and porosity (ε), which are a function of bulk density (ρ_b), particle density, (ρ_p) and hydraulic conductivity, ($K_{(\theta)}$). Since the physical parameters across the soil profile cannot be changed, there is need to understand the behavior of soil moisture content within a root zone defined by the different soil surface management and cropping systems.

The concept of soil water potential helps to estimate the amount of work the plant must expend to extract a unit amount of water from the soil. This quantity, expressed as absolute values of pressure head, $|h|$, describes the plant available water (PAW), and is often used to derive the vertical flux across different soil layers (soil depths) basing on a classical principle of physics, the '*law of conservation of mass*' (Hillel, 1980).

The amount and energy with which water is held on the soil matrix determines the magnitude of such processes like infiltration, surface runoff, evapotranspiration and consequently crop performance during the growing season. In the soil, water moves constantly in the direction of decreasing potential energy, since the crop water requirement is a factor in this quantity, then cropping systems are envisaged to influence the magnitude of water extraction from the soil system.

1.2.3.1 Flow of water in the soil

Soil is a porous medium where water flows in either saturated or unsaturated form and is dependent on pressure distribution within the soil profile following the principles described by Darcy in 1830. Darcy observed that the volumetric flow rate through a sand column was directly proportional to the column's cross-sectional area and its pressure head difference ($h_1 - h_2 = \Delta h$), and inversely proportional to the length of the sand column. Darcy defines flow rate as

$$Q = K.A\frac{\Delta h}{L}, \qquad (1.2)$$

where; Q is the flow rate (m^3s^{-1})

K is the hydraulic conductivity ($m\ s^{-1}$)

A is the cross-sectional area of the column (m^2)

Δh is the head loss (m)

L is the length of the column (m)

However, Bos (2006) notes that, Q/A (discharge per unit area) is not the actual velocity at which water moves through the soil pores in the unsaturated soil system hence, K (also referred to as 'proportionality coefficient') and porosity are important parameters in calculating the actual flow velocity, V_m = Q/A. In this context, water flow in dryland ecosystems is majorly governed by unsaturated hydraulic conductivity, K, which is a function of soil water content, θ, and the pressure head, h, giving the expression

$$\theta = f(h) \qquad (1.3)$$

However, the pressure head, h, is dependent on the depth of the point of interest to the point of reference within the different soil layers and time, sometimes referred to as boundary conditions. In this case h is a function of depth, z, and time, t. i.e. $h(z,t=0)=h_0$ is the initial condition at the soil surface where z = 0 at t = 0. This is the quantity described as Δh in Darcy's law (Equation 1.2). Similarly, the total water potential on a weight basis (ψ_t) is equivalent to the total pressure head (h_t). When we denote h_t as H (hydraulic head) then, $H = h_m + z$ where, z is the elevation head. The direction and magnitude of water movement can then be determined by the difference in heads. For instance, in a profile where the water table position is the reference level, $-\partial H/\partial z = 0$, no flow is observed, and when there is a change in this pressure head (h) the soil water content (θ) will change in a relationship called the ' soil-water retention curve'.

1.2.3.2 Factors influencing soil water content

The soil system as a reservoir of water is a factor of soil characteristics like; soil texture, organic matter content, soil aggregation, and evapotranspiration (Hillel, 1998) as well as climate and crop factors. Fine-textured clay soils have a greater total volume of pores than coarse-textured sands, with the majority of those pores being very small in size, so water does not move through quickly, and more water can be stored. The majority of soils in eastern Uganda are sandy, capable of quickly moving water but, low storage capacity.

Soil organic matter (SOM) enhances the soil's ability to retain moisture by improving soil aggregation, resulting in increased pore space. Soil organic matter physically and chemically binds the primary particles in the aggregate which in turn increases the stability of the aggregate and limits its breakdown during the wetting process (Craswell and Lefroy, 2001). Decrease in SOM translates to adverse effects like crusting, compaction, poor aeration, water logging, structural degradation, and low biotic activity (Troeh *et al.,* 1999). Soils with low aggregate stability are more susceptible to degradation (Diaz-Zorita *et al* 2002) such as seal formation resulting from raindrop impact, leading to lower infiltration rates.

The amount of water extracted from the soil and through the plants by the evapotranspiration process is dependent on the amount of water stored in the soil (Hillel, 1998). Evapotranspiration is a direct pathway for water movement from the soil to the atmosphere and is primarily influenced by the energy available for evaporation and the crop's ability to meet the atmospheric demand.

1.2.4 Plant available water (PAW)

Soil water that is readily available to plants referred to as 'plant available water' is determined by the ability of the soil to retain water. PAW is held in the soil profile between the drained upper limit (DUL) and the crop lower limit (CLL) at matric potentials 2.0 pF and 4.2 pF respectively. According to the classical principles of soil physics, PAW is the water held between field capacity (FC) and permanent wilting point (PWP) (Hillel, 1980). The PAW is a function of the effective rooting depth and also determines the actual quantity of water extracted by the plant from the soil profile.

The DUL and CLL values are often taken from the laboratory or in the field. Common laboratory techniques used to estimate DUL include equilibration of pre-saturated soils with a centrifugal force (gravity x 1000) or with a matric suction value of 10 or 33 kPa (Ritzema, 2006). However, the soil's upper water holding limits derived from laboratory methods often ignore several variables that influence field conditions such as: soil profile heterogeneity, preferential water flow, soil surface evaporation and plant uptake during drainage, root distribution, and plant species. The filed technique involves measuring the water content of a soil after it has been thoroughly wetted and allowed to drain until drainage has become practically negligible, i.e. when the soil moisture content is described as being at field capacity. The CLL is easily estimated following the lowest volumetric water content measured from a soil when plants are showing water stress because they have stopped extracting water as a result of water deficit. For laboratory estimation of CLL, a suction of 1500 kPa is subjected to soil samples and the remaining soil water content measured. For this study field-measured values were used to define the amount of water available to plants in the root zone.

1.2.5 Evapotranspiration

1.2.5.1 Reference crop evapotranspiration (ETc)

Following reviews and standardizations of the Penman-Monteith (1965) equation, ETc is defined as 'the rate of ET from a hypothetical crop with an assumed crop height (12 cm), and a fixed canopy resistance (70s/m), and a canopy reflection coefficient of 0.23, which would closely resemble ET from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground, and not short of water' (Smith, 1990 as quoted by Ritzema, 2006). For purposes of management of crop water requirement, the term crop ET is adopted and is defined as 'the evapotranspiration from a disease-free, well-fertilized crop, under optimum soil water conditions, and achieving full production under the given climatic conditions' (Allen *et al.*, 1998). Where crop and soil factors are not limiting, the evaporating power of the atmosphere at a specific location and time of the year is considered. In dryland ecosystems, the soil surface cover in terms of crop canopy and the soil moisture availability drive the ET process. The Penman-Monteith equation is derived from a combination of water and energy balance parameters like, daily temperature, humidity, solar radiation and wind speed, which need to be adjusted to local conditions. Thus for this study, where specific meteorological data was not available, the water balance approach using the mass transfer principles was adopted to derive actual evapotranspiration.

1.2.5.2 Actual evapotranspiration (ETa)

The soil water balance accounts for the incoming and outgoing moisture flux of a soil unit (root zone) over a period of time, usually the growing period (Ritzema, 2006) following one of the classical laws of physics - *conservation of mass*. The soil water balance parameters have been used by several scholars (Angus and van Herwaarden, 2001; Abbate *et al.*, 2004; Benli *et al.*, 2006; Bodner *et al.*, 2007), to derive *ETa*. The model can be easily manipulated where meteorological data is not available to run the original Penman–Monteith water balance model (Van Vosselen *et al.*, 2005). The equation reads;

$$\Delta S = P + I - RO + CP + \Delta SF - DP - ET \qquad (1.5)$$

where: ΔS is the changes in soil water storage within the root zone (mm);

P is precipitation (mm);

I is irrigation (mm);

RO *is* loss due to surface runoff (mm);

CP is capillary rise from the bottom horizon below the root zone (mm);

ΔSF is the change in horizontal sub surface flow within the root zone (mm);

DP is deep percolation across the lower boundary of the root zone (mm);

ET is evapotranspiration (mm)

It was not possible to estimate CP and DP properly however, the quantity, CP, is negligible since, there is no groundwater within reach of the root zone. Subsurface flow into (SF_i) and out (SF_o) of the plot are equal, mainly due to a small slope gradient (< 3%) in the study plots, therefore $\Delta SF = 0$. RO was negligible due to the infiltration capacity and surface condition (roughness) of the soil coupled with the low slope gradient. This is a rain-fed cropping system where irrigation is absent hence, I = 0. Also, water moves very slowly in the soil, the time of measurement is usually 7, 10, 15 or 30 day intervals. When soil moisture content, θ, and at known depths, z, at fixed times are available then soil moisture storage, S, is estimated by numerical integration. In this study, three basic parameters; P, ΔS and DP are measured, then used to derive ETa following the expression

$$ETa = P - DP - \Delta S \tag{1.6}$$

1.2.6 Soil surface roughness and runoff in agricultural land

Soil surface roughness (SSR), a micro-topographic variation in soil surface elevation, influences the rate of soil erosion and runoff generated from agricultural land. Literature indicates that in agricultural ecosystems, tillage and rainfall heavily impact on the surface micro-relief (Gilley and Kottwitz, 1995; Kamphorst *et al.*, 2000). Also, SSR can be used to predict water infiltration, surface runoff, wind and water erosion (Moreno *et al.*, 2008) as a function of aggregate size distribution and depressional storage.

Random roughness (RR) parameters for expressing soil micro-relief by taking point elevations of the surface developed by Allmaras and others as reported by Gilley and Kottwitz (1995) have been extensively used.

$$RR = s.\bar{h} \tag{1.6}$$

where s, is the standard error of the natural logarithm of 400 pin-height readings (adjusted for slope and tillage marks) and,

$\bar{h}$ is the mean of height elements.

Several tools have been developed for taking micro-relief measurements of which, the pin-meter technique based on principles initiated by Kuipers as reported by Gilley and Kottwitz (1995); Okwach, (2004); Moreno *et al.*, (2008) has been widely used. This study adopted the method of measurement described by Okwach, 2004 (the same pin-meter used by Okwach, 2004 was taken to the Soroti study site for this study).

In addition runoff, a major sub process in surface hydrology, determines soil moisture availability in most agricultural ecosystems. This surface runoff is only expected to occur when rainfall rate exceeds infiltration capacity of the soil (Beven, 2004). Also basing on Horton's papers (1933) on the infiltration process, the infiltration capacity of any soil may greatly exceed the interior body of soil if the soil surface has recently been loosened by cultivation or opened by drying. The runoff process is driven by both meteorological and edaphic factors occurring at field and watershed scale, but more closely associated with the nature of precipitation, evaporation and infiltration rate. Precisely, the volume and energy of runoff is a function of landscape position, soil surface roughness, antecedent soil moisture content, moisture storage capacity, and surface cover characteristics. These factors, in addition to subsurface hydraulic properties may influence the surface runoff yield. In water-limited agricultural systems, reduction of surface runoff can increase water uptake by plants (Guswa, 2005) and water use efficiency in cropping systems. Andales *et al.*, (2007) investigated temporal relationships between grain yield, soil water content, and topographic position on a dryland catena in eastern Colorado, USA, and observed landscape position to significantly affect the soil condition, water availability, and yield. This therefore, infers that runoff flow paths which are dependent on soil surface roughness are more predictable downslope. Where natural topographic depressions occur, most of the runoff is captured and infiltrates long after the rainfall event has ceased. Similarly, in a highly dissected landscape in central Uganda, land use in terms of surface cover gave stronger influence on soil loss and runoff than slope gradient (Mulebeke, 2004).

The slope gradient at the study site was characterized as class I (1-2%), hence runoff generated due to slope is negligible. Surface runoff is only expected to occur when rainfall rate exceeds the infiltration capacity of the soil (Beven, 2004). Also, basing on Horton's papers on the infiltration process, infiltration capacity may be influenced by the soil surface conditions especially when macro pores have been loosened by cultivation or opened up by drying and crusting. Furthermore, it is known that tillage management practices provide a soil surface roughness that encourages depressional water storage (Moreno *et al.*, 2008) hence, runoff is easily transformed into run-on even at field scale. Furthermore, the sandy nature of the upper 0-20cm layer of the profile allows for infiltration of most of the rain received. For this study, surface runoff was regarded to have minimal contribution to the water balance.

1.2.7 Water use efficiency (WUE) concept

Water use efficiency (WUE) is a concept in water balance studies that relates water supply to crop productivity. It is often used to assess agricultural water productivity in biophysical and socio-economic terms. WUE can be defined at different scales i.e. crop scale (transpiration efficiency)- a ratio of CO_2 assimilation rate to the transpiration rate; field scale (growth WUE)- biomass (dry matter) synthesized per unit of water lost and; ecosystem scale (crop WUE)- dry weight gain by plants (yield) per unit land to millimeters of water lost during evaporation and transpiration (Condon *et al.*, 2002; Nielsen *et al.*, 2005; Morison *et al.*, 2008; Hu *et al.*, 2010). Further still, to increase WUE especially in rain-fed dryland systems, a number of methods have been suggested at different levels. i.e. precipitation storage efficiency (PSE) as influenced by soil surface characteristics; WUE as a function of crop type and harvestable part; precipitation use efficiency (PUE) as influenced by cropping system (Nielsen et al., 2005). Similarly, WUE is used to describe the agronomic performance of a crop and is interchangeably used to describe crop water use index, i.e. a ratio of yield or economic return to crop evapotranspiration (Bouman, 2007; Arafa *et al.,* 2009). As farmers get exposed to water management strategies at farm, household, and watershed level (Cooper *et al.*, 2008) complexities and contradictions in the WUE concept arise. Since this study focuses on cropping systems performance, WUE as a ratio of yield (Y) to actual evapotranspiration (ETa) will be adopted (Xu and Hsiao, 2004; Hsiao *et al.* 2007).

1.2.8 Farmers' perceptions on soil moisture availability

Farmers in drylands have been exposed to several soil and water conservation technologies however, the incentive to improve water use efficiency is increasingly being put on socio-economic factors (Abbate *et al.*, 2004). A review of past research by Knowler and Bradshaw (2007), on farmers' adoption of conservation agriculture indicated that there is hardly any universal variable that can explain adoption of conservation agriculture. We agree that farmers' do host and generate knowledge within their social linkages and ecological settings which directs their actions and determines sustainability of a system (Rahman, 2003) in what is referred to as social and ecological resilience (Rocksröm, 2003). Perception, as a concept, guides and conditions farmers' behaviour, and/or decision making processes but is strengthened by availability and access to specified information. Whereas, adaptation principles refer to adjustment in natural or human systems in response to actual or expected stimuli or their effects, a good understanding of the system in which one operates is important in order to reduce harmful effects and exploit beneficial opportunities. The most relevant factors that can influence the decision making process are: Farmer characteristics- gender, education, age, experience; Farm structure- farm size, soil type, inputs, machinery; Farm management characteristics- input use, crop diversification, field practices; Exogenous factors- Institutional factors output and input prices, market size, subsidies, information access, transaction costs, policy; and Attitudes and opinions- farmer beliefs, acceptance, life style, health and environmental preoccupations (Knowler and Bradshaw, 2007). The decision making process is guided by the individual's competences, for instance in study of Kenyan farmers' knowledge and their perceptions of soil erosion and soil conservation measures by Okoba and De Graaff (2005) farmers based their classification of farm-types or land managers individual attitudes and practices in land management rather than on wealth or problem oriented aspects. Therefore, the farmers' perceptions (decision making) and understanding of soil moisture availability through a growing period or year could be exploited to improve water use efficiency in the drylands of eastern Uganda.

1.3 PROBLEM STATEMENT

Soil moisture flow is closely related to availability of water for crop production (Van de Giesen, 2005) and there is a possibility to increase the yields significantly through improved water management in a watershed (Kauffman *et al.*, 2005). Lack of accurate information on crop water requirements vis-à-vis the sources (water balance components) is a major constraint in planning agricultural systems that are efficient users of available water yet, it is a pre-requisite for assessing water productivity (Abbate, *et al.*, 2004, Boko *et al.*, 2007). It is also clear that farming decisions that facilitate soil moisture availability can positively influence crop production but, this depends on the farmers' knowledge and perceptions on soil moisture availability in a particular cropping system. Therefore there is need to determine the interaction of farmers' perceptions (decision making) with soil moisture conditions when planning and implementing cropping systems in drylands. This study evaluates the effects of; a) tillage practices and cropping systems on soil water storage, b) tillage practices and cropping systems on water use efficiency c) examine the farmers' perception, level of knowledge and understanding of soil moisture availability and establish whether soil moisture availability is a factor in their decision making when planning and implementing operations in the cassava-sorghum cropping system in eastern Uganda.

1.4 OBJECTIVES

1.4.1 Overall objective

To improve soil water storage and water use efficiency in cassava-sorghum based cropping systems in eastern Uganda.

1.4.2 Specific objectives

The following are the specific objectives of the study:

- Evaluate the effectiveness of minimum tillage in enhancing the soil moisture storage and yields in cassava and sorghum based cropping systems.
- Determine the water use efficiency in cassava and sorghum based cropping systems.
- To determine farmers' level of knowledge and perception on soil moisture availability and whether the knowledge on soil moisture availability is a factor in planning cropping cycles in the cassava and sorghum cropping system.

1.5 RESEARCH QUESTIONS

- Does soil moisture storage vary between cassava and sorghum based cropping systems?
- Does ripping increase soil moisture storage in the cassava and sorghum based cropping systems?
- What is the water use efficiency in the cassava and sorghum based cropping systems?
- Do household characteristics influence soil water management in the cassava-sorghum based farming systems?
- Does the knowledge (views and competences) on soil moisture availability affect adoption of efficient water use technologies in cassava sorghum cropping systems?
- Is knowledge of soil moisture availability a major factor in planning a cropping cycle in the cassava-sorghum cropping system?

1.6 STUDY AREA DESCRIPTION

1.6.1 Location

The study was located in eastern Uganda (34^0 0' E and 1^0 40' N) in the Usuk sandy farm-grasslands agroecological zone (Wortman and Eledu, 1999) found in the greater Teso farming system. The Teso farming system comprises of the districts of Soroti, Amuria, Katakwi, and Kumi (*Fig 1.2)* and is predominantly an agropastoral system (Parsons, 1960). The Teso system lies at approximately 1036 and 1127m above sea level.

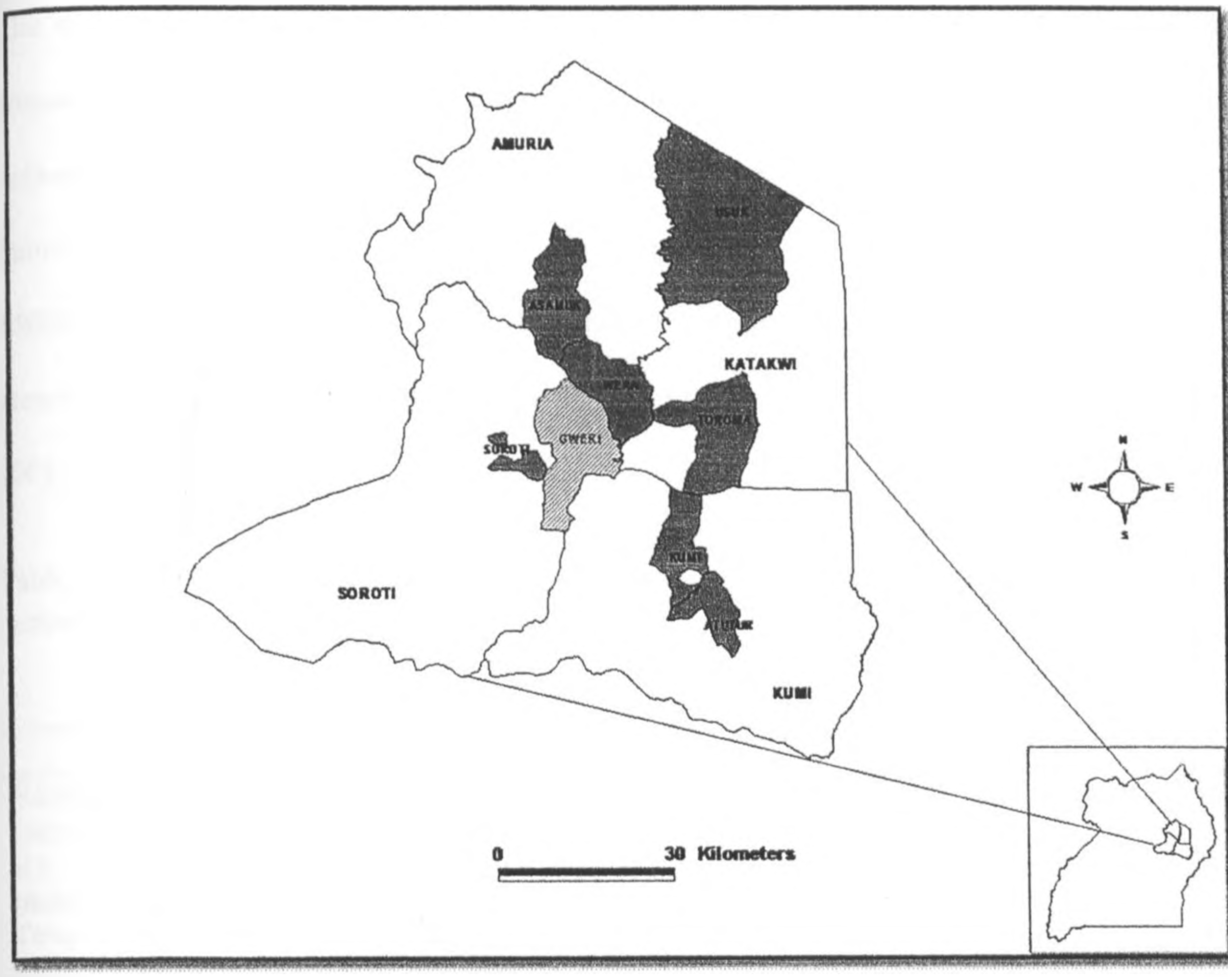


Figure 1.3 Map of the Teso region in eastern Uganda showing the Districts of Amuria, Katakwi, Kumi and Soroti including the experimental site (Gweri Village) and the survey locations.

1.6.2 Climate

The area experiences bimodal rainfall where the long rain season is usually from mid-March to June and the short rain season is from August to November. There is a short dry spell between the two rain seasons i.e. mid June – mid July, however areas bordering northeast experience earlier dry seasons. The seasonal mean precipitation ranges between 650 and 900 mm, but up to 25-30% of the precipitation is received outside the annual growing period (Kayizzi *et al.*, 2007).

The mean annual maxima and minima temperature is 31.3^0 C and 18^0C respectively with an annual mean of 24^0C. Extreme temperatures of approximately 35^0C are common in the month of February. Potential ET is higher than precipitation for most part of the year (Table 1.1). Relative humidity ranges from 66% to 83% at 0900hours East African time and 35% to 57% at 1500hours, thereby reducing chances of rainfall. This condition is expected to support crop growth but the seasonal growing period is reduced to 72 - 120 days (Komutunga and Musiitwa, 2001).

Table 1.1 Long-term mean monthly rainfall, evapotranspiration and temperature for Soroti, eastern Uganda.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Rainfall (mm)	20.1	47	72.9	182.9	192	125	125	184.9	142	116.1	72.5	38
ET (mm)	121.7	118.9	129	106.7	90.2	90.8	86.2	92.7	92.7	106	108.2	111
Temp (^{0}C)	25.5	25.9	25.9	24.4	23.5	23.1	22.5	22.6	23.3	24.1	24.5	24

Source: Major land resources areas of Uganda, Yost and Eswaran, (1990) pp 96.

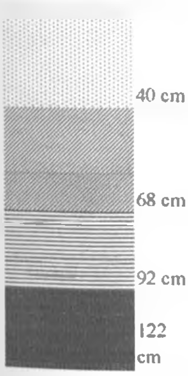
1.6.3 Soils

The soils of the Teso region originate from rocks of the precambrian age basement complex comprising mainly granites, mignalites, gneiss, schists and quartzites. These rocks give rise to four major soil series Serere and Amuria catenas, Metu complex and Usuk series that are mainly of the ferralitic type (sandy sediments and sandy loams). The dominant soil type in the area is *Petroferric Haplustox*. Sandy soils stand out in the area (Ssali, 2000) are well drained, friable and characterized by low water holding capacity and low organic matter levels which intensify the water deficit challenge. The soil profile description and soil properties at the experimental site are described in Table 1.2 and Figure 1.3 below.

Table 1.2 Soil Physical and Chemical characteristics at experimental site

	Profile depth	
	0-10cm	***20-40cm***
Clay (%)	4	4
Silt (%)	6	28
Sand (%)	90	68
OM (%)	2.72	1.01
Textural class (FAO)	Sandy	Clay loam
Bulk density (g cm^{-3})	1.63	1.54
K_{sat} (cm hr^{-1})	5.8	7.6
pH (H_2O)	5.9	5.2
CEC (me/100g)	9.2	10.2
N (%)	0.12	0.1
Av.P (me/100g)	2.15	1.25
K (me/100g)	0.2	0.21
Na (me/100g)	0.05	0.09
Ca (me/100g)	6.21	4.01
Mg (me/100g)	2.11	1.21

Profile



Depth /thickness	Colour	Texture	Boundary Sharpness	Boundary Regularity	Moisture	Structure	Consistency	Compaction	Fauna	Roots
40 cm	2.5Y 4/3 Dark Olive Brown	sandy	clear	smooth	moist	massive granular	non-sticky	friable	Black ants (20) Termites Sugar ants	frequent
28 cm	2.5Y 4/4 Olive brown	clay loam	gradual	smooth	moist	subangular blocky	non-sticky	compact	Black ants (10) Termites Sugar ants	few
24 cm	2.5Y 5/6 Light Olive Brown	clay loam	gradual	smooth	very moist	angular blocky	slightly sticky	tenaciuos	none	few
30 cm	2.5Y 6/3 Olive Yellow	clay loam	gradual	wavy	very moist	angular blocky	slightly sticky	tenaciuos	none	rare

Figure 1.4 Profile characteristics at the experimental site

1.6.4 Land use and livelihood strategies

Land use and livelihoods are inextricably linked (ecologically, economically, socially, and politically) that any change in former dramatically impacts on the latter. The eastern Uganda population is predominantly agro-pastoral basically producing at subsistence level (Whyte and Kyaddondo, 2006). Now, most households in the Teso region derive their livelihood on increasingly small land holdings ranging between 0.5 to 4 ha (national average = 0.4 to 3ha) per household (Okwi et al., 2006), hence forcing intensive production systems and/or seeking non-farm income in order to ensure food self-sufficiency. Crop production is reported to be declining (NARO, 2002), despite the use of nutrient inputs and pest management strategies (Kayizzi et al., 2007), a limitation thought to arise from water stress conditions. Cassava is a key root crop (NARO, 2002) serves both as a major source of calorie intake and a 'new' cash crop to over 60 % of the households in eastern Uganda (Otim-Nape et al., 2005) while, sorghum is ranked 2nd most important cereal in eastern Uganda. These major crops are grown in root crop/cereal/legume mixtures (Otim-Nape and Zziwa, 1990) like, the sorghum – cowpea intercrop (Adipala et al., 1997) or crop rotations beginning with cassava (Otim-Nape et al., 2005)mainly for pest management, soil fertility improvement and income aspects yet, these crop mixtures have a potential to exploit in integrated water resource management practices. Therefore, conditioning the already known crop, tillage and crop management practice to improve water use efficiency is thought to be a major contribution to land use and livelihood security in the cassava-sorghum based cropping systems in eastern Uganda.

CHAPTER TWO

SOIL MOISTURE DYNAMICS UNDER DIFFERENT TILLAGE PRACTICES IN CASSAVA-SORGHUM BASED CROPPING SYSTEMS IN EASTERN UGANDA

ABSTRACT

Soil moisture flow and storage in the root zone determines availability and use efficiency of water in crop production. Cassava and sorghum have been advanced as drought tolerant crops but, limited attention has been put on water resource management in this production system. This study evaluated effects of tillage and cropping systems on soil moisture storage in cassava and sorghum cropping systems in the drylands of eastern Uganda. Two tillage management practices; mouldboard and ripper ploughing and six cropping patterns; three sole crops of cassava, sorghum, and cowpea, as well as three intercrops of cassava + sorghum, cassava + cowpea, and sorghum + cowpea were the treatments laid out in randomised complete block design (RCBD) replicated three times. Soil surface roughness was measured immediately after ploughing and two months later. Soil moisture content was monitored fortnightly at two depths (0-10cm, 20-40cm).

Soil moisture content was higher under ripping than mouldboard ploughing. However, the mouldboard ploughed plots had more moisture in the upper (0-10cm) layer while, the ripped plots accumulated more moisture in the lower (20-40cm) layer of the root zone. Soil surface roughness was stable two months after ploughing leading to negligible surface runoff observed. Crop combinations and seasons influenced soil moisture storage over the growing period. The different cropping systems vary in their soil moisture extraction capacities at different growth stages, hence influencing the overall moisture storage and water used in the root zone.

Key words: *Ripping, Mouldboard, Soil water storage, Soil surface roughness, Crop water use*

2.1 INTRODUCTION

The soil moisture content in the root zone during the crop growing period appreciably affects crop growth, development and the overall land productivity especially in semi arid regions (Ali and Talukder, 2008; Bossio *et al.*, 2008). Much as availability of soil moisture may depend on biophysical (soil properties and processes) and climatic (rainfall and temperature regime) factors (Guswa, 2005; Hsiao *et al.*, 2007), it can be heavily influenced by management.

For example movement of water in the soil is governed by the soil's hydraulic properties which are a function of soil water content and the matric suction, commonly referred to as the soil water characteristic curve (Hillel, 1980). Also soil moisture loss through evaporation and transpiration processes can be driven by energy balance principles (Allen *et al.*, 1998). Where soil moisture is not limiting the evaporation demand, then meteorological parameters like; solar radiation, air temperature, air humidity, and wind speed (Rockström *et al.*, 2003; Zeppel *et al.*, 2006) drive the evaporation process. Similarly, the transpiration process is dependent on meteorological factors as well as crop, soil and management characteristics (Rockström, 2000). Besides, crop water use and yield is defined by the maximum rate of evapotranspiration which corresponds to ETa. Physical soil properties such as depth of impervious layer, soil porosity (Lipiec *et al.*, 2006), soil salinity, crust formation and soil organic matter content (Turner, 2004; Gicheru *et al.*, 2005) affect soil moisture availability and flow paths but, cannot be manipulated within a growing season to the benefit of a crop. Whereas soil surface characteristics, a function of soil management, are directly associated with runoff, infiltration, depressional storage, and water holding capacity (Okwach, 1994). Therefore management practices aimed at adjusting the soil surface characteristics can promote soil processes that encourage soil moisture storage within the root zone.

Dryland ecosystems worldwide are extremely vulnerable to resource over-exploitation and inappropriate land use (World Agroforestry Center, 2006), especially where agricultural production is increasingly being transformed from extensive to intensive systems. One of the key emerging issues in effective water resource management is the recognition that land use and water use are closely interconnected and consequently influence land productivity (Boko *et al.*, 2007; Bossio *et al.*, 2008). Land management techniques that encourage more rainfall to enter the soil are key strategies for improving productivity of rain-fed systems especially for resource-poor famers in sub-Saharan Africa. The FAO, in conjunction with the World Overview of Conservation Approaches and Techniques (WOCAT), identified methods that have proven workable under specific biophysical and socio-economic conditions.

In eastern Uganda, where crop production is predominantly rain-fed, soil moisture storage was estimated to be 8.3% of the rainfall received (Wasige *et al.*,2004), but basing on the soil water budget approach (Hillel, 1998; Palomo *et al.*, 2002; Bouman, 2007) storage can be improved and in turn positively influence crop yields. The seasonal mean precipitation is between 650 and 900 mm, of which 25-30% is received outside the annual growing period (Kayizzi *et al.*, 2007) Up to 93.2% of this precipitation is partitioned into evapotranspiration (Wasige *et al.*, 2004), with a ratio of evaporation to ET greater than 0.5 (Kizito, 2004). The annual mean temperature is 24^0C. The area experiences a seasonal growing period of 72 to 120 days (Komutunga and Musiitwa, 2001).

Cassava (root crop) and sorghum (cereal) dominate the area and are now both staple and cash food crops in most households in eastern Uganda (Whyte and Kyaddondo, 2006). These crops usually grown in rotation and/or intercrop combinations with cowpea (legume), but a 5 and 28% yield declined was reported for cassava and sorghum respectively (MAAIF, 2010), a situation thought to be influenced by the drought experienced in the last decade in Kenya and Eastern Uganda.

Most soil and water conservation strategies have emphasized; the relationship between soil erosion and water quality (Lal, 1991; Magunda and Tenywa, 2001), land use and soil and nutrient loss (Kironchi *et* al., 1999; Wortman, 1999, World Agroforestry Center, 2006), stabilizing soil structure and soil organic matter (Pagliai *et al.*, 2004; Pinheiro, 2004; FAO, 2007), and effects of conservation tillage on soil quality (Strudley *et al.*, 2008; Verhulst *et al.*, 2010). Cassava-legume intercropping systems are popular in terms of improving land use efficiency and economic returns. While, conservation tillage practices are built on the principle of encouraging rainwater infiltration, increasing storage capacity as well as minimizing losses by runoff, evaporation and deep percolation (Benli *et al.*, 2006; Turner, 2004). In order to exploit these practices there is need to understand the influence of tillage and cropping systems on soil moisture storage in dryland cropping systems. This study therefore evaluates soil moisture flow and storage in cassava-sorghum cropping systems in the drylands of eastern Uganda.

2.2 MATERIALS AND METHODS

2.2.1 Site characteristics

The study was done in eastern Uganda (34^0 0' E and 1^0 40' N) in the Usuk sandy farm-grasslands agroecological zone. The site is described in detail in Chapter one section 1.6.

2.2.2 *Experiment design and layout*

The study consisted of two seed bed preparation methods, i.e. mouldboard ploughing and ripping using ox-drawn equipment as is a common practice in the light sandy soils of eastern Uganda. Six cropping systems were selected for the experiment, i.e. i) sole cassava, ii) sole sorghum, iii) sole cowpea, iv) cassava + sorghum, v) cassava + cowpea, vi) sorghum + cowpea. The study was set in a randomised complete block design with treatments replicated three times. Replicates were located on a similar slope profile along a defined transect in order to minimise variations due to lateral soil moisture flux and soil fertility gradient. Each experimental unit was 10 x 7m separated by a 1m gap. The experiments were conducted in three growing seasons. Cassava was planted in the first rains of 2010 (late March), using a 20 ±5cm cutting with a spacing of 1 m x 1 m, giving a total plant population of 10,000 plants ha $^{-1}$. Harvesting was done in April 2011. Unlike the cassava crop, sorghum and cowpea were planted three times i.e. late march 2010, August 2010 and April 2011.

2.2.3 *Land preparation and field management*

The land was ploughed using ox-drawn plough fitted with a mouldboard (Mb) for block 1 and a ripper (Rp) for block 2.The same ploughing depth set at 15cm was used in both treatments. Local expertise and tools were used to plough block one using a mouldboard plough drawn by four oxen. For the ripper plough technical support was sought from the National Semi-Arid Resources Research Institute (NaSARRI), Serere, Uganda, where a ripper plough was attached to the local ox-drawn tool frame used in the area. It should be noted that for ripper ploughing only two animals were used. The first ploughing was done on 23rd March 2010, when the soil was relatively soft at the onset of the rain season and crops planted on 24th March 2010. Sorghum

(*Sorghum bicolour Var. Sekedo*) was planted at a spacing of 60 cm between rows and 30 cm between plants for pure stands while the inter-crop had cowpea at 20 cm x 30 cm. A planting hole 3-5 cm deep was scooped in the soil and three to five seeds thrown per hill. Cowpea (*Vigna inguculata Var. Secow 12*) sole crop treatment was planted at 60 cm x 20 cm for pure stands. The spacing for Cassava (*Manihot esculenta Var. 2619*) was 120 cm between rows and 100 cm within rows. The need to capture the moisture of the season which seemed uncertain all crops were planted on the same day per block, however this later revealed that cassava establishment in the cassava + cowpea intercrops was compromised by cowpea's fast growth habits. The common agronomic practices performed by an average farmer in the cropping system were adopted in order to capture data that is representative of the common practice.

2.2.4 Soil characteristics

A detailed soil profile description was done at the site in order to generate information that was used in the water balance calculations. Soil properties for two soil layers were considered for this study and are described in Chapter one (Table 1.1). The 0-10cm layer is the top layer where most evaporative forces apply, while the 20-40cm layer is the lower layer where most roots are found and moisture below this zone may not be available to the crops.

2.2.5 Measurement of soil surface roughness (SSR)

Soil surface roughness (variation in soil surface elevations due to tillage) measurement was done to provide information on the behaviour of soil surface characteristics (tilth) after ploughing and two months later. There were no crops planted in the area used for the measurements in order to eliminate the contribution of canopy cover from different crops on surface roughness. Hence, the contributing factors were the soil's physical properties and rainfall regime. The main reason for determining the soil surface characteristics was to estimate lack of or generation of surface run off on a plot prepared using the conventional mouldboard plough on soils in the study area. The block under ripper ploughing was exempted from the SSR study because it apparently had incomplete soil disturbance leading to non-uniformity of the water flow paths over the surface. Also, ripper plough pass at 60 ± 5 cm intervals was more likely to give predictable flowlines (along the furrows) which would then require a correction factor of higher magnitude than in the relatively uniform surface left after mouldboard ploughing.

The pin-meter technique was used to take roughness measurements with a pin-meter fabricated locally at the Department of Bio-systems Engineering, University of Nairobi (Okwach, 2004) and was comparable with the design essentials described by Moreno *et al.*, (2008). The technique takes measurements of point elevations (pin-heights) of the soil surface with adjustment for slope (*oriented roughness*) or without adjustments (*random roughness*).

A 1 m long frame was made with pins spaced at 50 mm intervals. The frame was set to level using a spirit level before the pins are released to touch the soil surface (see plate 2.1). Care was taken to have minimal soil disturbance after the release of the pins in order to take the readings that depict the surface under study. Three 1m^2 plots were randomly selected on the ploughed area where the measurements were done.

Plate 2.1 Pin-meter instrument being set before measurement are taken.

The frame was set on the x axis of the $1m^2$ plot then shifted after every height (z axis) reading at intervals of 50 mm on the y axis, giving a total of 400 data points. The pins were lowered over the sample plot then pin heights at that point were manually recorded. The positions used in the initial measurement were avoided due to soil tilth destruction arising from trampling. Literature suggests that micro-relief measurements are converted to some logarithmic scale especially for oriented random roughness however; random roughness seems a more realistic estimation of roughness elements with respect to overland flow hydraulics. A one square meter grid was randomly chosen in three locations within the ploughed field. Four hundred data points from each grid were recorded and processed to estimate the condition of the soil surface.

2.2.6 *Measurement of soil moisture content*

The gravimetric approach was used to measure soil moisture content. Samples were taken at two depths 0-10 cm and 20-40 cm from each treatment using 53 x 50 mm core rings. Samples were picked at 10-14 day intervals or 48-72 hours after the storm when the soil is known to have drained to field capacity. The samples were packed and transported to the laboratory in a well cushioned aluminum carry box and prepared for oven drying at 105°C for 24 hours. Soil moisture determination on weight/weight basis was done following laboratory procedures described by Okalebo *et al.*, (2002). The values were transformed to volume/volume or depth (mm) using bulk density values measured during profile pit characterization.

2.2.8 *Data analysis*

2.2.8.1 *Soil surface roughness data*

The SSR data was tabulated into x and y coordinates for both the initial and after readings with a spatial interval in increments of 5 mm from 0 to 100 mm. Standard deviation was used to account for random roughness (Moreno *et al.*, 2008). Furthermore, the InitialSSR and AfterSSR readings were subjected to a two-sample Poisson-test (mean of InitialSSR = mean of AfterSSR) in GenStat for Windows® - 13th Edition version 13.3.5165 (VSN International, 2010). The data was subjected to spatial analysis using GS^+ version 9.0 (Gamma Design Software, 2010) to generate a variogram and spatial representation of the surface.

2.2.8.2 *Soil moisture content data*

Restricted Maximum Likelihood (REML) method was used to fit mixed models for estimating the variance components by sequentially adding terms to the fixed model. Variance component analysis was used to identify differences between tillage practice, cropping systems and depth of soil moisture measurement over time. The GenStat for Windows® - 13th Edition version 13.3.5165 (VSN International, 2010) statistical analysis software was used.

2.3 RESULTS AND DISCUSSION

2.3.1 Soil surface roughness under mouldboard ploughing

The soil surface roughness (SSR) recorded immediately after ploughing, here referred to as initial soil surface roughness (Initial SSR), and after two months (After SSR) was used to estimate the soil surface condition. Box plots of data set suggested normality (Figure 2.1) hence, were able to run a variogram. A descriptive summary of soil surface roughness data is presented in Appendix 2. The difference between Initial and After SSR data points were best fitted to a spherical model (r^2 = 0.98; σ =0.70). There was no apparent variation in the soil surface roughness between the measurement points (Figures 2.2a, 2.2b, 2.2c, 2.2d).

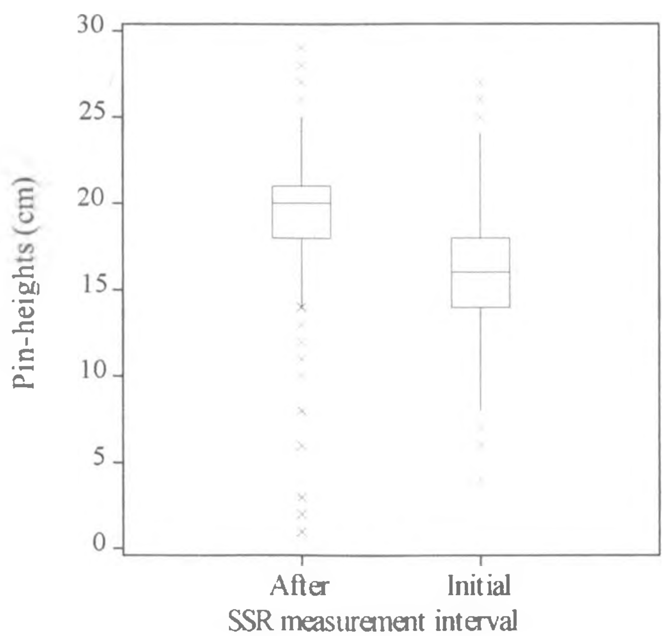


Figure 2.1 Box plot for Initial and After SSR showing normality of the data

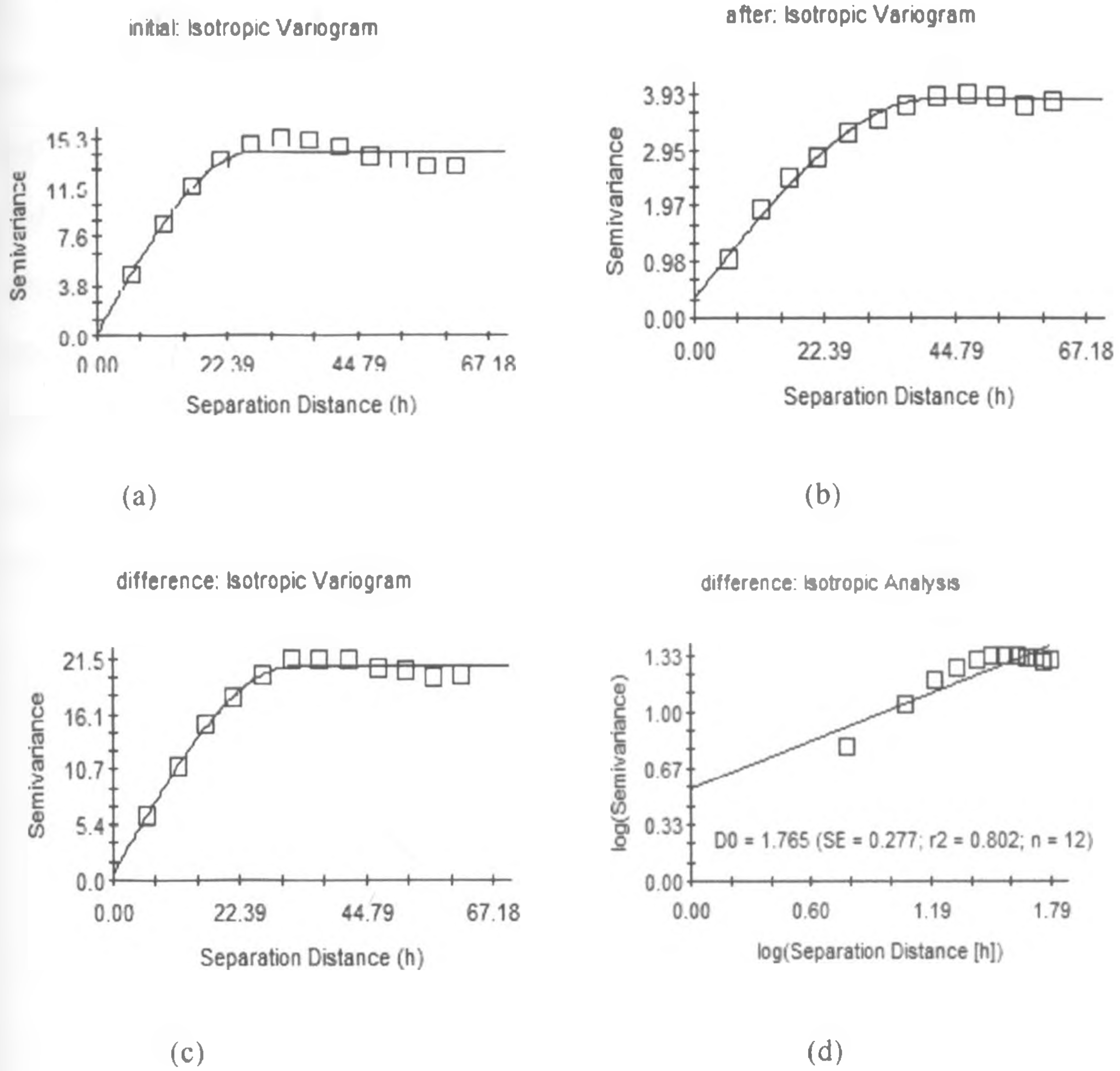


Figure 2.2 Variogram for a) Initial; b) After; c) Difference between Initial and After SSR and d) Fractal analysis of the difference

The soil surface condition described by the variogram indicates that depressions and ridges are randomly distributed across all directions giving no definite water flow paths that would subsequently grow into rills (Figure 2.3a, 2.3b, 2.3c). The higher the resistance to surface flow the more likely the water will infiltrate. Since the plot for this test was not under any crop treatment then the soil condition recorded here is better explained by the ability of the soil to keep stable clods after tillage when exposed to climatic factors like rainfall, temperature, and wind. This surface condition reduces the speed of water travel across the landscape and promotes infiltration. Okwach, (2004), related soil surface roughness to depressional water storage under different rainfall regimes and surface cover treatments and observed that canopy cover and/or mulch effectively reduced the effect on rainfall on soil surface roughness. Therefore the minimal surface runoff observed in this study can be attributed to the random roughness of the soil surface generated by the tillage practice.

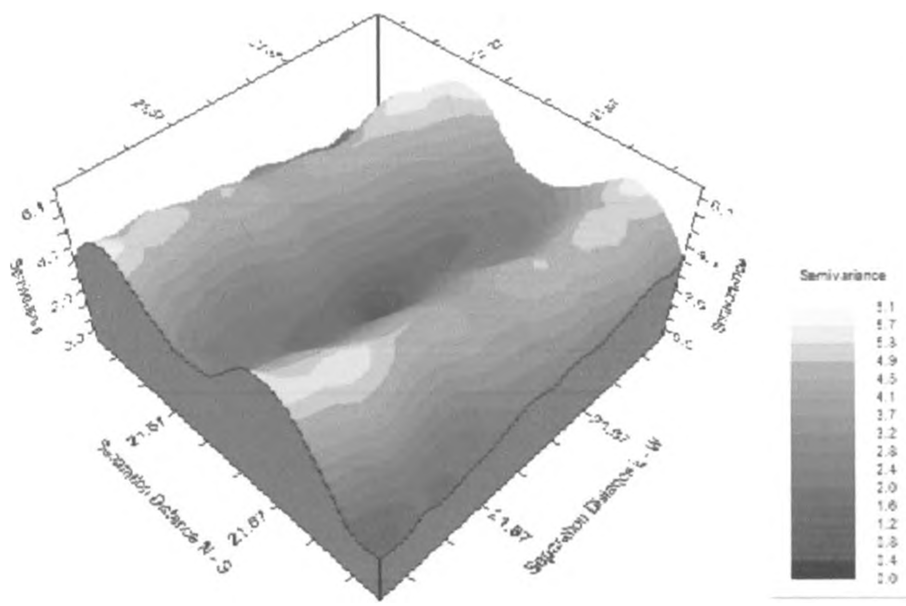


Figure 2.3a A 3-D presentation of the InitialSSR semivariogram

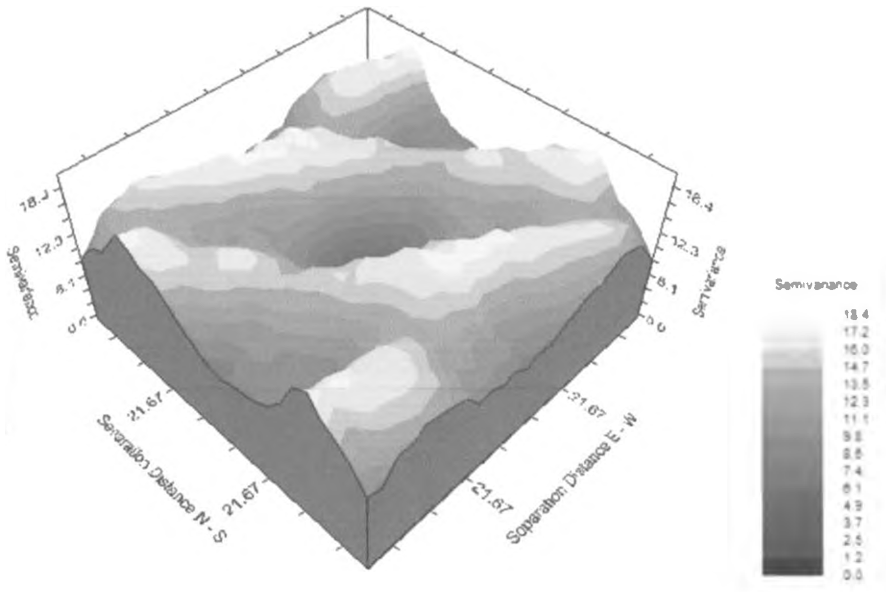


Figure 2.3b A 3-D presentation of the AfterSSR semivariogram.

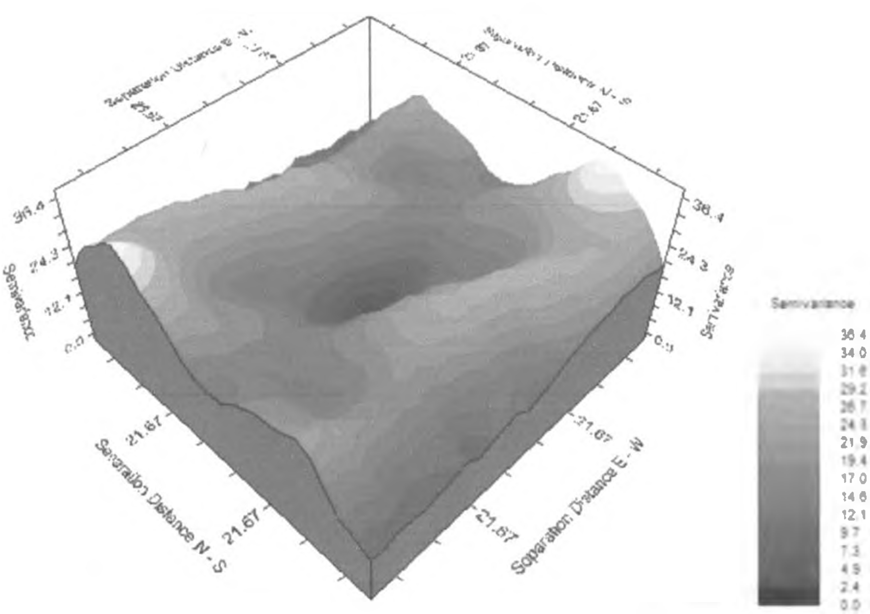


Figure 2.3c A 3-D representation of the difference between InitialSSR and AfterSSR in all directions using a semivariogram.

2.3.2 *Variation of soil moisture content under mouldboard and ripper ploughing in different cropping systems.*

At the onset of the rain season, when most farmers prepare fields for planting, the soil moisture level is assumed to have evened out after a prolonged dry season. Soil moisture content was significantly different between Mb and Rp tillage practices (F pr = 0.007) at 95% confidence level (Table 2.2a). Also, there were significant variations (F pr = <0.001) in the amount of moisture stored in the upper (0-10cm) and the lower soil layers (20-40cm) as the growing period progressed in all treatments (Table 2.2b).

Table 2.2a Effect of tillage practice on soil moisture (%) stored through the growing period (Apr-Nov 2010)

Time (date)	*Tillage practice*	
	Mouldboard(Mb)	*Ripper(Rp)*
10-May	14.8	15.25
20-May	14.77	15.07
09-Jun	14.36	15.25
26-Jul	14.20	15.29
14-Aug	14.92	15.43
28-Aug	14.21	15.29
09-Sep	13.56	14.87
28-Sep	6.84	7.25
29-Oct	12.73	15.03
s.e.d.	**0.3255**	

Table 2.2b Soil moisture storage at the two depths (0-10 and 20-40cm) through the growing period (Apr- Nov, 2010)

	Soil moisture content (%)	
Time (date)	*0-10cm*	*20-40cm*
10-May	12.9	17.15
20-May	12.88	16.96
09-Jun	12.24	17.36
26-Jul	12.86	16.63
14-Aug	13.24	17.11
28-Aug	12.84	16.66
09-Sep	12.11	16.32
28-Sep	7.34	6.75
29-Oct	11.88	15.88
s.e.d.	**0.3255**	

It was noted that soil moisture content in the upper layer (0-10cm) was similar up to 8 weeks after planting (WAP) then differences began to emerge albeit, at varying scales depending on the microclimate dictated by the cropping system. For the sole cassava plots, the moisture content in the 20-40 cm layer of Mb was more than in the Rp tillage practice up till about 12 WAP (Fig 2.4a).

The high moisture content within the plough layer (0-10cm) can be attributed to the effect of tillage on reducing surface runoff and evaporation, increasing infiltration and depressional storage, until later in the season when crop factors come into play. Soil surface disturbance during cultivation is known to increase the macropores but, for a limited period when the soil clods are still settling. Additionally, mouldboard ploughing increases the soil surface roughness known to positively influence depressional moisture storage (Okwach, 1994) and infiltration, while negatively impacting on soil loss, runoff (Idowu, *et al.,* 2002) and evaporation (Strudley et al., 2008). Ladha and Totawat, (1997) observed higher soil porosity and equilibrium infiltration rate under disc ploughing, followed by chisel ploughing than in minimum and zero tillage in the surface (0-15 cm) and sub-surface (15-30cm). A management challenge arising from the sole cassava cropping system would be how to exploit this soil moisture before establishment of the buds and roots from the cuttings. Among the local strategies is to intercrop or plant cassava in mid season after taking care of the short-term quick maturing crops that use only the moisture of the season. The cassava + cowpea (Fig. 2.4b) and sorghum + cowpea intercrops (Fig 2.4d), soil moisture content varied between Mb and Rp tillage in both layers (0-10 and 20-40cm layers) of the profile, but levelled off later as the growing season progressed. However, measurement done on 28th August and 9th September showed that there was more moisture in the 20-40 cm layer in Rp than in Mb ploughed plots. The difference in moisture content at the beginning of the season was majorly a factor of soil conditions i.e., soil surface roughness, soil porosity, initial soil moisture content, infiltration rate, and depressional storage arising from the tillage management practices. This corroborated with, Joyce *et al.* (2002) who reported improved rainfall infiltration in cover cropped fields compared to fallow while, Fabrizzi, *et al.*, (2005) reported that, soil moisture storage under minimum tillage and no-till practices was more in the 20-40cm layer than in the 0-10cm layer of the profile. Furthermore, increase in moisture in the 20-40cm layer can be attributed to the growth habit of the cassava and cowpea crops. The cowpea crop was able to achieve up to 50% surface cover at 6 WAP, thereby reducing the loss of moisture through evaporation. Also, for cassava crop the water demand is very lower early in the early growth stages before tuber formation (Odjugo, 2008) hence, accumulating soil moisture in the lower horizon.

Interestingly, in sorghum sole crop (Fig 2.4c), soil moisture content in the Mb ploughed plots was comparable to the ripped (Rp) plots. This means that most of the moisture that infiltrated in the upper soil layer was lost to soil evaporation or percolated and accumulated in the lower soil layers. The water transmission rate in the 0-10cm layer (Table 1) was further increased by ploughing (Mb) which encouraged loss through evaporation. Also the sorghum crop was extracting water from the 0-10cm soil layer, leaving the moisture in the 20-40cm layer intact.

The sole cowpea (Fig 2.4e) and cassava + sorghum (Fig 2.4f) plots showed no significant difference between Mb and Rp ploughing however, significant differences occur in moisture content between 0-10cm and 20-40cm at $\alpha = 0.05$.

The was an increase in moisture content under Mb than Rp between 20th May (8 WAP) and 9th June (11 WAP) in the 0-10cm but, remained stable at 20-40cm depth (Fig 2e). Variation in soil moisture storage in the 0-10cm depth was attributed to the friable soil surface conditions after ploughing, the canopy cover developed by cowpea and the demand for moisture as the crop develops. At both depths, the distinction in rate of moisture transmission (K_{sat}), reported Table 1, could have influenced moisture redistribution in the soil system, until when equilibrium is achieved. The main drivers of moisture flow therefore, would be the amount of rainfall received (rainfall depth or water head, *h*), infiltration rate and the amount extracted by the crop and the soil evapotranspiration, (*ET*). Surface run off was remarkably controlled by the soil surface roughness left by plough implements used in land preparation, the high rate of water transmission in the upper 0-20cm layer and the gentle slope gradient (< 2%), which are factor controls in the infiltration process. This corroborates with earlier observations by Beven (2004) and Moreno *et al.*, (2008) alluded to in the section above on surface runoff. Also, cowpea establishment led to surface cover of up to 60% by 8 WAP in the sole crop and up to 40% in the intercrops. Canopy cover contributes to rain fall interception, reducing crust formation due to the direct impact of rain drops on the soil particles, hence improving rainfall infiltration. It was observed that in all intercrops involving cowpea the moisture storage pattern was consistent in the order Rp 20-40cm > Mb 20-40cm > Rp 0-10cm > Mb 0-10cm. This conforms to the notion that soil disturbance and antecedent moisture content influence water intake into the soil until when the maximum holding capacity is achieved. The difference in water transmission (Table 1) at 0-10 and 20-40cm profile depths would be the most plausible reason for the variation. In comparison to the cassava + cowpea intercrop, the major source of variation here is the surface cover characteristics. Establishment of sorghum and cassava was less vigorous leading to relatively lower surface cover.

A noticeable change in behaviour of moisture content occurs in the second season, between 9th and 28th September. The sharp drop in soil moisture storage occurred at a time when cowpea and sorghum had attained maximum vegetative growth hence, ET demand was higher than water recharge through rainfall. In earlier studies to quantify the water balance and evaporation in Teso, eastern Uganda, it was reported that up to 93.2% of the soil water was lost through the ET pathway (Wasige, *et al.*, 2004) and, with particular reference to a sorghum crop, a magnitude of 100, 60, and 200% of rainfall received was lost through evapotranspiration during the establishment, vegetative and flowering growth stages respectively (Kizito, 2004). This soil moisture behaviour shows that the crop water demand (ET) at such critical stages can only be satisfied if the water stored from the previous water supply (rainfall) can be stored. In general, the area is estimated to store only up to 8% of the rainfall received (Wasige, *et al.*, 2004). Therefore, encouraging accumulation of moisture in the lower root zone (20-40cm) by reducing soil evaporation and runoff through tillage and choosing cropping systems that offer a quick soil surface cover can improve water use in the cassava-sorghum system.

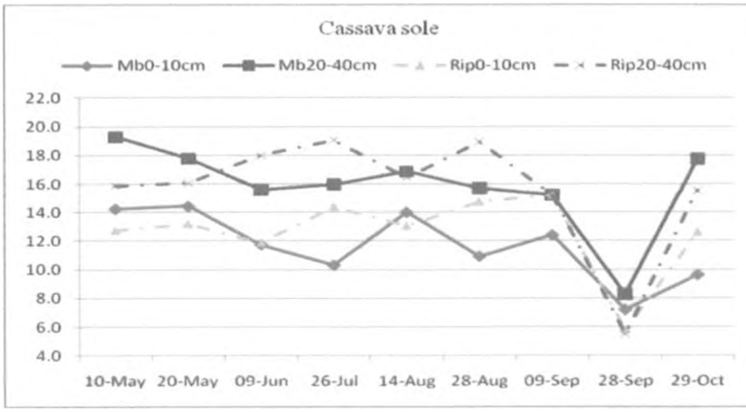


Figure 2.4a. Soil moisture content under mouldboard and ripper ploughing at 0-10and 20-40cm depths in sole cassava cropping system

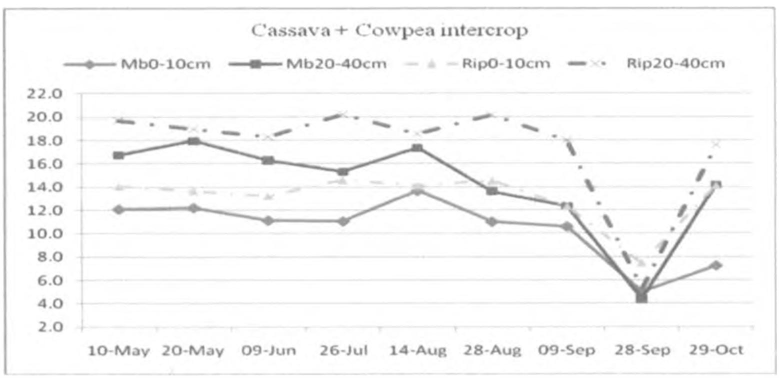


Figure 2.4b. Soil moisture content under mouldboard and ripper ploughing at 0-10and 20-40cm depths in Cassava + cowpea intercrop

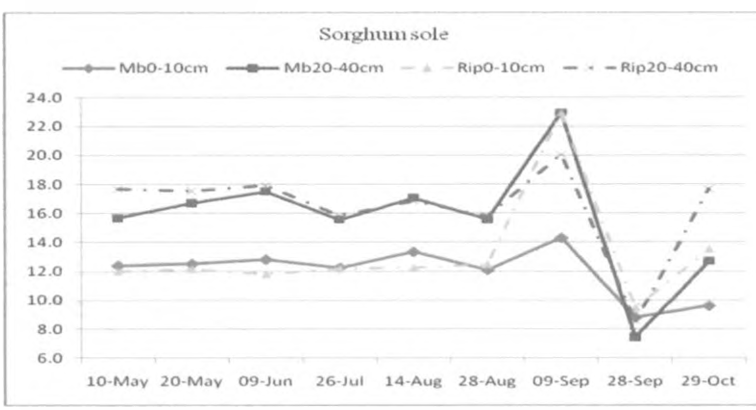


Figure 2.4c. Soil moisture content under mouldboard and ripper ploughing at 0-10and 20-40cm depths in sole sorghum cropping system

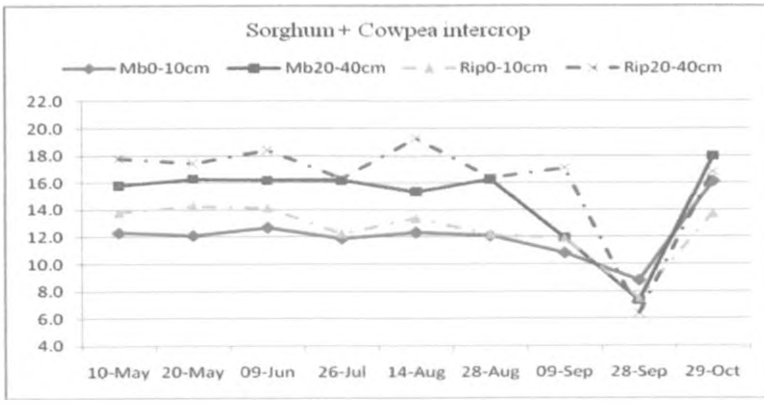


Figure 2.4d. Soil moisture content under mouldboard and ripper ploughing at 0-10 and 20-40cm depths in sorghum + cowpea intercrop

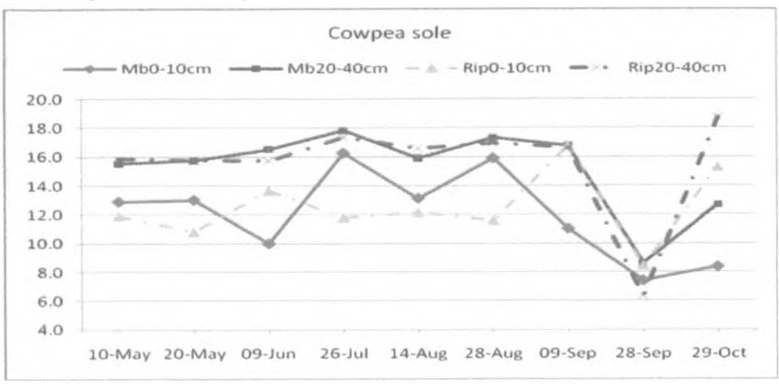


Figure 2.4e. Soil moisture content under mouldboard and ripper ploughing at 0-10and 20-40cm depths in sole cowpea

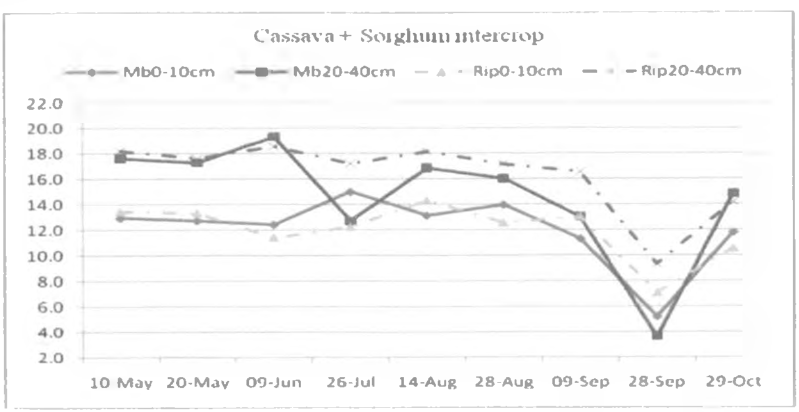


Figure 2.4f. Soil moisture content under mouldboard and ripper ploughing at 0-10and 20-40cm depths in cassava + sorghum intercrop

2.4 CONCLUSION

Soil surface roughness was similar immediately after ploughing and two months later under mouldboard ploughing in the sandy soils of semi-arid eastern Uganda.

Soil moisture content varied with tillage management practices. This is mainly because soil disturbance reduces surface runoff, increases infiltration, and water transmission to the lower root zone. This moisture is beneficial for growth and maturity of cassava during periods of drought.

The difference in moisture accumulation in the 0-10 cm and 20-40 cm layer of the profile in the different cropping systems was a function of soil surface conditions. Mouldboard ploughing opened up the macropores and left a rough tilth encouraging soil moisture storage in the upper (0-10cm) layer of the root zone while, ripper ploughing encourages accumulation of moisture in the lower root zone following the furrow.

Cropping systems that offer a quick surface cover will promote soil moisture accumulation by reducing evaporation and increasing infiltration. However, crop performance and yield seems to vary within crop combinations and seasons.

Assessment of both soil and crop water use efficiency in the different tillage practices and cropping patterns will help to promote the technology with the best water use per growing period. Also in ripper ploughing technology, synchronising planting with available soil moisture is vital for surface feeders like sorghum.

CHAPTER THREE

WATER USE EFFICIENCY OF CASSAVA-SORGHUM BASED CROPPING SYSTEMS IN EASTERN UGANDA

ABSTRACT

A remarkable challenge lies in maximizing agricultural water productivity, particularly in the drought-prone regions of sub Saharan Africa. It is hypothesized that water use efficiency (WUE) can be increased by selection of appropriate tillage and cropping systems. This study seeks to establish the effects of tillage and cropping systems on water use efficiency in cassava-sorghum cropping systems in the drylands of eastern Uganda. A randomised complete block design (RCBD) consisting of six treatments: sole cassava, sole sorghum, sole cowpea, cassava + sorghum, cassava + cowpea, and sorghum + cowpea, replicated three times were used. Tillage practices were mouldboard ploughing (Mb) and ripping (Rp) using ox-drawn equipment. WUE (kg ha^{-1} mm^{-1}) was calculated as a ratio of yield (kg ha^{-1}) to evapotranspiration (ET) (mm). Crop yield per hectare was determined on dry weight basis of the marketable yield for cassava, cowpea, and sorghum. ET was estimated using the soil water balance. WUE varied significantly (α= 0.05) between cropping systems with the highest observed in cassava (34.38kg ha^{-1} mm^{-1}) while the lowest was 3.76kg ha^{-1} mm^{-1} for sorghum. WUE did not differ appreciably in both Mb and Rp tillage practices. Farmers growing sole cassava could use either of the tillage practices. The best yield was recorded in cassava + cowpea cropping system under Mb ploughing and sole sorghum under Rp gave the poorest combined yield (1,676kg ha^{-1}).

Key words: *Tillage, Water balance, Soil moisture storage, Evapotranspiration*

3.1 INTRODUCTION

Low agricultural water productivity is implicated in the failure to meet the Millennium Development Goals (MDGs), especially where rainfall is limited and most times with erratic distribution in sub-Saharan Africa. Farmers have been exposed to water management strategies albeit in isolation at plant, plot, and farm level (Cooper *et al.*, 2008), but have not measured up to the challenge. Now, there is a paradigm shift among nations and international institutions towards integrated water resource management (IWRM) (Tollan, 2002; Schulze, 2004), where policy-makers are now focusing on demand management, carrying capacity of the natural environment (Snellen and Schrevel, 2004), while linking water resources directly to development initiatives (UN-HABITAT 2003). Among the biophysical measures driving this paradigm shift is the campaign to: 1) increase water use efficiency and land productivity, 2) continue efforts to explore ways to ''*grow more food with fewer drops*'' under sustainable conditions through research and development, capacity building and spread of technology (ICID, 2005).

A major challenge in the drought-prone regions of sub Saharan Africa is to balance the factors controlling crop water use and soil moisture availability (Rockström, 2003; Boko, *et al.*, 2007). Water use efficiency (WUE) is envisaged to provide a solution to this challenge by enhancing the partitioning of the available rainfall through manipulation of tillage and cropping systems. Well aware that efficiency is an input-output relationship, agricultural production undergoes several biophysical processes which most often dictate the final product (Hsiao *et al.*, 2007) therefore, ability to relate an appropriate biophysical process to the harvestable crop product is a must in improving agricultural water use efficiency. Further still, the socioeconomic implications of delivering, using, managing, or buying water have exacerbated the impacts of supplying water for agricultural production, making farmers in the drylands more vulnerable.

Suggestions to improve and sustain food production in the drylands can be through choice of practices and cropping systems that demand less nutrients, labour, and capital for the production process (Andales *et al.*, 2006) but also use water more efficiently. Reviews of WUE methods reported by Nielsen *et al.*, (2005) show that use of crop residues on the soil surface increased WUE of corn and sunflower by 28 and 17% respectively due to change from conventional tillage to no-till in Kansas, USA while, WUE of winter wheat at Akron, Colombia increased from 6.9 to 7.5 and to 8.4kg ha^{-1} mm^{-1} in a wheat-fallow-conventional till, wheat-fallow no-till, and wheat-corn-fallow no-till respectively. On the contrary, crop residues have several competing users in eastern Uganda like: dry season feed for livestock, thatching material for houses and, are easily damaged by termites, therefore use of crop residues for soil surface cover may not be feasible.

Much as soil moisture fluxes, a function of precipitation, runoff, infiltration, and evapotranspiration, determine crop water use (Allen *et al.*, 1998; Angus and Herwaarden, 2001; Nielsen *et al.*, 2005) nonetheless, water use can be regulated through choice of seedbed management practices that make soil moisture more available for uptake by crops. On the other hand water use is dependent on the inherent physiology and growth habit of the plant vis-à-vis the environmental stresses (Nielson *et al.*, 2005; Makoi and Ndakidemi, 2010), though, the prevailing microclimate can be engineered through choice of crops and cropping systems. Indeed, the process that we aim to exploit in this soil-plant-atmosphere relationship is how rainwater is partitioned into water used by the crop and/or stored within the root zone ("green" water) in the different tillage and cropping systems. In this case, WUE would refer to a ratio of crop yield to water used (yield/evapotranspiration) yet crop water use is subject to how farmers manage the crop in question.

In eastern Uganda cassava, sorghum and cowpea are dominant crops, cultivated as pure stands in a crop rotation plan or intercropped (Adipala *et al.*, 1997; Ainembabazi *et al.*, 2005; Otim-Nape *et al.*, 2005; Whyte and Kyadondo, 2006). Another common practice is to till the soil using animal power (Tenywa *et al.*, 1999), usually up to a plough depth of 20cm therefore moisture storage and consequently root penetration is limited to this volume. For purposes of this study, crop combinations and field management strategies used in growing the crops is what we refer to as the cassava-sorghum based cropping system. Additionally, rainfall in this area was estimated to be partitioned thus: 93.2% ET, 3.8% runoff (Wasige, *et al.*, 2004), however, ET of up to 200% was recorded in a sorghum indicating a severe negative water balance (Kizito, 2004). Therefore, the possibility of translating this magnitude of ET (93 to 200% of rainfall received) into yields is great, especially when the proportion of evaporation to ET is reduced and a steady water supply to the crop is ensured through improved soil moisture storage.

Crop and seedbed manipulations that positively impact on the soil water balance were suggested (Benli *et al.*, 2006; Lipiec *et al.*, 2006; Turner, 2004) and have been popularized as 'conservation agriculture' (FAO, 2007, Verhulst *et al.*, 2010), basing on promotion of biophysical processes above and below the ground. These soil and crop manipulations could target reducing evaporative losses from plant and soil surfaces while, increasing storage in the root zone and transpiration (Gicheru, *et al.*, 2004; D'Haene, *et al.*, 2008), with the resultant quantity being improved WUE. Agronomists have defined water use efficiency as a ratio of harvestable yield to water consumed by the crop (Turner, 2004; Passioura, 2006; Rijsbern and Manning, 2006; Bouman, 2007; Hsiao *et al.*, 2007) in a simplified expression;

$$WUE(\text{kg ha}^{-1}\text{mm}^{-1}) = \text{Crop yield (kg ha}^{-1}) / \text{Water supply (mm)} \qquad (3.1)$$

In this study we define WUE as the ratio of harvestable (marketable) crop yield to evapotranspiration (water used by the crop) on the understanding that, the maximum rate of evapotranspiration, usually a function of available water in the soil, determines water uptake by a crop (Abbate *et al.*, 2004; Ritzema, 2006; Bodner *et al.*, 2007) and consequently the total yield. Water supply and water used by the crop are related and can be derived from the water balance components. Since it was not possible to precisely account for the loss of productive water through evaporation, the collective term of evapotranspiration was adopted to refer to water used by the crop.

Taking advantage of the knowledge on water balance parameters, seedbed management practices and manipulation of cassava, sorghum, cowpea cropping cycles to manage water resources in rainfed agricultural ecosystems is still a challenge. This study therefore, aimed at establishing the effect of tillage and cropping systems on water use efficiency in cassava-sorghum cropping systems in the drylands of eastern Uganda.

3.2 MATERIALS & METHODS

3.2.1 Experiment design

This study was carried out in eastern Uganda (34^0 0' E and 1^0 40' N) in the Usuk sandy farm-grasslands agroecological zone (Wortman and Eledu, 1999), described in Chapter One (Section. 1.5). The study was set in a randomised complete block design (RCBD). The treatments consisted of six cropping systems, i.e. i) sole cassava, ii) sole sorghum, iii) sole cowpea, iv) cassava + sorghum, v) cassava + cowpea, vi) sorghum + cowpea, replicated three times. The blocks were two tillage (seed bed management) practices, i.e. mouldboard ploughing and ripping using ox-drawn equipment. Details of the experimental units are as described in Chapter Two (Section 2.2.2).

3.2.2 Crop yield determination

Cassava

The main yield components used was fresh and dry storage root weight (Ntawuruhunga *et al.*, 2001). Measurements were done on five plants from each plot randomly chosen during harvest of cassava in the different treatments. Total fresh weight was taken after uprooting the plant and weighed in the field using a commercial (Salter) weighing scale (25 kg ±10g), and then marketable storage roots were removed and weighed separately. For the measurements done in the laboratory, one storage root was randomly taken from each of the five plants selected in each plot. This was used to obtain the average diameter, length and fresh weight of the storage root. The storage root was prepared for drying by manually removing the peel (corky periderm and cortex) using a kitchen knife, then the starchy flesh was sliced to thin chips to ease sun drying. In order to ensure uniform level of drying, the materials were placed in an oven at 60°C for 24 hours before taking the dry weight measurements. The dry weight of the storage roots was taken using a precision laboratory scale (1000g ± 0.001g) and the values used to derive the yield per hectare.

Cowpea

The yield parameters taken for cowpea included; number of pods per plant, number of seeds per pod, weight per hectare. A one square meter area was randomly chosen in each plot then the number of plants counted and the average number of pods per plant determined. Mature pods were harvested, air dried and hand threshed. Grain weight was taken after all seeds were oven dried at 60°C for 24 hours.

Sorghum

The sorghum variety grown has one head (panicle) per plant. Ten plants were randomly selected from the mid rows per plot from which panicles were cut using a hand knife. Heads from each plot were sun dried, then threshed by abrasion using light pressure from a piece of wood. Traditionally, in eastern Uganda sorghum and millet are threshed by beating harvested heads with a dry smooth piece of wood after sun drying.

3.2.3 Determination of evapotranspiration

The soil water balance was used to derive ET (Abbate *et al.*, 2004; Benli *et al.*, 2006; Bodner *et al.*, 2007). When micro-meteorological data is not available to run the original Penman–Monteith water balance model (Van Vosselen *et al.*, 2005), some parameters representing the classical law of mass conservation are used. Precipitation (P) was the only source of moisture into the soil system because there was no irrigation (I = 0) and there was no groundwater within reach of the root zone (CP = 0). Subsurface flow into (SF_i) and out (SF_o) of the was negligible due to the small slope gradient (< 3%) and the surface conditions could not allow runoff to take place (RO = 0). Therefore the soil water balance equation (1.5) is re-arranged to give the expression;

$$P = ET + DP + \Delta S \qquad (3.2)$$

where; ET is evapotranspiration,

DP is loss to the soil layers below the root zone, and

ΔS is the amount stored in the soil at a given period.

The basic soil-plant-atmosphere relationship being explained here is the balance between rainfall received (P), water retained in the root zone (ΔS), water percolating beyond the root zone (DP) and, water used by the crop (ET). We notice here that two basic parameters; P and ΔS are measured and DP is estimated. But in principle, DP only occurs when the upper horizons are saturated and can be estimated based on Darcy's law (Ritzema, 2006) using the equation;

$$DP = -k\frac{\partial H}{\partial Z} \tag{3.3}$$

where; k is hydraulic conductivity (mm day^{-1})

$\frac{\partial H}{\partial Z}$ is the hydraulic gradient

However literature indicates that in dryland agricultural ecosystems, where the slope gradient is almost flat deep drainage is negligible. In particular, a water balance model for this catchment indicated that only 8.3% of the rainfall received was stored (Wasige *et al.*, 2004), hence a minimal volume is expected to go to deep percolation. Therefore, to estimate ET throughout the life cycle of a crop, we need to determine soil moisture content at planting time and at crop maturity. Angus and van Herwaarden (2001) used the expression;

$$ET = P + \Delta S \tag{3.4}$$

where, ΔS represents soil water content at sowing time minus soil water content at maturity.

3.2.4 Calculation of water use efficiency

The yield obtained is dependent on the water used (evapotranspiration) throughout the growing period, which defines WUE. Therefore after substituting water supply with ET in equation 3.1, we obtain a working expression following similar arguments by Moitra *et al.*, (1996), Xu and Hsiao, (2004), and Payero *et al.*, (2008).

$$WUE(\text{kg ha}^{-1}\text{mm}^{-1}) = \text{Crop yield (kg ha}^{-1})/\text{ET (mm)} \quad (3.5)$$

3.2.5 *Data analysis*

Data were analysed using GenStat software. Analysis of variance (two way ANOVA) was performed to identify differences between treatments and means separated using LSD at p=0.05. However, the cowpea and sorghum crop was grown for three seasons hence a variation due to season introduced. The first two seasons had three replicates and the third season was replicated four times, so the ANOVA for unbalanced designs was adopted where season and replication were blocked as nuisance factors. However, some further analysis would require introduction of season as a factor.

3.3 RESULTS AND DISCUSSION

3.3.1 *Effect of tillage practice and cropping systems on water use efficiency*

Water use efficiency (WUE) varied significantly between cropping systems (F pr = < 0.001) but was similar under mouldboard (Mb) and ripper (Rp) ploughing (F pr = < 0.166) at 95% confidence level (Appendix 8). The highest WUE was recorded in cassava at 34.38kg ha^{-1} mm^{-1} and the lowest was in sorghum at 3.76kg ha^{-1} mm^{-1} (Figure 3.1). When the effect of season was considered as a main factor in the analysis, there were significant variations (F pr = <0.001) in WUE across the three seasons (Figure 3.2).

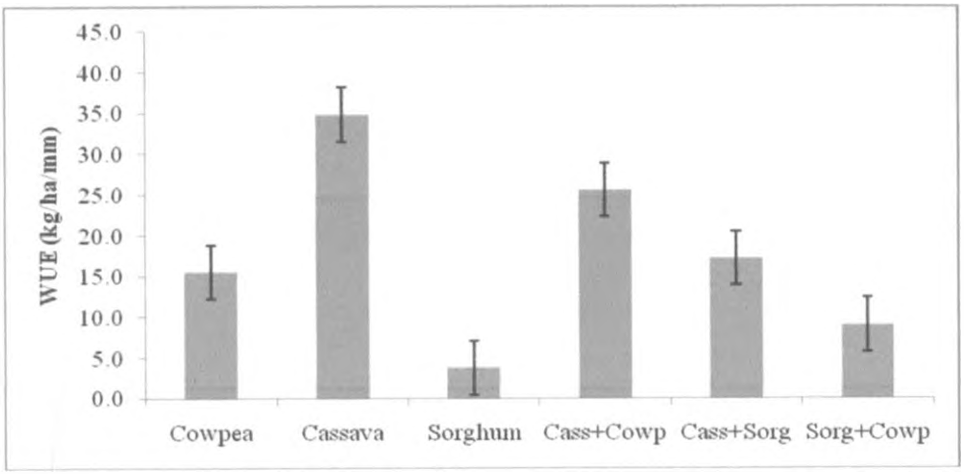


Figure 3.1 Behaviour of WUE under different cropping system in eastern Uganda

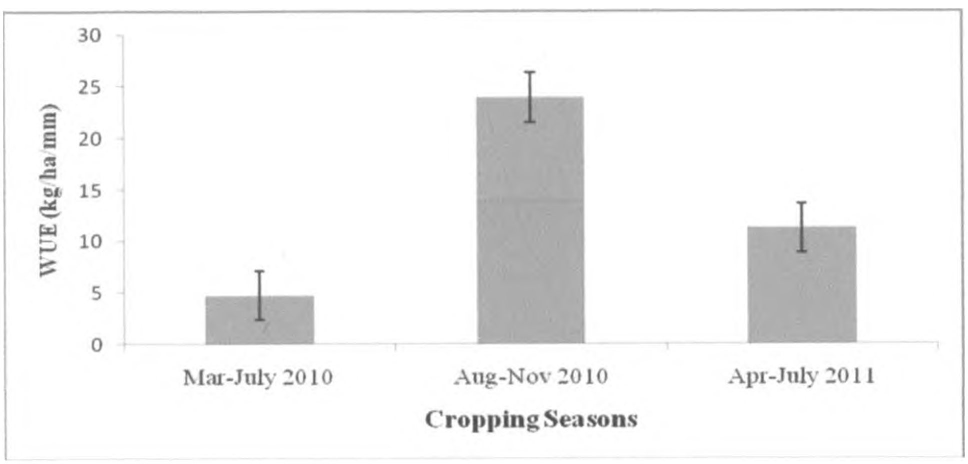


Figure 3.2 Variation of WUE per season in the cassava-sorghum cropping systems during the study period (March 2010- July 2011) in eastern Uganda.

The variation in WUE observed between cropping systems could be attributed to soil moisture characteristics, although growth and physiological characteristics of the crop could be considered. The material that constitutes the yield could partially contribute to the difference i.e. root tuber in cassava compared to the grains in sorghum and cowpea (Steduto *et al.* 2007). The ability of the crop to convert assimilates to biomass is primarily determined by chemical composition of the crop and is not easily changed by environmental factors such as water supply except, where there are extreme changes in respiration due to change in thermal regimes (Hsiao, *et al.*, 2007).

For instance, the cassava crop was in the field through two seasons and was able to use most of the moisture that was stored in the soil even during the dry season of the year. This is evidenced by the negative change in soil moisture storage recorded for this cropping system and the variation in soil moisture content described in the previous chapters of this report (Chapter Three Table 3.2). Particularly, there was a noticeable decrease in soil moisture content (Chapter Two Figure 2.4a) for the cassava cropping system as crop growth progressed. Much as ET for cassava was high the crop seems to have been able to reduce the proportion of moisture losses arising from evaporation.

Interestingly though, cassava + cowpea intercrop recorded better WUE than sorghum + cowpea. The feeding volume of the cassava and cowpea is stratified through the root zone that instead of resource competition there is a synergistic relationship. The moisture available before the cassava crop establishes is exploited by the quick growing cowpea. It is also observed that cowpea offered a surface cover of over 50% by 8 weeks after planting hence, reducing evaporation losses and encouraging transmission to the lower section of the root zone. The cassava later took advantage of the water stored in the lower section of the rooting zone as indicated by the highest soil moisture deficit (-4.74 mm) explained in Table 3.2. Hsiao *et al.*, (2007) noted that the water stored in the root zone can merge with water from the rain at the point of root zone water hence improving efficiency of water delivery at the soil-plant-atmosphere interface. Therefore, for farmers in eastern Uganda who usually intercrop cassava with sorghum or cowpea, this study shows that cassava + cowpea maximizes the use of available water in the soil system. As earlier explained in Chapter Two, tillage using a ripper plough stored more water in the 20-40cm rooting zone then, this process can be enhanced by carefully synchronizing tillage practices with cropping systems to improve water use efficiency in the cassava-sorghum cropping system.

3.3.2 *Effect of tillage and cropping systems on yield of cassava, cowpea, and sorghum*

Cassava was grown for one season (March 2010 – April 2011) while, the cowpea and sorghum crop was grown for three seasons (March – July 2010; August – November 2010; April – July 2011). Generally, the yield of cassava cowpea, and sorghum varied between the two tillage practices and the cropping systems (Table 3.1). On introduction of the effect of seasons only intercrops involving sorghum varied significantly (F pr = 0.001) at 95% confidence level.

Much as the marketable yield of cassava can be both in terms of fresh weight and dry weight, for this study dry weight was used in order to harmonise the crop yield records for all crops. The yield of cassava differed significantly between cropping systems but was similar as a sole crop under mouldboard and ripper ploughing practices. The cassava + cowpea intercrop in the mouldboard ploughed plot recorded the highest cassava yield (20,023 kg ha^{-1}) compared to other treatments.

Cowpea yield was significantly different in both tillage (F pr = 0.013) and cropping systems (F pr = <0.001) but, the interaction between tillage and cropping systems were insignificant (F pr = 0.102). Additionally, variation due to seasons was not significant (F pr 0.161) at 95% confidence level.

The yield of sorghum was significantly different between tillage practices (F pr = 0.009), cropping systems (F pr = 0.004) and season (F pr = 0.001) was recorded.

Table 3.1 Effect of tillage practice and cropping systems on yield of cassava, cowpea and sorghum

Treatments		*Yield (kg ha^{-1})*		
Tillage Practice	**Cropping system**	**Cassava**	**Cowpea**	**Sorghum**
Mouldboard	Sole Cassava	16560b		
	Sole Cowpea		8397d	
	Sole Sorghum			1179b
	Cassava + Cowpea	20023c	3570b	
	Cassava + Sorghum	11101a		1279c
	Sorghum + Cowpea		2853a	894a
Ripper	Sole Cassava	14282b		
	Sole Cowpea		5771c	
	Sole Sorghum			1679d
	Cassava + Cowpea	11962a	2320a	
	Cassava + Sorghum	11247a		1260c
	Sorghum + Cowpea		2703a	1110b

Note: *Different letters against the values down each column indicate significant differences at 955 confidence level*

The traditional practice of growing cassava as a sole crop under mouldboard ploughing gave similar yields like ploughing using a ripper. However, the high yield recorded when cassava was intercropped with cowpea (20,023 kg ha^{-1}) under mouldboard ploughing is evidence that these crops complemented each other in resource use. Agronomists and fertility scholars have advanced the contribution of legume in soil fertility enhancement in mixed cropping systems however, efficient use of soil moisture explained in the previous sections of this chapter could have provided the missing link in enhancing productivity in this cropping system. Additionally, the cowpea yield in the cassava + cowpea intercrop was still better than in the combinations involving sorghum under both tillage practices. The observed yield here is majorly contributed by the first season crop which used most of the soil moisture before the cassava crop established. Overall, cowpea yield was higher under Mb than Rp across all three seasons (March – July 2010; August – November 2010; April – July 2011). It was observed that cowpea under Rp had a thick vegetative cover and was frequently attacked by pests. Adipala *et al.*, (1997) reported that high humidity under the leaves of cowpea encourage pest build up, hence the cowpea yield here was compromised by pest damage. Additionally it is a traditional practice in eastern Uganda to harvest cowpea leaves for use as a vegetable and studies show that grain yield improved with a degree of defoliation (Rahman *et al.*, 2008) but, here farmers would give priority to the mouldboard plots than the ripper plots. To this effect the highest yield (8397 kg ha^{-1}) recorded for the sole crop was under mouldboard ploughing were preferential leave harvesting occurred because the field was cleaner. Also the yield difference could be attributed to the optimum plant population (av. plant density = 12667 plants ha^{-1}) giving a relatively maximum and uniform use of soil and water available.

The yield of sorghum was highest in the sole crop under ripper ploughing (1679 kg ha^{-1}). The cassava + sorghum intercrop in both tillage practices was comparable (Table 3.1) while, the lowest yield was observed in the sorghum + cowpea intercrop in Mb. Cowpea has a quicker growth and establishment habit hence, could have out competed the sorghum crop for nutrients and moisture. We also noted that in the cassava + sorghum intercrop, the sorghum crop is not stressed by the cassava crop since it has a much slower rate of establishment.

3.3.3 Effect of tillage practice and cropping systems on evapotranspiration (ET)

Evapotranspiration (*ET*) was calculated following the water balance model described in the section 3.2.3 above. Since precipitation (P) cannot vary in all treatments, and the change in soil moisture content (ΔSM) is known then, ET as a sum of P and ΔSM, is dependent on soil moisture storage, represented by the soil water content at sowing time minus soil water content at maturity and the ability of the crop to extract moisture from the soil (see Appendix 9 for data used to calculate ET).

ET varied significantly between cropping systems (F pr = <0.001) but, did not show any difference with respect to tillage practice (F pr = 0.105) at 95% confidence level. On the contrary, the interaction between tillage practices and cropping systems showed significant differences (F pr = <0.001). The sole cassava (526.5 mm) and cassava + cowpea (524.0) cropping systems showed higher ET under Rp than Mb while, the sorghum + cowpea intercrop performed slightly better in Mb(526.5mm) than Rp (519.3) ploughed plots. The ET for sole cowpea cropping system was similar and highest in both tillage practices (Figure 3.3).

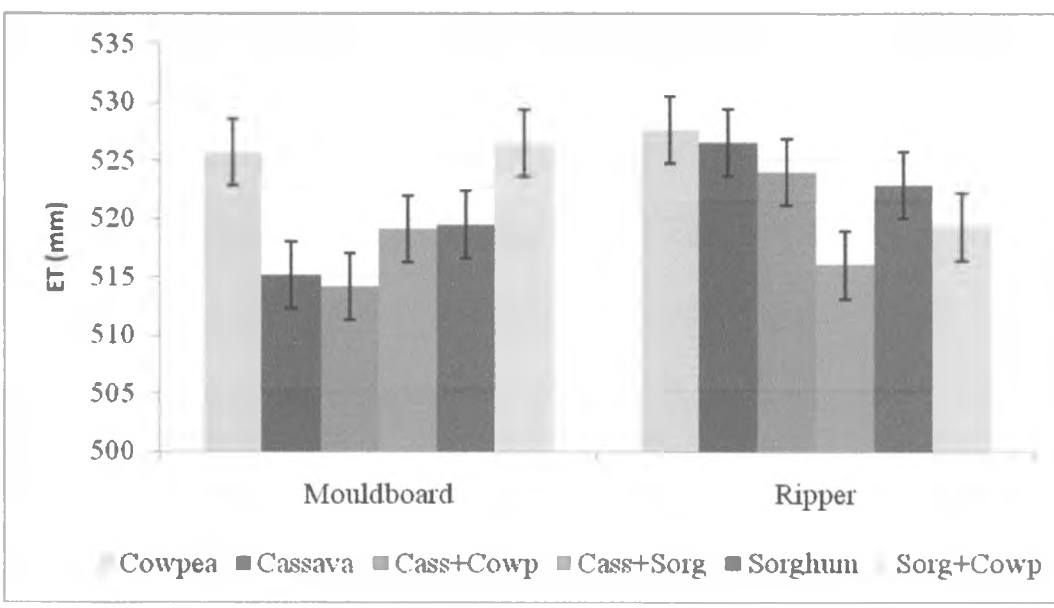


Figure 3.3 Effect of tillage and cropping systems on evapotranspiration in the cassava-sorghum cropping system

The rainfall data used here are averaged records of two non-recording rain gauges, one located adjacent to the experiment site and the other at the Soroti Flying School Meteorological Department located about 3 km from the experiment site. The amount of rainfall received during the growing seasons was 728.4, 350.0 and 477.0mm for season I (March – July 2010), season II (August – November 2010) and season III (April – July 2011) respectively. See Appendix 5 for the monthly rainfall totals at the study location.

The ΔSM was derived from soil moisture content observations made through the growing period at two soil profile depths (0-10 and 20-40 cm). There was a significant difference in ΔSM between, cropping systems, tillage x cropping system interaction, seasons (F pr = < 0.001) and tillage practice (F pr = 0.044) at 95% confidence level.

When effect of seasons was removed and each season analysed independently, it was observed that tillage practice in season I (F pr = 0.065), tillage practice x cropping system interaction in season II (F pr = 0.165) were not significantly different at 95% confidence level. In season III all treatments were significant (F pr = <0.001) as detailed in Appendix 6. Therefore for the calculation of the water balance, the accumulated means for the three seasons were used.

There was more water extracted from the soil system during the growing period as indicated by the negative sign on the values where cassava was grown as a sole crop or as an intercrop (Table 3.2; Appendix 7). The high negative values exhibited by sole cassava, cassava + cowpea, cassava + sorghum, and sole sorghum cropping systems under mouldboard ploughing compared to the positive and relatively low values under ripper ploughing show that the crops under ripping are less likely to show signs of water stress during the growing period. In the earlier discussion in Chapter two, it was noted that the ripper ploughing practice could hold more water in the 20-40 cm horizon which could then be made available to deep rooted crops like cassava and cowpea.

Table 3.2 Effect of tillage practice and cropping systems on change in soil moisture content

Tillage Practice	*Cropping system*	*ΔSM(mm)*
Mouldboard	Sole Cassava	-4.215*d*
	Sole Cowpea	1.031*ba*
	Sole Sorghum	-2.054*c*
	Cassava + Cowpea	-4.736*d*
	Cassava + Sorghum	-2.275*c*
	Sorghum + Cowpea	1.410*b*
Ripper	Sole Cassava	1.441*b*
	Sole Cowpea	1.962*bc*
	Sole Sorghum	-0.390*a*
	Cassava + Cowpea	0.175*a*
	Cassava + Sorghum	-3.832*d*
	Sorghum + Cowpea	-2.154*c*

Note: *Different letters against the values indicate significant differences at* $\alpha = 0.05$

3.4 CONCLUSION

Water use efficiency (WUE) was similar in both mouldboard and ripper ploughed plots, however there were variations due to choice of cropping systems. Cassava had the best WUE (34.38 kg ha^{-1} mm^{-1}) while sorghum (3.76 kg ha^{-1} mm^{-1}) posted the lowest performance. However, there is need for further studies to ascertain the contribution of physiological factors on this difference. There is a strong indication the measures taken to maintain soil moisture will improve water use efficiency in dryland cropping systems.

Much as there were differences in total yield between tillage practices and cropping systems, sole cassava cropping system was similar under both mouldboard and ripper ploughed plots.

Cassava + cowpea intercrop under mouldboard ploughing gave the best cassava yield compared to other treatments.

Tillage and cropping systems significantly influenced the yield of cowpea across the three seasons. Overall, cowpea yield was higher under mouldboard ploughing than ripper ploughing across all three seasons and can be related to the availability of soil moisture in the 0-10cm layer early in the season for quick establishment.

Sorghum responded differently to tillage practices, cropping systems and exhibited a strong variation between the three seasons.

The change in soil moisture content was more negative in the mouldboard ploughed plots indicating that a lot more water is extracted than in the ripped plots. The sole cassava, cassava + cowpea, cassava + sorghum, and sole sorghum cropping systems under mouldboard ploughing had a more negative change in moisture content compared to the positive and relatively low values under ripper ploughing.

CHAPTER FOUR

FARMERS' PERCEPTIONS ON SOIL MOISTURE AVAILABILITY IN CASSAVA AND SORGHUM CROPPING SYSTEMS IN EASTERN UGANDA

ABSTRACT

Farmers' perception of soil moisture availability is a key phenomenon in sustainable resource use since it allows for exploitation of social and ecological resilience in management of natural resources. Addressing the soil moisture availability problem is primarily based on the farmers' decisions/actions which are dependent on their perception of the problem. This study was set to examine the farmers' perception, level of knowledge and understanding of soil moisture availability and establish whether soil moisture availability is a factor in their decision making when planning and implementing operations in the cassava-sorghum cropping system in eastern Uganda. A household-level survey was carried out in the administrative districts of Amuria, Katakwi, Kumi and Soroti. Responses were collected on household, production and field management characteristics and, knowledge on soil and water management in the cassava-sorghum cropping systems. One third of the household heads were women and each household hosted up to 12 persons. The household is a major source of labour for the cassava and sorghum farms where 53.8 % of the households offered 4-6 persons to work on the farms. Labour and knowledge at household level was used to manage the land and most households derived their livelihood from exploiting land. Farmers own small landholdings ranging between 1-4 hectares and majority practice either intercropping or crop rotation. Up to 65 and 59% percent of the farmers allocated about a quarter of their land to sorghum and cassava respectively. Farmers' acknowledged that soil and water management has long term benefits, reduces soil erosion, and is likely to increase yields on the farm. Farmers' positively exploited their competence in using crop rotation plans, selecting the right seed and evaluating the soil fertility status on field. However, the competence in detecting water stress in crops and altering crop spacing to manage soil moisture was not exploited when planning cassava-sorghum cropping cycles.

Key words: *Household characteristics, Farmers' competences, Soil and water management*

4.1 INTRODUCTION

Soil moisture availability is a key factor in agricultural production and farmers' perceptions of this phenomenon ensures sustainable soil resource use. Soil moisture availability is a major production constraint among smallholder farmers in rain-fed agricultural systems in the drylands of sub Saharan Africa (SSA) (FAO, 2003; Guswa, 2005; Cooper *et al.*, 2008). Over 40 % of the SSA people derive their livelihood from agricultural related activities which are now threatened by water scarcity. Specifically, improvements in rain-fed agricultural systems support 60% of cereal production in SSA (Boko *et al.*, 2007), and these systems are estimated to provide up to 50% more produce than improvements done in irrigated systems. Also, the agricultural systems in drylands are very fragile and exhibit high level of vulnerability to unpredictable and variable climate. The Millennium Ecosystem Assessment conceptual framework (MA, 2005) recognizes freshwater as a service provided by ecosystems as well as a system, with the different components overlapping as supporting, regulating, or provisioning services. In this case, the agricultural ecosystems in the drylands offer a platform for partitioning water (precipitation) to perform multiple tasks at different magnitudes. However, the capacity of agricultural ecosystems to absorb environmental shocks like floods and droughts is not only limited by biophysical and economic factors but also the human and institutional aspects.

A recent school of thought is to exploit social and ecological resilience in management of natural resources (Rockström, 2003) especially the drylands. This recognises that vulnerability of people to environmental shocks depends on their understanding and perception of the problem. For example drought can be expressed in two ways; 'meteorological drought'- when the rainfall amount is below the minimum required to generate fundamental ecosystem services and 'agricultural drought'- when the soil moisture available in the root zone is not enough to support plant growth. The latter, which is the focus of this study, is attributed to soil-plant-atmosphere relationships and their interaction with human decision making traits. The farming decisions taken, when aware that up to 70 % of the rainfall received in rainfed cropping systems in semi-arid lands is lost through surface runoff, evapotranspiration, and deep drainage (Rockström, 2000), will arguably augment improved agricultural production campaigns.

Generally, approaches have been recommended for increasing food production in the drylands thus; 1) increasing water use efficiency and land productivity, 2) continue efforts to explore ways to '*grow more food with fewer drops*' under sustainable conditions through research and development, capacity building and spread of technology (Kijne, 2003; ICID, 2005). Literature suggests that climate- rainfall, solar radiation, temperature (Inocencio *et al.*, 2003; Abbate *et al.*, 2004; Hsiao *et al.*, 2007), soil factors- soil moisture storage, evaporation, infiltration(Gicheru *et al.*, 2004; Guswa, 2005; Ali and Talukder, 2008) and, plant factors- evapotranspiration, surface cover (Allen *et al.*, 1998; Benli *et al.*, 2006; Bodner *et al.*, 2007) impact on plant water availability. Also, scientists have attempted to define water use and water use efficiency (Turner, 2004; Passioura, 2006: Rijsbern and Manning, 2006; Bouman, 2007), and efforts have been made to develop water use models (Palomo *et al.*, 2002; Hsiao *et al.*, 2007). Furthermore, economically oriented factors that drive development and uptake of improved water use technologies have received great attention (Shiferaw *et al.*, 2007). But still, for these approaches to be implemented, combinations of disciplines have to interface i.e. hydrology, engineering, eco-physiology, soil sciences, plant sciences, and social sciences.

Dryland systems have multiple production options limited by various social and ecological conditions. Consequently, agricultural production in water-scarce environments is subject to cultural factors, institutional and management decisions, and environmental influence. In most cases there is insufficient practical incentive for farmers to improve water use efficiency including the motivation to conserve water, given the common perception that water provision is a prime function of nature. Although, these factors affect crop production, greater value must be put on local knowledge systems with special consideration of farmers' perceptions and knowledge of the water stress condition in the cropping cycle. However, farmers' understanding and perception of soil moisture availability, as a key factor in a cropping cycle, will determine their capacity to make plausible decisions on agricultural water use with respect to cropping system.

In real life, farmers' livelihoods are intricate and dynamic in nature owing to differences between households' endowments as determinants for decision making. Traditionally research and development approaches in soil and water management have often emphasized the 'top-down' approach which is poor in encouraging farmer participation while, the 'bottom-up' participatory interventions, often using indigenous technical knowledge are said to be popular with farmers but, have faced major difficulties in implementation. The lesson in these approaches is failure to capture diversity and dynamism generated by level of knowledge, perceptions, and mismatch between farmers and local professionals' needs. The common outcome has been blanket recommendations that are insensitive to different locations or farmers, also research generated options that are too inflexible to diverse and changing conditions. After review of the difficulties that researchers, managers and policy-makers have faced in addressing the complexity of livelihoods and ecosystems in drylands (Reynolds *et al.*, 2007), the capacity of local communities and policy-makers to target specific biophysical features, cropping systems and/or farmer groups needs to be recognized. For example, Chizana *et al.*, (2007) examined smallholder farmers' perceptions of soil erosion factors in relation to land degradation in Zimbabwe and noted that farmers have set down priorities to address immediate and short-term needs and want conservation practices based on existing practices.

Current research and policy trends relevant to drylands and community development practices link agricultural ecosystems with human livelihoods and highlight five general lessons (Reynolds *et al.*, 2007): integrated approach, awareness, nonlinearity of processes, cross-scale interactions and local knowledge systems. In this study only two dryland management principles are salient: i) dryland systems are dynamic, connected and co-adapting with no apparent static equilibrium hence, require concurrent consideration of farmers' decisions vis-à-vis the bio-physical characteristics. ii) up to date local/farmers' knowledge should be maintained for co-adaptation to be practical. The eastern Uganda population is predominantly agro-pastoral producing at subsistence level (Whyte and Kyaddondo, 2006). A seasonal growing period of 72-120 days is common (Komutunga and Musiitwa, 2001) with characteristically 25-30% of the annual rainfall is received outside the annual growing period (Kayizzi *et al.*, 2007) and a mean annual temperature $\geq 24^0$C. The main food crops are sorghum, millet, cassava, sweet potatoes, cowpeas and groundnuts. These food crops are now a recognized source of income in eastern Uganda (Whyte and Kyaddondo, 2006) and are enjoying an increase in acreage. Crop production is reported to be declining (NARO, 2002), despite the use of nutrient inputs and pest management strategies (Kayizzi *et al.*, 2007), a limitation thought to arise from water stress conditions. Nowadays, most households derive their livelihood on increasingly small land holdings, hence forcing intensive production systems and/or seeking non-farm income in order to ensure food self-sufficiency.

Addressing the soil moisture availability problem is primarily based on the farmers' decisions/actions, which are dependent on the level of knowledge and information available to them. In the recent years, soil and water management innovations in dryland areas have been centered on climate-soil-plant interactions (Bodner *et al.*, 2007; Jensen *et al.*, 2003) while, human characteristics have majorly reported how demographic, economic and institutional factors influence adaptation, adoption and transfer of a given technology (Ainembabazi *et al.*, 2005; Knowler and Bradshaw, 2007; Shiferaw *et al.*, 2007).

Perception is a concept that guides and conditions farmers' behaviour and/or decision making processes (Rahman, 2003). Farmers' perceptions are therefore critical in production decision processes, shaping farmers' behavior, and determining sustainability of the system. It is apparent that farmers express their basic values on soil moisture in a cropping system and recognize its connection with human and environmental wellbeing. Since farmers are the ultimate users of the soil and water resources, their understanding of the soil moisture phenomenon is important to sustaining production. It is against this background that there is need to determine the interaction of farmers' perceptions (decision making) with soil moisture conditions when planning and implementing cropping systems in drylands.

The main objective of this study was to examine the farmers' perception, level of knowledge and understanding of soil moisture availability and establish whether soil moisture availability is a factor in their decision making when planning and implementing farm operations in the cassava-sorghum cropping system in eastern Uganda. Specifically the study was set to;

- determine whether household characteristics influence soil water management in cassava-sorghum based farming systems

- evaluate the level of knowledge and sources of information available to farmers on soil moisture availability
- examine whether knowledge of soil moisture availability is a major factor in planning a cropping cycle in the cassava-sorghum cropping system

4.2 MATERIALS AND METHODS

4.2.1 Study location

The study was done in eastern Uganda, Teso sub-region lying at 34^0 0' E and 1^0 40' N occupying the Usuk sandy farm-grasslands agroecological zone (Wortman and Eledu, 1999) as described in Chapter one Section 1.6 (Figure 1.2). The area occupies the transition zone between the uni-modal rainfall pattern in northern Uganda and the bimodal pattern experienced in the southern part of the country. Eastern Uganda is the leading producer of cassava and the second largest producer of sorghum in the country (MAAIF, 2010).

4.2.2 Survey approach

A household-level survey on farmers' perceptions on soil moisture availability and management in planning cassava-sorghum based cropping systems was carried out in Teso sub-region comprising the administrative districts of Amuria, Katakwi, Kumi and Soroti. These districts were purposively selected to represent the geographical scope of the broad Teso farming system. The Sub-counties of; Asamuk, Atutur, Gweri, Soroti, Kumi, Toroma, Usuku, and Wera, were selected for the survey taking Gweri-Dokolo village in Gweri sub-county as a focal point which hosted the field experiments described in Chapter 1, 2 and 3. Meetings with Agricultural

Officers (DAO) at the districts, and Assistant District Agricultural Officers (A/DAO) and Production officers from the selected sub-counties were held to obtain general farming information in the study location. Households growing cassava and sorghum were identified with the help of Local Council and Extension and Production Officers. Twelve (12) households were randomly selected from two villages in each sub-county giving a total of 96 responding households.

4.2.3 *Instrumentation*

The key instrument used in this study was semi structured interview schedule for the 96 responding farmers administered using the Participatory Rural Appraisal (PRA) techniques. Key informant meetings were used to clarify the information obtained from open-ended questions and generating qualitative data to depict the farmers' perspective. The instruments were designed to evoke responses concerning; household characteristics, farm production characteristics, field management and, knowledge on soil water management.

4.2.4 *Data management and analysis*

Eight enumerators were identified and trained in a one-day workshop to ensure consistency and reliability of data captured. The production officer in the respective sub-counties was available to direct and introduce the enumerators to the selected respondents. Every evening on each of the field days a one-hour meeting was held with the enumerators to assess the progress, share experiences and clean up the questionnaires. Each enumerator was able to administer 5-6 questionnaires per day.

Qualitative and quantitative data were collected through open-ended and structured questions administered during personal interviews with the selected respondents guided by a questionnaire.

Responses to questions addressing household characteristics, farm production, field management and knowledge on soil and water management in cassava-sorghum cropping systems were recorded. Data from both continuous and non-continuous variables were coded and transferred to excel spreadsheets for easy transfer to the statistical analysis software platform.

Descriptive statistics was applied to describe the basic features of the data in the study using simple measures of dispersion and central tendency and also to provide guidance for more advanced quantitative analyses. The data was subjected to multivariate analysis using the discriminant and canonical correlation functions in GenStat software for biosciences (2010) to examine associations between continuous variables. The possibility of association of key variables in the study was determined in a proximity matrix by calculating the Euclidean distance, A, between variables. The smaller the A values the shorter the distance and the larger the value the more distant the relationship between variables.

4.3 RESULTS AND DISCUSSION

4.3.1 Structure of the households

Farmers in the study area exhibited a household structure common in the rural setting of eastern Uganda with up to 65% of the respondents were aged 20-45 years old (Appendix 3) thus their experiences and knowledge in cropping and weather patterns were vividly explained. This gives an indication that the responses given here are reliable and verifiable. In this study it was observed that up to 34.5% of the households were headed by women. The size of the household was generally made of 12 persons, of which 46.2 % hosted 4-6 males while 45.2 % had 4-6 females. The family constituted the major source of labour for the cassava and sorghum farms.

Majority (52.7%) of household heads had only attained primary school level of education (Figure 4.1). However, it was observed that most residents were able to speak, read, and write either English or Kiswahili or both. This confirms a report by Epeju (2003), that these two languages in addition to the native language (Ateso) are major mediums of communication in formal, trade and social interactions.

Up to 67.7% of the farmers have been resident in this area and 52.7% have been involved in farming for over 20 years (Figure 4.2). Their production decisions are built on the perceptions and opinions which are driven by past experiences about cropping systems in this area.

Most households (61.3%) own small land holdings (1-4 ha) which are used for both crop and livestock production in this agro-pastoral community. Mixed cropping (95.5%) is a dominant practice where farmers employed either intercropping (50.6%) or crop rotation (44.9%). It was observed that 65.6, 59.1, and 53.8 % farmers in the Teso farming system who allocate more than

25% of their landholdings to sorghum ,cassava and other crops respectively. This gives the area comparative advantage in improving the cassava-sorghum cropping system in eastern Uganda.

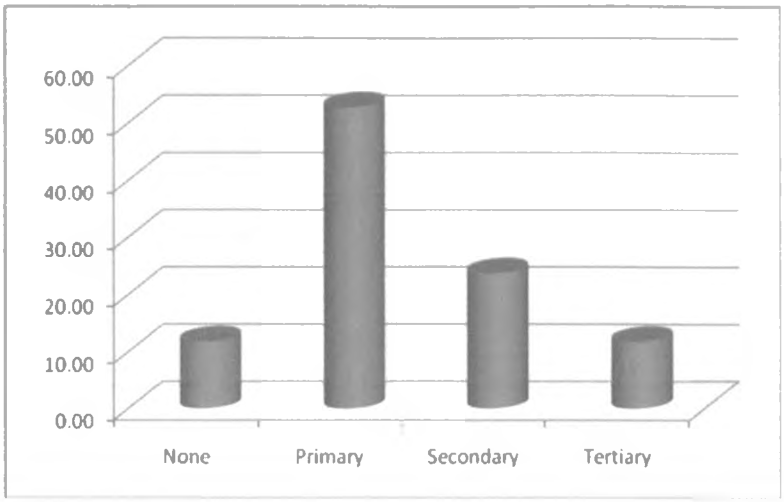


Figure 4.1 Education level of the heads of household in the study area

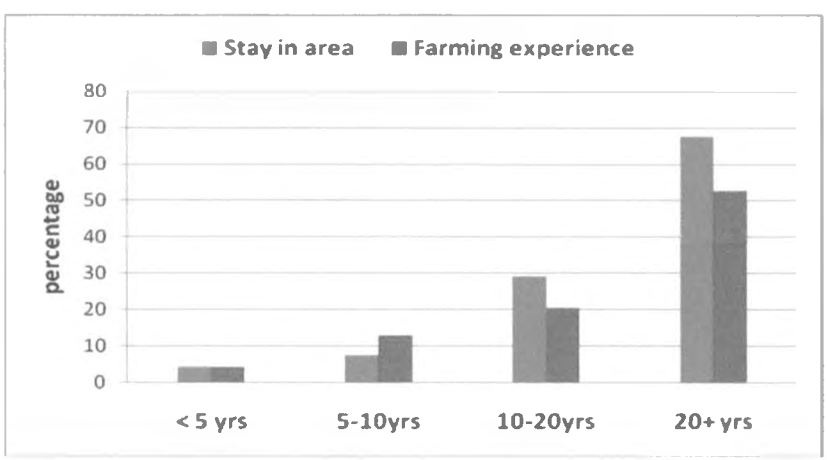


Figure 4.2 Number of years the respondents have stayed in the area and years of farming experience

Generally, 4 to 6 persons offer farm labour in 53.8% of the households while up to 28% of the households had nobody offering off-farm labour (Figure 4.3). The households' cultural and socio-economic characteristics can be used to explain the farmers' ability to sustainably use the available resources. Farming experience was closely associated with number of years stayed in the area ($A = 6.481$) while, provision of family labour was distantly associated with offering off farm labour ($A = 35.777$) (Table 4.1). This establishes that these households derive most of their livelihood from farming, albeit at subsistence level, hence any improvement in the farming system will directly impact on the livelihood and sustainability of the agro-ecosystem. The ability to offer off-farm labour as a supplementary source of livelihood was closely associated with education level ($A = 27.386$). Therefore, there is reason to believe that the population is semi-skilled and may not compete for lucrative jobs, with less drudgery in the urban centres. The only sure source of livelihood left is through exploiting the land. Additionally, it means all the labour and knowledge used to manage agricultural production is generated within the household and will more often than not depend on natural resources available. In order to improve productivity, it is imperative to understand the farmers' knowledge, perceptions, and opinions on soil moisture management in cassava-sorghum based cropping system of eastern Uganda.

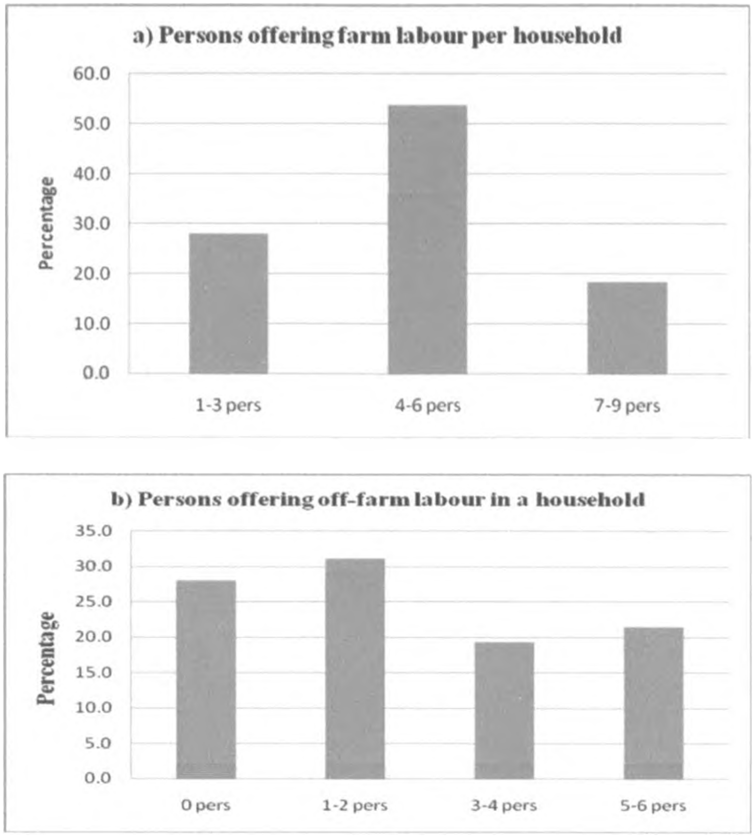


Figure 4.3 Distribution of persons in a household offering a) farm labour, and b) off-farm labour in the study area

Table 4.1 Proximity matrix of key variables describing the characteristics of the households in the study area

	Euclidean Distance				
	Educ	Yrs Stay	Farming exp	Family labor	Off-Farm labor
Educ	0	16.4316767	15.74801575	30.65941943	27.38612788
Yrs Stay	16.43168	0	6.480740698	22.13594362	26.57066051
Farming exp	15.74802	**6.4807407**	0	22.53885534	25.96150997
Family labor	30.65942	22.1359436	22.53885534	0	35.77708764
Off Farm labor	27.38613	26.5706605	25.96150997	**35.77708764**	0

4.3.2 Farmers' views and competence on soil water management (SWM) in the cassava-sorghum cropping system of eastern Uganda

4.3.2.1 Test for homogeneity of sample population for views and competence on SWM

The sample population was tested for homogeneity to confirm whether the responses given by the respondents represent to a good degree the views of the population in the Teso farming system. The data collected from the different areas (districts) showed close correlation and overlaps between districts. Also, the responses on farmers' views on soil water management (Figure 4.4a) and farmers' knowledge and competences on soil moisture availability (Figure 4.4b) were randomly distributed over the sample population.

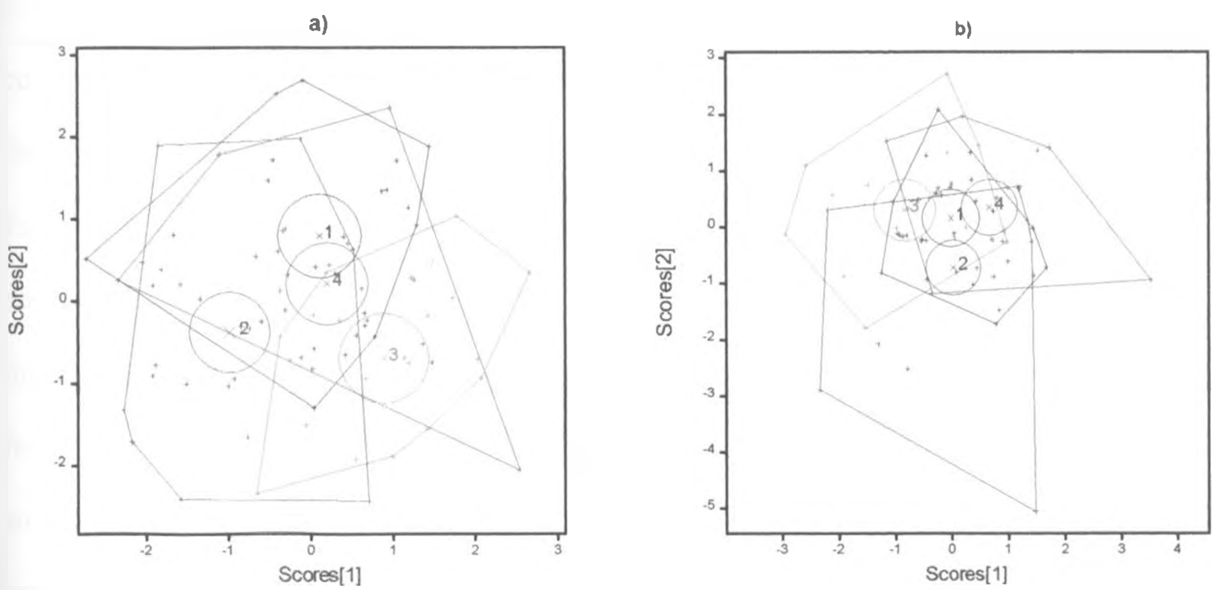


Figure 4.4 Homogeneity of responses on a) views on SWM during farm operations and b) knowledge/competence on soil moisture availability as a factor in planning cropping cycles, from the four sample units (districts) representing the Teso farming system.

4.3.2.2 Farmers' views on soil water management (SWM) during farm operations

The statements describing the farmers' views on soil water management were subjected to canonical correlation analysis. The first two scores explain 86% of the variation in the responses, with score 1 taking 44% and score 2 taking 42%. This is way above the 60% limit for reliability and validity of the responses. Also, the data shows that there is no strong correlation between variates used in this study, hence each statement could independently explain the farmers' views on soil water management during farm operations.

Score 1 is strongly positively correlated with the long-term benefits (r = 0.99), SWM reduces soil erosion (r = 0.93), SWM increases yield on the farm (r = 0.65) but, negatively correlated with availability of indigenous knowledge for SWM (r = -0.82). Score 2 is strongly positively correlated with need for frequent supervision (r = 0.99), but negatively correlated with the view that SWM increases water in the soil (r = 0.99).

Farmers were aware of several soil and water management practices and had positive opinions about them. The results of this study show that farmers recognize that soil and water management has long term benefits, reduces soil erosion, and is likely to increase yields on the farm. Interestingly, the farmers could hardly relate available indigenous technical knowledge to soil water management for the cassava-sorghum cropping system. There is a strong belief that soil and water management practices are a preserve of high value crops like citrus and vegetables. Therefore there is hope that this could be exploited in encouraging farmers to adopt soil and water management practices in the sorghum-cassava cropping system.

4.3.2.3 Farmers' knowledge and competence on soil moisture availability

The canonical correlation analysis of the responses on farmers' knowledge/competences on soil moisture availability needed when planning a cropping cycle reveals that the first two scores explain 78% of the variation in responses. Score 1 explains 48% while score 2 explains 30%. Score 1 is strongly negatively correlated with ability to detect water stress in crops ($r = 0.89$) and taking advantage of crop spacing ($r = 0.74$). Score 2 was strongly correlated with using a crop rotation plan (0.81), selecting the right seed ($r = 0.72$), and evaluating soil fertility status on the field ($r = 0.62$) but, negatively correlated with interpreting forecasting messages ($r = {}^{-}0.84$). Results show that farmers hardly use their competences in detecting water stress in crops and altering the crop spacing in managing soil moisture availability when planning the cropping cycles for cassava and sorghum. The results indicate that 53.7 % of the respondents were not sure or did not use the knowledge on soil moisture availability when choosing fields for cassava and sorghum. This is partly attributed to the belief that these crops are genetically drought tolerant. Indeed, Ali and Talikuder's (2008) synthesis reveals that social and economic conditions of the farmers/stakeholders determine the enhancing of agricultural water productivity.

On the other hand, farmers can positively exploit their competence in using a crop rotation plan, selecting the right seed and evaluating the soil fertility status on field when planning cassava-sorghum cropping cycles. Up to 95.5% of the farmers employ either intercropping (50.6%) or crop rotation (44.9%). The sorghum varieties (*Sekedo, Lulu, Seredo, Serena* and *Epurpur*) commonly grown in the area were selected on the strength of their improved yield (3-5 t ha^{-1}), resistance to *anthracnose* and the early maturing trait that helps to escape drought if planted at the onset of the rains. Therefore agronomic technologies can be exploited to enhance water use efficiency and productivity in the cassava-sorghum cropping systems of the drylands in eastern Uganda.

4.4 CONCLUSION

The household structure in the study area represents the rural setting found in most parts of eastern Uganda. Over one third of the household heads were women and host up to 12 persons with an almost equal distribution of males (46.2%) and females (45.2%). Half of the household heads attained up to primary school level of formal education and were able to speak or read or write English or Kiswahili or both.

The household is the major source of labour for the cassava and sorghum farms with 53.8 % of the households offering 4-6 persons to work on the farms, while up to 28% of the households could not offer any one for off-farm labour. Therefore most households derived their livelihood from exploiting the land. The labour and knowledge used to manage the land is propagated at household level.

Farmers own small landholdings ranging between 1-4 hectares and 95.5% practiced either intercropping or crop rotation. Sixty five and 59 % of the farmers allocated up to 25 % of the land to sorghum and cassava respectively.

Farmers believe that soil and water management has long term benefits, reduces soil erosion, and is likely to increase yields on the farm. However, farmers could not relate available indigenous technical knowledge in soil and water management for use in the cassava-sorghum cropping system.

Farmers' positively exploit their competence in using crop rotation plans, selecting the right seed and evaluating the soil fertility status on the field. However, the competence in detecting water stress in crops and altering crop spacing to manage soil moisture was not used when planning cassava-sorghum cropping cycles.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY

Water use efficiency (WUE), as a premise in improving crop productivity, is a basic tool for managing available water in the soil system especially, in dryland ecosystems. The people of eastern Uganda are characteristically resource-strained, derive their livelihood from smallholder agriculture, and are very vulnerable to variations in climate. Well aware of the relationship between precipitation and soil moisture content, it is still a difficult to strike a balance between crop water requirements and soil moisture flows in this farming system. Worse still farmers are exposed to environmental calamities such as droughts followed by flooding at 5-7year cycles. This has impacted on their food security situation and livelihood patterns, hence the call for strategies to address short-term and long-term needs. However this should be augmented by integrated approaches across sectors and harnessing of local knowledge systems. It is clear that these farmers ably articulate their views on soil moisture, but are yet to connect the knowledge on rainfall regimes and soil moisture availability to increasing crop WUE for sustainable water resource management in dryland cropping systems.

It is against the aforesaid that this study was envisaged to provide information on how tillage practices and cropping systems can be manipulated to improve soil moisture storage and WUE in cassava-sorghum based cropping systems. And also to examine the farmers' perceptions on soil moisture availability and how it can be exploited in selecting and adopting strategies that increase WUE in the cassava-sorghum cropping system in eastern Uganda.

5.2 CONCLUSIONS

Soil moisture content under mouldboard and ripper ploughing varied at both the 0-10 and 20-40 cm depth. Mouldboard ploughing encouraged soil moisture storage in the upper (0-10cm) layer of the root zone and is capable of reducing surface runoff by maintaining a stable soil surface roughness. On the other hand, Ripper ploughing encouraged accumulation of moisture in the lower root zone (20-40cm) which can be made available to the cassava crop during periods of drought or in between rainfall seasons.

Crop performance and yield varied with cropping systems. The cropping systems influence soil moisture extraction therefore shallow rooted crops are more suited to mouldboard ploughing than deep rooted crops like cassava. This is a plausible opportunity to exploit when improving the cassava-sorghum cropping systems in the sandy soils of semi-arid eastern Uganda.

The sole cassava cropping system had the best water use efficiency while sole sorghum had the poorest, collaborating with the low yields obtained in the study. However, when growing sole cassava use of either mouldboard or ripper ploughing would give similar WUE, save for other benefits that need to be further evaluated. Besides WUE, cassava + cowpea cropping system under mouldboard ploughing gave the best yield while sole sorghum performed poorest under ripper ploughing.

The household is a major source of labour and knowledge used to manage the cassava and sorghum farms. Most households derived their livelihood from exploiting land with over 53 % of the households offering between 4-6 persons to work on the farms. Landholdings ranged between 1- 4 hectares with up to 25 % of this land allocated to cassava and sorghum. The most common cropping practice was intercropping and crop rotation.

Farmers' agreed that soil and water management has long term benefits, reduces soil erosion, and is likely to increase yields on the farm. Farmers' positively exploited their competence in using crop rotation plans, selecting the right seed and evaluating the soil fertility status on field. However, the competence in detecting water stress in crops and altering crop spacing to manage soil moisture was lacking when planning cassava-sorghum cropping cycles.

5.3 RECOMMENDATIONS

Mouldboard ploughing promotes soil moisture storage in the upper layer of the rooting zone which is suitable for a crop that establishes quickly. Ripper ploughing promotes soil moisture storage in lower layer which is easily exploited by deep rooted crops especially during dry spells or in between rain seasons.

There is need to evaluate both soil and crop water use efficiency in the cassava and sorghum based cropping systems so as to establish the most critical sub process for effective soil water use in these farming systems.

The combination of cassava + cowpea performed well under mouldboard ploughing implying that there is synergistic relationship between cassava and cowpea which should be exploited.

The labour and knowledge at the household can be used to enhance sustainable management of land and water resources.

Participatory on-farm demonstrations are needed to assist the farmers correlate the available indigenous technical knowledge on soil and water management to the cassava-sorghum cropping systems.

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APPENDICES

Appendix 1.

a) Tests for fixed effects model for soil moisture content for growing period Apr-Nov 2010 at 0-10cm and 20-40cm depths in the cassava sorghum cropping systems in eastern Uganda.

Fixed term	*Wald statistic*	*n.d.f.*	*F statistic*	*d.d.f.*	*F pr*
Time	2597.89	8	318.57	226.7	<0.001
Tillage practice	20.05	1	20.05	73.2	<0.001
Cropping system	10.78	5	2.16	73.2	0.068
Depth	684.11	1	684.11	73.2	<0.001
Time*Tillage practice	22.27	8	2.73	226.7	0.007
Time*Cropping system	254.38	40	6.22	372.9	<0.001
Time*Depth	264.42	8	32.43	226.7	<0.001

b) Tests for fixed effects model for soil moisture content for growing period Apr-Aug 2011 at 0-10cm and 20-40cm depths in the cassava sorghum cropping systems in eastern Uganda.

Fixed term	*Wald statistic*	*n.d.f.*	*F statistic*	*d.d.f.*	*F pr*
Time	473.01	3	157.67	93	<0.001
Tillage practice	171.24	1	171.24	31	<0.001
Cropping system	3.43	2	1.72	31	0.196
Depth	20.27	1	20.27	31	<0.001
Time*Tillage practice	20.39	3	6.8	93	<0.001
Time*Cropping system	27.48	6	4.58	93	<0.001
Time* Depth	5.1	3	1.7	93	0.172

Note: there was no cassava crop in the April-July 2011 season.

Appendix 2.

Descriptive summary of soil surface roughness data initially and two months after ploughing

	Mean	*Min. value*	*Max. value*	*Sample Variance*	*Std. dev*	*skewness*	*kurtosis*
Initial SSR	16.233	10.67	23.33	4.79	2.189	0.56	0.22
After SSR	19.522	13.00	22.67	2.25	1.499	-1.02	2.81

Appendix 3.

Frequencies describing the age of the heads of households in Teso farming system

Age of household head

	Frequency	Percent	Valid Percent	Cumulative Percent
20-35yrs	30	32.3	32.3	32.3
36-45yrs	30	32.3	32.3	64.5
46-55yrs	19	20.4	20.4	84.9
56-65yrs	6	6.5	6.5	91.4
above 65yrs	8	8.6	8.6	100.0
Total	93	100.0	100.0	

Appendix 4.

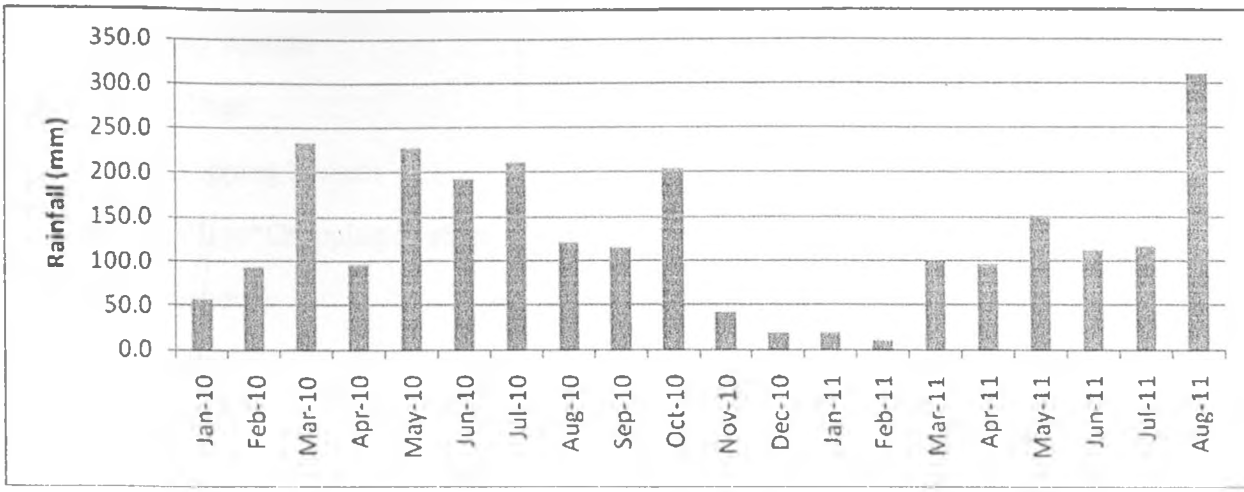
Frequencies describing the sex of the household head in Teso farming system

Gender of household head

	Frequency	Percent	Valid Percent	Cumulative Percent
Male	59	63.4	63.4	63.4
Female	34	36.6	36.6	100.0
Total	93	100.0	100.0	

Appendix 5.

Monthly rainfall totals at the study location



Appendix 6

Accumulated ANOVA for change in soil moisture (ΔSM) between tillage and cropping systems for the three seasons

Variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Season	2	181.6	90.8	9.11	<.001
Replication	3	2.487	0.829	0.08	0.969
Depth	1	0.802	0.802	0.08	0.777
Tillage	1	41.005	41.005	4.12	0.044
Cropping system	5	363.613	72.723	7.3	<.001
Tillage*Cropping system	5	473.584	94.717	9.51	<.001
Residual	174	1733.842	9.965		
Total	191	2796.933	14.644		

ANOVA for change in soil moisture (ΔSM) between tillage and cropping systems for season I (Mar-July 2010)

Source of variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep stratum	2	2.158	1.079	0.22	
Tillage	1	17.055	17.055	3.54	0.065
Cropping System	5	162.037	32.407	6.73	<.001
Tillage*Cropping System	5	333.511	66.702	13.85	<.001
Residual	58	279.234	4.814		
Total	71	793.995			

ANOVA for change in soil moisture (ΔSM) between tillage and cropping systems for season III (Apr-Aug 2011)

Source of variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep stratum	2	7.839	3.92	0.61	
Tillage	1	150.182	150.182	23.2	<.001
Cropping System	5	309.546	61.909	9.56	<.001
Tillage*Cropping System	5	709.794	141.959	21.93	<.001
Residual	58	375.446	6.473		
Total	71	1552.807			

Appendix 7

Change in soil moisture content (Δ*SM*) in the different tillage practices and cropping systems per season

Tillage practice	*Cropping system*	*Mar-Jul 2010*	*Aug-Nov 2010*	*Apr-Jul 2011*
Mouldboard	Sole Cassava	4.5	-6.35	NA
	Sole Cowpea	-5.75	-2.91	4.13
	Sole Sorghum	-1.95	-7.75	0
	Cassava + Cowpea	-2.09	-2.69	NA
	Cassava + Sorghum	-0.21	-6.41	NA
	Sorghum + Cowpea	-0.06	5.08	-0.07
Ripping	Sole Cassava	1.04	4.24	NA
	Sole Cowpea	3.76	-1.11	1.11
	Sole Sorghum	0.85	-0.72	-1.11
	Cassava + Cowpea	-1.74	-6.15	NA
	Cassava + Sorghum	-1.26	1.66	NA
	Sorghum + Cowpea	-2.37	-1.61	-2.23
Rainfall (mm)		728.4	350.0	477.0

NA: There was no cassava crop grown in the third season

Appendix 8

Accumulated ANOVA for water use efficiency in the cassava-sorghum cropping systems in eastern Uganda including the effect of season

Change	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep	3	197.51	65.84	1.08	0.364
Season	2	9289.82	4644.91	76.09	<.001
Tillage Practice	1	119.46	119.46	1.96	0.166
Cropping Syst	5	5615.14	1123.03	18.4	<.001
Tillage Practice*Cropping Syst	5	549.86	109.97	1.8	0.123
Residual	72	4395.03	61.04		
Total	88	20166.83	229.17		

Appendix 9

Data on rainfall (P), change in soil moisture (ΔSM), and the calculated evapotranspiration (ET)

				ΔSM (mm)**				
Season*	Tillage practice	Cropping System	Rep	0-10cm	20-40cm	0-40cm	P (mm) †	ET (mm) ‡
1	Mb	Cp	1	4.99	1.96	6.94	728.4	735.34
1	Mb	Cp	2	5.74	5.14	10.88	728.4	739.28
1	Mb	Cp	3	5.67	3.53	9.20	728.4	737.60
1	Mb	Cs	1	-6.54	-5.78	-12.31	728.4	716.09
1	Mb	Cs	2	-6.49	-4.08	-10.57	728.4	717.83
1	Mb	Cs	3	-6.15	-5.48	-11.63	728.4	716.77
1	Mb	Sg	1	-0.05	-0.14	-0.19	728.4	728.21
1	Mb	Sg	2	0.62	0.40	1.02	728.4	729.42
1	Mb	Sg	3	-1.27	-0.82	-2.09	728.4	726.31
1	Mb	CsCp	1	-1.86	-2.85	-4.71	728.4	723.69
1	Mb	CsCp	2	-2.23	-1.82	-4.05	728.4	724.35
1	Mb	CsCp	3	-0.98	-1.96	-2.93	728.4	725.47
1	Mb	CsSg	1	3.67	-8.49	-4.82	728.4	723.58
1	Mb	CsSg	2	3.62	-7.53	-3.91	728.4	724.49
1	Mb	CsSg	3	2.85	-6.65	-3.80	728.4	724.60
1	Mb	SgCp	1	-0.80	0.68	-0.12	728.4	728.28
1	Mb	SgCp	2	-1.37	0.40	-0.97	728.4	727.43
1	Mb	SgCp	3	0.05	0.66	0.71	728.4	729.11
1	Rp	Cp	1	-2.67	-0.75	-3.43	728.4	724.97
1	Rp	Cp	2	1.40	3.54	4.94	728.4	733.34
1	Rp	Cp	3	0.68	4.05	4.73	728.4	733.13
1	Rp	Cs	1	1.55	4.05	5.60	728.4	734.00
1	Rp	Cs	2	2.10	5.90	8.00	728.4	736.40
1	Rp	Cs	3	4.32	4.65	8.97	728.4	737.37
1	Rp	Sg	1	1.56	-1.45	0.12	728.4	728.52
1	Rp	Sg	2	-0.15	-3.51	-3.66	728.4	724.74
1	Rp	Sg	3	-0.39	-3.60	-3.99	728.4	724.41
1	Rp	CsCp	1	0.39	1.05	1.44	728.4	729.84
1	Rp	CsCp	2	1.14	0.71	1.85	728.4	730.25
1	Rp	CsCp	3	0.99	0.80	1.80	728.4	730.20
1	Rp	CsSg	1	-1.17	-1.65	-2.82	728.4	725.58
1	Rp	CsSg	2	-3.03	-1.39	-4.42	728.4	723.98
1	Rp	CsSg	3	-1.58	-1.60	-3.18	728.4	725.22
1	Rp	SgCp	1	-0.46	-1.66	-2.12	728.4	726.28
1	Rp	SgCp	2	-3.98	-2.97	-6.95	728.4	721.45

1	Rp	SgCp	3	-3.06	-2.11	-5.17	728.4	723.23
2	Mb	Cp	1	-6.75	-3.54	-10.29	350.0	339.71
2	Mb	Cp	2	-7.87	-4.82	-12.69	350.0	337.31
2	Mb	Cp	3	-8.64	-6.48	-15.12	350.0	334.88
2	Mb	Cs	1	-5.05	2.76	-2.30	350.0	347.70
2	Mb	Cs	2	-8.83	-1.88	-10.71	350.0	339.29
2	Mb	Cs	3	-7.56	3.14	-4.42	350.0	345.58
2	Mb	Sg	1	-5.54	-5.65	-11.19	350.0	338.81
2	Mb	Sg	2	-5.49	-4.03	-9.53	350.0	340.47
2	Mb	Sg	3	-7.25	-10.47	-17.73	350.0	332.27
2	Mb	CsCp	1	-11.13	-6.47	-17.60	350.0	332.40
2	Mb	CsCp	2	-10.82	-5.14	-15.97	350.0	334.03
2	Mb	CsCp	3	-9.60	-3.33	-12.93	350.0	337.07
2	Mb	CsSg	1	-3.19	-6.64	-9.83	350.0	340.17
2	Mb	CsSg	2	-1.53	-1.03	-2.56	350.0	347.44
2	Mb	CsSg	3	-1.89	-1.83	-3.72	350.0	346.28
2	Mb	SgCp	1	7.07	4.19	11.26	350.0	361.26
2	Mb	SgCp	2	5.07	3.56	8.63	350.0	358.63
2	Mb	SgCp	3	6.32	4.25	10.57	350.0	360.57
2	Rp	Cp	1	5.10	4.22	9.32	350.0	359.32
2	Rp	Cp	2	4.27	1.79	6.06	350.0	356.06
2	Rp	Cp	3	6.05	4.00	10.05	350.0	360.05
2	Rp	Cs	1	-2.15	-4.19	-6.34	350.0	343.66
2	Rp	Cs	2	-1.65	-0.66	-2.31	350.0	347.69
2	Rp	Cs	3	1.60	0.42	2.01	350.0	352.01
2	Rp	Sg	1	2.97	5.47	8.43	350.0	358.43
2	Rp	Sg	2	1.29	-3.94	-2.65	350.0	347.35
2	Rp	Sg	3	1.96	2.25	4.20	350.0	354.20
2	Rp	CsCp	1	0.00	-2.00	-2.00	350.0	348.00
2	Rp	CsCp	2	0.37	-1.99	-1.61	350.0	348.39
2	Rp	CsCp	3	-0.24	-0.48	-0.72	350.0	349.28
2	Rp	CsSg	1	-6.45	-5.96	-12.41	350.0	337.59
2	Rp	CsSg	2	-5.93	-5.16	-11.09	350.0	338.91
2	Rp	CsSg	3	-6.10	-7.32	-13.41	350.0	336.59
2	Rp	SgCp	1	1.24	-2.09	-0.86	350.0	349.14
2	Rp	SgCp	2	0.23	-6.41	-6.18	350.0	343.82
2	Rp	SgCp	3	0.20	-2.83	-2.64	350.0	347.36
3	Mb	Cp	1	4.04	1.70	5.74	477.0	482.74
3	Mb	Cp	2	5.28	4.78	10.06	477.0	487.06
3	Mb	Cp	3	4.93	3.28	8.21	477.0	485.21
3	Mb	Cp	4	4.93	4.11	9.04	477.0	486.04

3	Mb	Sg	1	-0.05	-0.13	-0.17	477.0	476.83
3	Mb	Sg	2	0.54	0.36	0.90	477.0	477.90
3	Mb	Sg	3	-1.18	-0.74	-1.93	477.0	475.07
3	Mb	Sg	4	-0.21	1.39	1.18	477.0	478.18
3	Mb	SgCp	1	-0.74	0.55	-0.19	477.0	476.81
3	Mb	SgCp	2	-1.11	0.37	-0.74	477.0	476.26
3	Mb	SgCp	3	0.04	0.61	0.65	477.0	477.65
3	Mb	SgCp	4	-0.53	0.27	-0.26	477.0	476.74
3	Rp	Cp	1	-2.33	-0.66	-2.98	477.0	474.02
3	Rp	Cp	2	1.35	3.29	4.64	477.0	481.64
3	Rp	Cp	3	0.68	3.77	4.45	477.0	481.45
3	Rp	Cp	4	0.01	2.81	2.82	477.0	479.82
3	Rp	Sg	1	1.39	-1.17	0.22	477.0	477.22
3	Rp	Sg	2	-0.13	-3.23	-3.36	477.0	473.64
3	Rp	Sg	3	-0.32	-3.14	-3.45	477.0	473.55
3	Rp	Sg	4	0.18	-2.49	-2.31	477.0	474.69
3	Rp	SgCp	1	-0.40	-1.53	-1.93	477.0	475.07
3	Rp	SgCp	2	-3.66	-2.59	-6.24	477.0	470.76
3	Rp	SgCp	3	-2.82	-1.96	-4.78	477.0	472.22
3	Rp	SgCp	4	-3.49	-1.37	-4.87	477.0	472.13

• *Season: 1= Mar-Jul 2010; 2= Aug-Nov 2010; 3= Apr-Jul 2011*

•• *ΔSM was calculated following the approach used by Angus and Harwadeen (2001) and a combined depth of 0-40cm was used to derive the volume of moisture in the soil*

† *Rainfall totals for each season were used*

‡ *ET was estimated using the expression $ET = P + \Delta SM$*

Appendix 10

Accumulated ANOVA for ET in the cassava sorghum cropping systems in eastern Uganda

Source of Variation	*d.f.*	*s.s.*	*m.s.*	*v.r.*	*F pr.*
Rep Stratum	3	12391.53	4130.51	135.31	<.001
Season	2	2672145	1336073	43768.61	<.001
Tillage Practice	1	82.03	82.03	2.69	0.105
Cropping System	5	727.29	145.46	4.77	<.001
Tillage Practice*Cropping System	5	947.17	189.43	6.21	<.001
Residual	79	2411.54	30.53		
Total	95	2688705	28302.16		