WATER USE IN AGROFORESTRY SYSTEMS

By

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SUBMITTED IN FULFILLMENT OF THE ACADEMIC REQUIREMENTS FOR THE DEGREE OF

MSC AGRIC: CROP SCIENCE

IN THE DISCIPLINE OF CROP SCIENCE

COLLEGE OF AGRICULTURE, ENGINEERING, AND SCIENCE

SCHOOL OF AGRICULTURAL, EARTH AND ENVIRONMENTAL SCIENCES

UNIVERSITY OF KWAZULU-NATAL

PIETERMARITZBURG

SOUTH AFRICA

APRIL 2017

PREFACE

The research contained in this thesis was completed while based in the discipline of Crop Science, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa. The research was supported by Institute of Natural Resources.

The content of this work has not been submitted in any form to any other university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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(Professor Simon Lorentz: Co-supervisor)

DECLARATION

I Misheck Musokwa declare that:

1. The research work reported in this thesis, except where otherwise indicated or acknowledged is my original work.
2. This thesis has not been submitted for any degree examination at any other university
3. This thesis does not contain other person`s data, pictures, graphs, or other information unless specifically acknowledged as being source from other researchers.
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6. This study was funded by the Water Research Commission of South Africa (WRC) Project No. K5/2492//4 titled Water use of agroforestry systems for food, forage and/or biofuel production

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(Misheck Musokwa)

As research supervisor, I agree to submission of this thesis for examination

Signed……………………………………………… Date…………………………….
(Professor Paramu L. Mafongoya: Main supervisor)

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(Professor Simon Lorentz: Co-supervisor)

ACKNOWLEDGEMENTS

First and above all, I praise God, the almighty for providing me this opportunity and granting me the capability to proceed successfully. I would like to express my special gratitude and appreciation to my supervisors Prof Paramu Mafongoya and Prof Simon Lorentz for their immense knowledge, support, dedication and encouragement.

I am also extremely thankful to Institute of Natural Resources (INR) for recruiting as postgraduate student. I further wish to express my sincere thanks to Brigid Letty and INR staff who helped me to settle in Pietermaritzburg and make sure that resources were available all times to carry out the research work. My special thanks go to Nonjabulo Bambele, Thabo Makhubedu, Jon McCosh, Zinhle Ntombela and Zanele Shezi for helping in data collection as well as constructive criticism. In addition, I would like to appreciate the technical advice rendered by Dr Tafadzwaunashe Mabhaudi throughout the course of this study.

Sincere gratitude is sincerely extended to the South African Water Research Commission for funding my studies through the Project No. K5/2492//4 titled Water use of agroforestry systems for food, forage and/or biofuel production which was implemented by Institute of Natural Resources. I am grateful to University of KwaZulu-Natal for paving way for my dreams by accepting me and fee remission. I want also to extend my gratitude to Fountainhill Estate management, especially Edwin Gevers for rendering the site to carry out the research work. I also like to acknowledge with gratitude, the support and love of my lovely wife Nyengetarai Mokore, my son Kunashe Lemuel Musokwa, all my relatives and friends

Dedication

To my late brother

Samuel Musokwa (1964-2012)

Who was my inspiration

Abstract

Water scarcity and declining levels of soil fertility are the major causes of low crop productivity under smallholder farmers in Southern Africa. A field experiment was conducted in 2015/16 season at Fountainhill Estate, Wartburg to evaluate water use, water use efficiency, productivity and Land Equivalent ratio in Zea-mays (maize) intercropped with either *Cajanus cajan* (L) Millsp (pigeonpea) or *Sesbania bispinosa* (Jacq) A. Wright var. bispinosa (*S. bispinosa*).The experiment had 5 treatments: sole maize; sole pigeon pea; sole *S. bispinosa*; maize + *S. bispinosa* and maize + pigeonpea laid out in a randomized complete block design (RCBD) replicated three times. Time domain reflectometry (TDR) probes were placed at 20 cm, 50 cm and 120 cm below ground level at each treatment component to measure soil water content. Sole treatments of maize and pigeonpea had significant ($P<0.05$) higher WUE of 6.28 kg/ha mm and 5.77 kg/ha mm respectively. Pigeonpea + maize recorded a significantly ($P<0.05$) higher WUE of 5.47 kg/ha mm. The lowest was recorded on *S. bispinosa* + maize (0.292 kg/ha mm) and sole *S. bispinosa* (0.425 kg/ha mm) subject to the provision that the calculations were based on changes in soil water content rather than actual measurements of water uptake by the trees and crops. Sole maize had significant ($P<0.05$) higher grain yields of 1867 kg/ha while maize + pigeonpea yielded 604 kg/ha and the lowest maize yield was 538 kg/ha from maize + *S. bispinosa*. Pigeonpea had significant ($P<0.05$) higher seed yield of 1073 kg/ha for monoculture and 1029 kg/ha for intercrop as compared to 207 kg/ha for sole *S. bispinosa* and 58.3 kg/ha in intercrop. Land Equivalent ratio (LER) was higher in maize + pigeonpea (1.23), as compared to maize + *S. bispinosa* (0.6). Overall sole maize outperformed maize + tree intercrops in terms of grain yield. The least grain yield was recorded on maize + *S. bispinosa* which again recorded lowest WUE. Sole pigeonpea had higher seed yield although statistically there were no difference with pigeonpea + maize intercrop. In terms of WUE similar results were recorded among sole pigeonpea and pigeonpea + maize. It is beneficial to have a combination of pigeonpea + maize in smallholder farming systems because pigeonpea can act as a 'risk crop' during drought years. This combination is also supported by higher LER values. Despite low yields of maize which can be compensated by the yield, the practice of agroforestry involving pigeonpea saves a substantial (23%) land which can be subsequently be used for other production crops.

Key words: cropping systems, maize, pigeonpea, water use efficiency,

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CHAPTER ONE

1.0 INRODUCTION

Global climate changes have negatively affected the provision of water to agriculture; however, it is one of the major agricultural challenge facing smallholder farmers in sub-Saharan Africa (Gregory and Ingram 2000, Fischer et al., 2005, AGRA 2014). It is projected that by 2050 two thirds of the World`s population will experience water shortages (Rosenzweig et al., 2004). Water is one of the natural resources which will be impacted in an already water-scarce country such as South Africa. Natural resources like water need to be used efficiently to increase food production among smallholder farmers in South Africa. With increasing populations and more pressure on land, increasing outputs per hectare and per unit of water is crucial to improving rural livelihoods.

Climate smart agriculture (CSA) is one of the sustainable options which seek to promote efficient use of natural resources like water. CSA focusses on proven practical technologies such as agroforestry. Agroforestry (AF) is the deliberate incorporation of trees and other woody species of plants with agricultural components (Cornell 2014). Unlike monoculture, agroforestry fosters an agro-ecosystem that is like that of a natural system while improving the productivity and fertility of the agricultural land (Zerihun et al., 2014). The integration of trees and shrubs into cropping systems has the potential to improve the use of available water by intercepting water that has percolated through the root zone of the agronomic crop. Tree roots that access groundwater can increase water use above the levels of rainwater input (Asbjornsen et al., 2011). Agroforestry systems may be used to cope with climate change, which is expected to have a major impact in sub-Saharan Africa where three-quarters of the countries are predicted to experience unstable water supplies and increased exposure to high temperature stress (De Wit and Stankiewicz 2006). Agroforestry systems can improve water productivity mainly by two forms. The availability of trees may increase the quantity of water used for crop or tree transpiration and may also improve the productivity of the water that is transpired by increasing the biomass of trees and crops produced per unit of water used.

Tree species have deeper rooting system as compared to companion crops which have shallow rooting system hence trees theoretically utilize water at soil depths beyond the rooting depths of crops. Studies by Sekiya and Yono (2004) revealed that deeper-rooting species can lift water hydraulically, and providing this water to adjacent crops through a "sprinkler-like" distribution. Hydraulic lift is a process by which deep-rooted plants take in water from lower soil layers and exude that water into upper, drier soil layers hence it is beneficial to the plant transporting the water, and may be an important water source for neighboring plants (Horton and Hart 1998). Hydraulically lifted water can promote greater plant growth, and could have essential implications for net primary productivity, as well as ecosystem nutrient cycling and water balance (Horton and Hart 1998).

Three studies discovered downward transfer of water to deep soil layers which other authors refer it as either “inverse hydraulic lift” (Schulze et al., 1998) or “downward siphoning” (Smith et al., 1999). “Inverse hydraulic lift” was demonstrated in dry sand soil over short measurement period (~3 days), the results showed that it allows the roots of plants growing in water-scarce environments to penetrate dry soil layers and reach deep sources of moisture (Schulze et al., 1998). Simultaneous cropping has been recommended to improve water use efficiency and soil nutrient status in semi-arid regions. Improvement of water use through simultaneous agroforestry systems in semi-arid areas is based on assumed root synergistic effect between crops and trees (Ong et al., 1996). Successful agroforestry systems depend on trees capturing resources that crops cannot. Crop synergistic effect requires that annual and perennial crops should have roots that utilize different soil zones, usually with annual crops exploiting the shallow rooting depths, and perennial crops exploiting the deeper zones (Rethman et al., 2007). Intercropping trees and crops complement each other in terms of root distributions, with tree roots exploiting subsoil and crop roots exploiting topsoil. One of the principal biophysical premises of agroforestry in dryland systems is to conserve and maximize the use of limited water supplies (Broadhead et al., 2003a, Ong et al., 2006). The logic underpinning agroforestry systems is that trees grown in mixtures with crops should either have a beneficial influence, whereby crop performance is enhanced, or should exert minimal competitive effects on associated crops (Ong *et al*., 2006). Research carried out by Siriri (2013) suggests that *Sesbania sesban* can be planted on smallholdings without compromising water supply to adjacent crops.

Pigeonpea (*Cajanus cajan* (L) Millsp) is a multipurpose legume has a potential to improve soil fertility. In terms of its ecological services, pigeonpea is useful as an intercrop, in agroforestry systems. Thus, it is an important pulse legume grown due to its wide range of products (Dasbak and Asiegbu 2009). Pigeonpea is an excellent source of organic nitrogen and nutrient recycling. It increases organic matter and improves the soil structure and the soil quality.

In South Africa, pigeonpea is not widely grown as a field crop. However, pigeonpea can also serve as an important grain legume crop that can be used in rural areas for human consumption and supplements the range of food crops available. In addition, pigeonpea is usually grown singly or as a hedge plant in home gardens or around the sugarcane (*Saccharum officinarum*) fields (Saxena et al., 2001). Mathews (2001) reported that maize can be intercropped with pigeonpea. Therefore, maize (Zea mays (L.) is a major cereal crop grown in South Africa for human consumption, for livestock feed and for industrial purposes. Soil moisture stress is a problem for many farmers who continue cultivating maize under rainfed conditions. The erratic nature of rainfall, including distribution leads maize to severe soil moisture stress; reducing yields significantly. Poor soil fertility is also one of the challenges for small-scale farmers (AGRA, 2014).

1.1 PROBLEM STATEMENT

In South Africa, less than 15% of the land is arable. Beside the limited arable land; water scarcity and declining levels of soil fertility is another challenges threatening agricultural productivity among smallholder farmers. The rainfall is below the world-average, and its distribution is unreable. This challenge is persisting each year as evidenced during the 2015-16 season when significant rainfall events were limited to most of the central regions of the country (DWA 2013, RSA Food Security Bulletin - January 2016).

Research conducted on rural small-scale farmers in KwaZulu-Natal has revealed shortage of water and expensive chemical fertilizers as major limitations of agricultural productivity (Everson et al., 2011). These factors have led to low land productivity. One way to abate this problem is to improve land and water productivity through intensification of agroforestry systems. Agroforestry systems, (whereby trees are intentionally combined or planted with food/forage crops for the benefit of humans and the environment) have been reported to be potentially productive in degraded and marginal soils. Simultaneous agroforestry systems involving legume trees such *Cajanus cajan* (L) Millsp (pigeonpea) and *Sesbania bispinosa* (Jacq) A. Wright var. bispinosa (*S. bispinosa*). intercropped with *Zea-mays* (maize) can increase productivity through soil nitrogen fixation and improve water use efficiency (AGRA 2014).

1.2 MAIN OBJECTIVE

To evaluate simultaneous agroforestry system (maize + legume tree) as compared to sole cropping in terms of productivity, land equivalent ratio (LER), water use (WU) and water use efficiency (WUE).

1.2.1 Specific objectives

i. To evaluate water, use and water use efficiency in maize intercropped with either pigeonpea or *S. bispinosa***.**

ii. To evaluate productivity and Land Equivalent ratio of maize intercropped with either pigeonpea or *S. bispinosa*

1.2.2 Hypothesis

i Intercropping maize with either pigeonpea or *S. bispinosa* would result in low water use and high water use efficiency (WUE) as compared to sole cropping.

ii Intercropping maize with either pigeonpea or *S. bispinosa* would result higher land productivity and Land Equivalent ratio as compared to sole cropping.

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CHAPTER TWO

LITERATURE REVIEW

2.0 INTRODUCTION

Rainfall is decreasing across sub-Saharan Africa which implies food shortages if the current farming practices do not `shift` to cope with these changes. Low rainfall is a serious challenge as most of the agricultural systems of southern Africa rely on rain-fed agriculture as irrigation systems are not well developed (Camberlin et al., 2009). In Sub-Saharan Africa agriculture represents the main water-consuming sector. Measures to increase water use efficiency and enhance resilience of the agricultural system are particularly relevant in coping with future climate variability developments (AGRA 2014).

Agroforestry practices is one of the sustainable agricultural systems which improve water use efficiency. There are several agroforestry mechanisms which use available water more effectively than the annual monocropping systems where land is bare for longer periods. Agroforestry systems with perennial tree component make use of the remaining water in the soil after harvest and the rainfall received outside the crop season. Agroforestry increase productivity of rain water by reducing runoff and by using the water stored in deep layers. The changes in microclimate (lower temperature, wind speed and saturation deficit of crops) reduce the evaporative demand and make more water available for transpiration. The tree canopies in agroforestry systems intercept the rain and reduce runoff (Khan et al., 1995). Annual crop systems use 30 to 35% of rain water, and the remaining is wasted through soil evaporation, surface runoff, or is lost in residual humidity at the end of harvest (Ong et al., 2006). Agroforestry system presents the opportunity of complementing water use both spatially and temporally, which can result in better water use in comparison with single crops (Ong et al., 1996).

The success of agroforestry systems in semi-arid areas depends on efficient use of available water and maximum productivity. Water use efficiency (WUE) is the biomass produced per unit of water transpired (Everson et al., 2011), while water productivity refers to the ratio of the net benefits from rainfed cropping or other agricultural production systems, to the amount of water required to produce those benefits (Molden et al., 2010). Unlike water use efficiency, which calculates crop yield per unit water used, water use productivity considers broader objectives of producing more food, income, livelihoods, and ecological benefits at less social and environmental cost per unit of water used (Green et al., 2011, Molden et al., 2007: 2010, Igbadun et al., 2005). Limited water supplies usually affect biomass production, mostly in annual cropping systems, as residual water in the soil profile following harvest of annual crops and off-season rainfall is not used (Ong et al., 2006). A major question in agroforestry water use systems is, does intercropping trees and crops increase total harvestable produce by making effective use of rainfall water? In theory, it is possible in a situation where rainfall is not completely used, that the inclusion of trees may improve rainfall water use efficiency in two ways. More rain used as transpiration, or indirectly as by improved transpiration efficiency which translates to more dry matter produced per unit of water transpired.

2. 1 Definition of Agroforestry

Agroforestry is an integrated land use management system where trees or shrubs are deliberately cultivated on the same piece of land as crops and / or livestock (Killough et al., 2002). Agroforestry has gained attention in recent years due to its potential to increase food production among smallholder farmers in Sub-Saharan Africa (Garrity et al., 2010)

2.2 Highlights of Agroforestry Systems/Technologies in Southern Africa

Agroforestry (AF) was introduced in South Africa around 1887 (Nair 1993), However, it was lagging behind in terms of agroforestry research and development as compared to other southern African countries which include Malawi, Namibia, Tanzania, Zambia, and Zimbabwe who have benefited from the Southern African Development Community (SADC)-International Center for Research in Agroforestry (ICRAF) now called World Agroforestry Centre Zambezi Basin AF Project since the mid-1990s. Since then agroforestry technologies have increasingly become available to smallholder farmers in Southern Africa (Mafongoya et al., 2000, Sileshi et al., 2011). Most promising low cost agroforestry practices for soil fertility replenishment are the use of improved tree fallows, biomass transfer, relay cropping and mixed inter- cropping (Ajayi et al., 2008, Ajayi and Catacutun 2012, Kuntashula et al., 2004). Other technologies that have been developed include fodder (Angima et al., 2002, Guto et al., 2011), domestication of indigenous fruit trees (Akinnifesi et al., 2004) and fuelwood provision (Liyama et al., 2014**).**

2.3 Tree Crop Interactions

Agroforestry is a method of farming in which trees are grown as part of an agricultural system. Integrating agroforestry with traditional agricultural systems has the potential to provide the ecosystem management benefits of trees while maintaining profitable growth of traditional crops (Ong et al., 2002). There are several mechanisms in which the components of an agroforestry system can be integrated spatial or temporal. In some systems, trees are grown in association with field crops (maize grown with pigeonpea). Examples include isolated trees in fields (*Faidherbia albida)* trees in West Africa), trees grown as windbreaks and trees providing cover for a shade tolerant crops such as *coffee arabica*. In other systems, spatial arrangement changes with time: for example, taungya systems of southeast Asia, high-value timber trees are grown amongst annual crops and is allowed overshadow the crop. And in other systems, such as improved fallows, the trees and the annual crop are not grown together at the same time. The central biophysical hypothesis of agroforestry (Cannell 1996), is that for the system to outperform a monoculture, the trees must acquire nutrients, water or sunlight that would not have been acquired by the crop. The basic sequence which explains the effect of agroforestry trees on crop yield can be described as follows:

$$\mathrm{I} = \mathrm{F} - \mathrm{C} \qquad \text{Equation 2-1}$$

Where $\mathrm{I} = \text{increase in crop yield}$

$\mathrm{F} = \text{soil fertility} - \text{ enhancing effect of trees}$

$\mathrm{C} = \text{competitive effect of trees}$

This can be further refined as:

$$\mathrm{I} = \mathrm{Fnoncomp} - \mathrm{Ccomp, nonrecyc} \qquad \text{Equation 2-2}$$

$$\mathrm{Fnoncomp} = \text{fertility} - \text{enhancing effect of trees that does not depend on resources obtained competitively from the crop} \qquad \text{Equation 2-3}$$

$$\mathrm{Ccomp, nonrecyc} = \text{competition effect of trees due to the appropriation of resources that are not ultimately recycled back to the crop}$$

Agroforestry trees can benefit the crop indirectly through effects on microclimate, water, and soil conservation.

These biophysical explanations of complementarity do not involve the more complicated issue of economic complementarity. Beside from their direct impact on crop yields, agroforestry trees also provide the farmer with other essential benefits such as fodder, fruit, fuelwood, timber, nuts, honey, and medicine which can generate cash income, as well as biodiversity conservation and carbon sequestration. Depending on the timing and the value of these other outputs, this economic complementarity can also justify the use of an agroforestry system even when the crop does not directly benefit.

Despite all the benefits associated with agroforestry, competition between the crops and trees remains a challenge (Ong et al., 2007, Sun et al., 2008, Siriri et al., 2010). In the agroforestry system, there should be a better utilization of resources such as light, water and nutrients, however, this can only happen if trees are complementary rather competitive with the associated crops (Ong et al., 2007). Spatial complementarity means the trees and crops would exploit different resource pools and temporal complementarity means trees and crops impose demands on available resources at different times (Black and Ong 2000, Broadhead et al., 2003a, Ong et al., 2006).

The main aim of simultaneous agroforestry system is to create positive interactions between woody perennials, herbaceous crops and pastures and their biotic and abiotic environments which improve the overall performance of the land use system and its sustainability (Schroth et al., 1995). These interactions are classified into two categories which include aboveground and below ground interactions.

2.3.1 Above ground interactions

Combining trees and agricultural cropping systems have multiple ecological effects. The tree canopy intercepts rainfall and reduces impact of raindrop. In South Africa measurement of below different types of canopies showed the importance of water interception by the canopy (average of 15%) and by the litter (>7%) before infiltration (Bulcock and Jewit 2012).

In Kenya, *Acacia tortilis* and *Adansonia digitata* trees in savanna systems have been found to improve the microclimatic conditions of the understorey component. The thermal environment was moderated and incident radiation and atmospheric saturation vapour deficit was reduced and ultimately growth was improved (Ong et al., 2007). Tree canopy of *Acacia. tortilis* reduced the availability of photosynthetically active radiation (PAR) under the canopy, which lowered the temperature and raised the relative humidity (Mishra et al., 2010). In combination, these factors led to reduced evapo-transpiration, which resulted in increased soil moisture content. The canopy also resulted in an increase in height of the grass below, but was also associated with a decrease in the number of leaves and tillers per tuft, which reduced the leaf area index under the tree canopies. There was also an increase in the quantity of chlorophyll b, which is normally associated with shade-tolerant grasses (Mishra et al., 2010). In another study gliricidia + cacao agroforests in Indonesia had 12% higher relative humidity than sole cacao (Steffan-Dewenter et al., 2007), shaded *coffee arabica* agroforests in Mexico had 32% lower evaporative demand than unshaded systems (Lin 2010).

The presence of trees can reduce evaporative demand in crop canopies not only by affecting air and soil temperature, but also by increasing local humidity via transpiration and by reducing wind speed. Some studies have shown that size of the tree crown rather than the density of the crown has a negative impact on above-ground net primary production of grass in an agroforestry system. Shading also resulted in a change in composition of the grassland, leading to a higher biomass of forbs, which are more tolerant of low levels of irradiance, having C_3 metabolism (Rusch et al., 2014).

2.3.2 Below ground interactions

Below ground interactions can be facilitative, complementary or competitive. An example of a facilitative relationship is soil physical improvement or supply of hydraulically lifted water. Complementarity would be the case of trees using water that is below the rooting zone of the crop, while competitive interactions would be the case of trees using limited resources from the same pool as the crop (Fernandez et al., 2008).

Soil water content shows temporal and spatial variation because of the variability of soil properties and the existence of soil water sinks/sources (Beff et al., 2013). Ecohydrological processes in watersheds are tightly coupled with soil properties. For example, soil texture and soil depth control the available soil water, which in turn controls leaf area index (LAI), which increases under abundant soil moisture availability. The interactions between the spatial patterns of plant communities and soil patterns is recognized since plants are affected by soil moisture as well as nutrient availability and soil properties affect resource pools (Robinson et al., 2008).

Where subsoil conditions affect root penetration of the tree crop, there is greater competition with the crop for soil water. Furthermore, water balance simulations demonstrated that during dry periods when deeper soil layers are not recharged, there is more competition with the crop (Rethman et al., 2012). Competition for moisture, which generally is a problem close to the hedgerow of an alley cropping system, can result in severe reductions in crop yield. In fact, yield reductions are mainly due to competition for water and under these conditions it is necessary to reduce the population of the tree species. Smith et al., (1999) argued that if the population is reduced to reduce their demand for water then this will diminish their benefits for nutrient cycling as well as their social and economic benefits. It is necessary to determine the optimum spacing where the benefits exceed the costs of competition.

Studies on soil-water competition in South Africa involving a hedgerow system using four tree species (Acacia *karoo, Leucaena leucocephala, Morus alba* and *Gleditsia triacanthos*). The area received good rainfall for the duration of the trial and the plants were not stressed (under these conditions the trees did not compete with the crop for water). Across all tree species, the soil water content in the upper 0.3 m did not differ significantly between the maize and tree rows so competition for water in the upper horizon was not responsible for the reduced maize yields. (Everson et al., 2009). At greater soil depth, the trees with narrow spacing used more water than those at wider spacing. Light interception was also responsible for reducing maize yields in the line closest to the tree row – this might call for a wider gap between the tree and row and the first line of the crop. Everson et al., (2009) also mentioned that other authors are suggesting that in water-limited environments spatial complementarity may be limited to situations where the tree crop has access to deeper ground water reserves.

Generally, it is understood that trees with few superficial lateral roots are more suited to agroforestry as they will compete less with the crop, but a study of a *Grevillea robusta* + maize system in a semiarid region (with annual rainfall 782 mm) in Kenya revealed that there was no spatial separation of the two root systems and therefore there was still competition for water. In short there needs to be sufficient rainfall to allow for recharge of the soil below the rooting zone of the crop if complementary water use is to occur (Smith et al., 1999). Smith et al., (1999) found that when low rainfall was experienced, the inclusion of trees reduced the length of maize roots, but was not affected by proximity to the trees. When the rains were good and the trees were severely pruned then the tree roots did not have this effect. Complementarity between trees and crops in the AF system is most likely to be achieved when the trees have access to an alternative source of water (Smith et al., 1999). Alternatively, there needs to be sufficient drainage for large quantities of water to be stored beyond the root zone of the crop, but this is potentially not likely in semi-arid areas (Smith et al., 1999).

Lehmann et al., (1998) investigated the effects of intercropping *Acacia saligna* and sorghum (4 m alley width) in a part of Kenya with an annual rainfall of 318 mm. The authors explored the effect on root distribution of the two components. Comparing alley cropping with sole cropping, it was found that the sorghum had more roots in the topsoil while the trees had more roots in the subsoil. Soil water depletion was higher under the tree row than in the alley. It was concluded that the alley cropping arrangement made more efficient use of the soil water between the hedgerows because the trees' roots could reach deeper while the sorghum could use topsoil water better (i.e. the trees made use of different root zones). Lehmann et al., (1998) found that the sorghum roots invaded into the main root zone of the trees. They suggested that this was due to greater N availability under the trees which may have stimulated root production of the sorghum or the trees could have provided hydraulic lift and supplied water to the annual crop. The phenomenon of hydraulic lift was proposed as a possibility by Fernandez et al., (2008) considering an agroforestry system combining ponderosa pine trees and a patagonian grass in a temperate semi-arid area. Evidence of hydraulic lift is the detection of reverse fluxes in roots during the night (Fernandez et al., 2008, Ludwig et al., 2003).

2. 4 Agroforestry system improves water use (WU) and water use efficiency (WUE)

Water use efficiency (WUE) is defined as the biomass produced per unit of water transpired (Everson et al., 2011), while water use productivity refers to the ratio of the net benefits from rainfed cropping (or other agricultural production systems), to the amount of water required to produce those benefits (Molden et al., 2010). Unlike water use efficiency, which calculates crop yield per unit water used, water use productivity considers broader objectives of producing more food, income, livelihoods, and ecological benefits at less social and environmental cost per unit of water used (Green et al., 2011, Molden et al., 2007, 2010, Igbadun et al., 2005). Ong et al., (2007) concluded that agroforestry can potentially improve water use productivity by either (1) increasing the quantity of water used for tree or crop transpiration or (2) improving the productivity of water transpired by increasing the biomass of trees and crops produced per unit of water used.

Intercropping has been recommended to improve water use efficiency and soil nutrient status in semi-arid regions (Ong et al., 2006). Successful agroforestry systems depend on trees capturing resources that crops cannot access. Crop cooperation requires that annual and perennial crops should have roots that use different soil zones, usually with annual crops exploiting the shallow rooting depths, and perennial crops using the deeper zones (Rethman et al., 2007). Lehmann et al., (1998) concluded that root length density decreased more with depth in wet seasons than in dry seasons, which means that intercropped trees tend to penetrate deeper during dry periods scavenging for soil water. Lehmann et al., (1998) argued that intercropping resulted in the spatial separation of the root systems of trees and crops between the hedgerows, with more crop roots in the topsoil and tree roots in the subsoil as compared to monocultures.

Soil water depletion was higher for hedgerow soils than for monocultures, and higher under the tree row than in the intercrop. Lehmann et al., (1998) argued that agroforestry system used the water between the intercropped more efficiently than the sole-cropped trees or crops.

Cropping systems in semi-arid regions often use less than half of rainfall water due to significant losses of water through evaporation, runoff and drainage (Ong et al., 2006). Studies showed that annual cropping systems do not make use of available rainfall to its full potential (Ong et al., 2006). Substantial losses from runoff (26%), deep drainage (33-40%) and soil surface evaporation (up to 40%) were reported by Ong et al., (2007). Simultaneous agroforestry systems provide an opportunity to improve water use both spatially and temporally (Ong et al., 1996). Tree roots that access groundwater can increase water use above the levels of rainwater input (Asbjornsen et al., 2011). Tree roots can use water accumulated deeper in the soil profile, which can benefit crop growth, resulting in water deficit for shallow rooted crops (Nyamadzawo et al., 2012) and can use residual available water outside the crop growing season (Ong et al., 2002, Barrios and Ong 2004).

A study on investigation of water use in a grevillea + maize agroforestry system in semi-arid regions of Kenya found that the agroforestry system used water more efficiently that annual cropping systems (Lott et al., 2003). Tree species have deeper rooting system as compared to companion crops which have shallow-rooting system hence trees theoretically they make use of water at soil depths beyond the rooting depths of crops. Gebrekirstos et al., (2011) investigated the relationships between annual wood stable carbon isotope composition ($\delta^{13}C$), dry season midday plant water potential, and annual growth rate to assess the water use efficiency of agroforestry species. The results of the study revealed that species with lower mean $\delta^{13}C$ values showed high plant water potential and hence better growth during moist years. Thus, indicating low water use efficiency. On the other hand, species with lower water potentials showed relatively better growth performance and less increase in $\delta^{13}C$ in drought years, reflecting their high WUE and conservative water use strategy (Gebrekirstos et al., 2011).

2.5 Hydraulic lift a mechanism for facilitating water movement in agroforestry

Hydraulic lift is a process by which deep-rooted plants take in water from lower soil layers and release that water into upper, drier soil layers. This is beneficial to the plant transporting the water, and may be an essential water source for neighbouring plants (Horton and Hart 1998). Trees can bring water up from depth and release it into the surface layers of the soil in a process called hydraulic lift (Caldwell et al., 1998). This effect has been demonstrated in the agroforestry species *Cajanus cajan*, though no such effect could be found for *Sesbania sesban* (Sekiya and Yano, 2004). In this process water movement is from relatively moist to dry soil layers using plant root systems as a conduit. At night when transpiration ceases and water is not used for photosynthesis, it is released from the roots into the upper soil layers then absorbed the next day and transpired. (Ludwig et al., 2003, Ward et al., 2013). Under dry conditions, a tree is unlikely to release water into surface soils, thus its net effect on nearby shallow-rooted species will likely still be neutral or negative (Ludwig et al., 2003). Part of the process involves reverse flow, i.e., passive movement of water from roots to soil when reduced transpiration allows xylem water potential to rise above water potential in drier soil layers. Studies by Sekiya and Yono (2004) proved that deeper-rooting species can lift water hydraulically, and providing this water to companion crops through a "sprinkler-like" distribution.

Hydraulically lifted water can promote greater plant growth, and could have important implications for net primary productivity, as well as ecosystem nutrient cycling and water balance (Horton and Hart 1998). The opposite of hydraulic lift has been reported in Machakos and elsewhere, where water is taken from the topsoil and transported by roots into the subsoil (Smith et al., 1999). This mechanism, termed 'downward siphoning' by Smith et al., (1999), other authors have termed either 'inverse hydraulic lift' (Schulze et al., 1998), would lead to the opposite effect of hydraulic lift and would enhance the competitiveness of deep-rooted trees and shrubs. An "inverse hydraulic lift" was proved by Schulze et al., (1998) in very dry sand over a short measurement period (~3 days) and he interpreted the importance of this process as mainly allowing the roots of plants growing in water scarce environments to penetrate dry soil layers and reach deep sources of moisture. Deeper-rooting tree species have been proven not only lifting water hydraulically for their own use, but to also transfer lifted water to surrounding plants (Sekiya and Yono (2004) using deuterium isotopes to observe hydraulic lift by leguminous companion crops, pigeonpea and sesbania in a study in semi-arid Zambia, noted that through hydraulic lift, water was made available not only to the legume, but also to the accompanying intercrop, maize. Sekiya and Yono (2004) also noted that the "sprinkler" effect of distribution to accompanying crops occurred only with pigeonpea, and not with Sesbania. Liste and White (2008) discussed the implications of hydraulic lift for crop production and land restoration. They argued that hydraulic lift acts as a biological subsurface sprinkler and provides additional water to the roots exposed to soil drying. Additionally, hydraulic lift has a beneficial effect on nutrient uptake and rhizosphere biology.

2.6 Agroforestry systems improves infiltration and reduce runoff

Agroforestry (AF) system enhances water infiltration, improves soil water storage capacity, reduces runoff, and changes the macro porosity and mesoporosity of the soil (Anderson et al., 2009). Increase in soil infiltration rates through several ways: improves soil structure and porosity, channels left by dead tree roots (Chirwa et al., 2003b), and changes in small-scale soil topography (Lin and Richards 2007). Many studies found that above ground stems and roots can reduce the runoff flow rate and enhance sedimentation and water infiltration (Seobi et al., 2005). Bharati et al., (2002) found that infiltration rates were five times greater in multi-species riparian buffer than that of cultivated and grazed fields. Many AF trees have large and deep roots, that when they grow and decay, result in a greater proportion of larger pores in the soil. Thus, soil hydraulic properties are improved (Anderson et al., 2009). This benefit is very important in clay pan soils since these soils have low hydraulic conductivity.

Wang et al., (2015) investigated the effect of agroforestry systems on soil infiltration over a period of 11 years. The study determined the regularity of infiltration and its relationship with rainfall temporal distribution. The results of the study showed that the temporal distribution of infiltration rate in alley cropping systems had a strong relationship with temporal distribution of rainfall when compared with monoculture systems. However, it was also realized that the alley cropping effect on infiltration capacity was only significant in shallow soil layers (Wang et al., 2015). Besides improving grain yields of maize in rotation, sesbania fallows have the potential to recharge the subsoil water through increased subsurface drainage and increase nitrate leaching below the crop root zone in excess rainfall seasons in depleted soils of eastern Zambia (Phiri et al., 2003).

2.7 Maize Production in South Africa

Maize (*Zea mays L.*) is the most essential grain crop in South Africa and is produced throughout the country under diverse environments (ARC-Grain Crops Institute 2003).

Nearly all resource produces maize - poor farmers in South Africa from within the semi-arid regions to the high rainfall provinces. Dryland production of maize takes place mainly in the Free State (34%), North West (32%), Mpumalanga (24%), Limpopo (17%) and KwaZulu-Natal (3%) provinces (RSA Food Security Bulletin -January 2016). The main growing season under rainfed conditions is between October and March. Maize is very sensitive to drought and the optimal rainfall requirement is between 500-1000 mm. Smallholder farmers grow maize during the rainy season and very little is grown during the dry season.

The main limitations to crop growth and production in African soils are nitrogen and phosphorus which must be supplied in large quantities. The escalating prices of inorganic fertilizers on the world market have threatened African farmers' hopes of improving their farm productivity (Hargrove 2008). Inorganic fertilizers are an important means of restoring soil fertility, but the prices are escalating, putting fertilizer use further out of reach by most smallholder farmers.

Research conducted on rural small-scale farmers in KwaZulu-Natal, South Africa has revealed many challenges which include expensive inorganic fertilizer and shortage of water (Everson. et al., 2011). Maize can therefore benefit from nitrogen fixing tree species in agroforestry systems. Frequent drought periods during the rainy season or delays in the start of the rains often reduce crop yields (Sanchez, 1995). Mulch from tree species can retain moisture and increase crop yields.

2.8 Competition indices

Various indices such as land equivalent ratio, competitive ratio, relative crowding coefficient, actual yield loss have been established to explain competition within advantages of intercropping systems (Agegnehu et al., 2006, Banik et al., 2006, Dhima et al., 2007). These indices may be equally used in agroforestry systems. The beneficial effect of the trees intercropped with crops, can be justified by the land equivalence ratio (LER). LER verifies the effectiveness of the intercropping for using resources of the environment compared to sole cropping (Workayehu 2014):

- The Land Equivalent ratio (LER) can be used to determine land productivity in agroforestry systems involving fertilizer trees and cereal (Ijoyah et al., 2013, Workayehu 2014).
- When LER is greater than one (LER>1), the intercropping favours the growth and yield of species. In contrast, when LER is lower than one (LER<1) intercropping negatively affects the growth and yield grown in mixtures (Dhima et al., 2007).
- Aggressivity (A), which is often used to determine the competitive relationship between two crops used in mixed cropping (Dhima et al., 2007).
- The third coefficient is the Relative Crowding coefficient (K) which is a measure of the relative dominance of one species over the other in association (Banik et al., 2006).
- Competition ratio (CR) is another way to assess competition between different species.
- CR gives more desirable competitive ability for the crops and is also advantageous as an index over K and Actual Yield Loss (AYL) (Dhima et al., 2007).
- The CR represents simply the ratio of individual LER of the two components and considers the proportion of the crops in which they are initially sown.
- Actual yield loss (AYL) index, which gave more accurate information about the competition than the other indices between and within the component species and the

behaviour of each species in the intercropping system, as it is based on yield per plant (Banik et al., 2000).

- The AYL is the proportionate yield loss or gain of intercrops in comparison to the respective sole crop for example it considers the actual sown proportion of the component crops and with sole crop stand.

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CHAPTER THREE

Evaluation of agroforestry systems for Maize (*Zea mays L*.) productivity in South Africa

Abstract

Maize (*Zea mays* L) is the staple food crop grown by most smallholder farmers in South Africa. Low inherent soil fertility is one of the identified limitations in maize production under smallholder farming systems. A field experiment was established in 2015/16 season at Fountainhill, Wartburg where maize was intercropped with pigeonpea or *S. bispinosa* to test the hypothesis that pigeonpea or *S. bispinosa* trees may be used to support maize production in subsistence farming systems where inorganic fertilizers are either unavailable or expensive and to evaluate competition between trees and maize crop using different competition indices. The experiment had 5 treatments: sole maize; sole *Cajanus cajan* (L) Millsp (pigeonpea) and *Sesbania bispinosa* (Jacq) A. Wright var. bispinosa (*S. bispinosa*); maize + *S. bispinosa*; and maize + pigeonpea laid out in a randomized complete block design replicated three times. Sole maize had significant (P>0.05) higher grain yields of 1867 kg/ha while maize + pigeonpea yielded 604 kg/ha and maize + *S. bispinosa* being the least with 538 kg/ha. Land equivalent ratio (LER) were higher in maize-pigeonpea (1.23), as compared to maize + *S. bispinosa* (0.6). Pigeonpea is recommended in agroforestry systems with maize due to its higher land equivalent ratio and combined production of grain for human and livestock consumption, soil fertility replenishments and firewood.

Key words: land equivalent ratio, pigeonpea, soil fertility

3.0 INTRODUCTION

Maize (*Zea mays* L) is the dominant staple food crop grown by most smallholder farmers in South Africa (Mashingaidze 2006). Low inherent soil fertility is one of the identified limitations in maize production in the smallholder farming systems (Swift et al., 2007). Agroforestry soil fertility replenishment systems have been adopted by smallholder farmers in southern Africa to solve the problem of inherent low soil fertility. Agroforestry fertilizer tree systems were developed as a technological innovation to help smallholder farmers build soil organic matter and fertility in their fields (Mafongoya et al., 2006, Oluyede et al., 2011). The escalating prices of inorganic fertilizers on the world market have threatened African farmers' hopes of improving their productivity (Hargrove 2008). Research conducted in KwaZulu-Natal, South Africa, has revealed expensive chemical fertilizer as one of the challenges faced by small-scale farmers (Everson et al., 2011). Chemical fertilizers are an essential means of restoring soil fertility, but the prices are escalating, putting fertilizer use out of reach by most smallholder farmers. Fertilizer use alone is not enough to address the biological and physical degradation of soils. Fertilizer response is also very low on already degraded soils (Sileshi et al., 2009). Even if inorganic fertilizers are readily available for use, if the field is not managed well (through incorporation of organic inputs and conservation practices), fertilizers will not be utilized by the crop more efficiently as much of it will be lost though leaching and soil erosion (Sileshi et al., 2009).

In simultaneous agroforestry systems, the crops and trees co-exist at the same time on the same piece of land. It is a recognized practice for economizing the use of growth resources and increasing the productivity per unit area and time. In maize intercropping system, selection of an appropriate intercrop having a desirable crop type and growth pattern assumes greater importance (Mucheru-Muna et al., 2010). One of the main aim of the agroforestry systems is to maximize use of production resources such as nutrients, light, water and space (Ong et al., 2006).

Competition among intercrops is believed to be the main factor affecting yield as compared to sole cropping (Banik et al., 2000). In fact, yield benefit occurs when intercrop components compete only partly for the same crop growth resources when interspecific competition is less than intraspecific competition (Andersen et al., 2009). Ideally, species suitable for intercropping should enhance synergistic effects of intercropping. In this case, yield of one species surpasses the other and makes up for the inferior performance of the component crop (Hauggaard-Nielsen and Jensen 2001). Smallholder farmers in the semi-arid tropics intercrop cereals with grain legumes, especially pigeonpea (*Cajanus cajan L. Millsp*.), as a strategy for diversifying food production and household income since the legumes are both cash and food crops (Rao and Mathuva, 2000, Mafongoya et al., 2006).

Several indices such as Land Equivalent ratio (LER), Relative crowding coefficient (K), Competitive ratio, Aggressivity (A), Actual yield loss (AYL) have been developed to describe competition (Banik et al. 2006, Dhima et al., 2007). However, such indices have not been used in simultaneous agroforestry systems involving maize intercropped with legume trees in South Africa.

In the present study, maize was intercropped with pigeonpea or *S. bispinosa* to test the hypothesis that pigeonpea or *S. bispinosa* trees may be used to support maize production in subsistence farming systems where inorganic fertilizers are either unavailable or expensive. Specific objectives were to evaluate grain yields and productivity in cropping systems containing maize, pigeonpea and *S. bispinosa* to evaluate competition between trees and maize crop using different competition indices.

3.1 MATERIALS AND METHODS

3.1.1Study site

The experiment was established at Fountainhill Estate (latitude 29°27'2" S; longitude 30°32'42" E and altitude 853 m above sea level) in the uMshwathi Local Municipality, near Wartburg approximately 30km northeast of Pietermaritzburg in KwaZulu-Natal, South Africa. The vegetation type of the area is Ngongoni veld, with an annual precipitation of 805 mm. The minimum temperature is 3.3 °C and the maximum is 37.4°C,

3.1.2 Agroforestry system to be tested

Research conducted on rural small-scale farmers in KwaZulu-Natal, South Africa have revealed many challenges which include expensive inorganic fertilizer, a shortage of water and a lack of suitable crops (Everson et al., 2011). In response to the declining soil fertility in southern Africa and the negative effects that it has brought, such as food insecurity, fertilizer tree systems were developed as technological innovation to help smallholder farmers to build soil organic matter and fertility in a sustainable manner (Oluyede et al., 2011). Studies by Mafongoya et al., (2006) revealed that simultaneous agroforestry (AF) is one of the options appropriate and available to smallholder farmers to replenish soil fertility in Southern Africa.

3.1.3 General information on legume trees in simultaneous agroforestry system

Pigeonpea (*Cajanus cajan* (L) Millsp) is a multipurpose legume tree. It is grown for its wide range of products (Dasbak and Asiegbu, 2009). Biological Nitrogen Fixation and nutrient recycling is one the most important trait. The tree exhibits biological ploughing due to deep rooting systems-breaking hard pans thereby improves soil structure (Mafongoya et al., 2006).

In South Africa, pigeonpea is usually grown singly or as a hedge plant in home gardens or around sugarcane (*Saccharum officinarum*) fields (Mathews and Saxena 2005). Being one of the most drought tolerant legumes, pigeonpea has a great potential to increase the sustainability of cropping systems in the arid and semi-arid regions

Sesbania bispinosa (Jacq) A. Wright var. bispinosa (*S. bispinosa*) is a legume plant which fixes atmospheric nitrogen can grow in alkaline or saline soils of low fertility. It is recommended for nutrient cycling. *S. bispinosa* has been incorporated in agroforestry practices in mixed-farming systems (Orwa et al., 2009).

3.1.5 Experimental design and treatments

The experiment had five treatments (1) sole maize, *(*2) sole pigeonpea, (3) sole *S. bispinosa* (4) maize + *S. bispinosa,* (5) maize + pigeonpea. The experiment was laid out in a randomized complete block design (RCBD) replicated three times as shown in table 3.1.

Table 3.1 Plot layout at Fountainhill Estate

Rep I	1. Mz + Sb	2. Mz + Pp	3. Pp	4. Sb	5. Mz
Rep II	6. Mz + Pp	7. Mz	8. Pp	9. Mz + Sb	10.Sb
Rep III	11. Mz + Sb	12. Pp	13. Mz	14. Mz + Pp	15. Sb

Where Mz=maize, Sb=*S. bispinosa*, Pp=pigeonpea

3.1.6 Soil sampling

Soil samples were taken from the study site using a soil auger at 0-20 cm soil depths across 8 points within the experimental field before planting. Laboratory analyses were done at Cedara where the following pH, N, P, K, Mg, Ca and organic carbon percentage were determined.

3.1.7 Trial establishment and management

The field was then ploughed using a disc plough in December 2015. Planting was done in January 2016. Raised seedlings of *S. bispinosa* were watered after transplanting. During planting Pigeonpea was direct seeded and an open pollinated maize variety, Okavango, which was selected on the basis that smallholder farmers usually retain seed. Two legume tree species (pigeonpea and *S. bispinosa*) were planted at spacing of 1 m inter-row and 1 m intra-row spacing, while the mixed crop of trees and maize had 1 m inter-row and 0.4 m intra row spacing. Sole maize had 0.8 m inter-row and 0.5 m intra-row spacing with 120 plants per plot but the same maize plant population was maintained of 25 000 plants/hectare. Each treatment was replicated three times consisting 15 plots (6 m x 8 m) representing five treatment. 576 trees were planted for the whole trial while each replication had 192 trees, which translate to 48 trees per plot. The trial area was sprayed with 3 L/ha of glyphosate prior to ploughing. Weeds were controlled twice during the entire growing season using hand-hoes.

3.1.8 Maize growth, development and yield measurement procedures

Data were recorded for various agronomic traits on a plot basis, as described by Magorokosho et al., (2009). A phonological event was deemed to have occurred if it was observed in at least 50% of plants. Days to maturity was defined in terms of physiological maturity when at least 50% of leaves in at least 50% of plants had senesced. Maize at physiological maturity was harvested from all replicate plots of each treatment and subjected to 80 °C for 48 hours in an oven at the end of cropping season. A net plot area of (5m x 7 m = 35m^2) was harvested from each plot. Plants harvested from the net plot area were pooled before separating them into stover and cobs. A subsample of 50 plants in the net plot of maize stover was oven dried at 80 °C for 48 hours to determine stover yield on a dry mass basis. All the cob and grain from the net plot was weighed and recorded. This was used to extrapolate yield on a hectare basis.

3.1.9 Tree growth rate data measurements procedures

The data on growth rate which was collected on trees include days to emergence or establishment, days to 50% flowering, days to 50% pod formation and days to 50% physiological maturity. This was done by visual counting on the number of trees if it reached 50% on the parameter mentioned above. Tree productivity was determined by measuring height from ground level to tip of the youngest leaf and measuring basal stem diameter 5cm from the ground using Vernier callipers at 110 days after establishment (Muthuri et al., 2005). Tree biomass was determined by weighing fresh biomass and then oven drying samples at 80^{o}C. A representative tree was sampled from the net plot (5m x 7 m = 35m^2.) This was used to extrapolate yield on a hectare basis.

3.1.10 Data analysis

Data were analyzed using GenStat version 17 (VSN International Ltd, UK). Analysis of variance was carried out using general analysis of variance. Where significant differences were found, the multiple comparisons were made by Least Significant Differences (LSD) test ($P<0.05$).

The Land Equivalent ratio (LER) values were calculated as:

i) $LER = LERmaize + LERtree$ Equation 3-1

ii) $Where\ LERmaize = \frac{Ymi}{Ym}\ and\ LERtree = \frac{Yti}{Yt}$ Equation 3-2

Where $\mathrm{Ymi} =$ maize yields as intercrop $\mathrm{Ym} =$ sole maize yields

$\mathrm{Yti} =$ seed yield of tree as intercrop $\mathrm{Yt} =$ sole seed yield of tree,

The Aggressivity (A) was formulated as follows:

iii) $Atree = \left(\frac{\mathrm{Yti}}{\mathrm{Yt}} \mathrm{x\ Zti}\right) - (\frac{\mathrm{Ymi}}{\mathrm{Ym}} \mathrm{xZmi})$ Equation 3-3

$\mathrm{Amaize} = \left(\frac{\mathrm{Ymi}}{\mathrm{Ym}} \mathrm{xZmi}\right) - (\frac{\mathrm{Yti}}{\mathrm{Yt}} \mathrm{xZti})$ Equation 3-4

Zmi and Zti were proportions of maize and tree yields in a mixture respectively for example if

$\mathrm{Amaize} = 0$ both crop yield and tree seed yield are equally competitive

If $\mathrm{Amaize} =$ positive then the maize species is dominant

If Amaize is negative then maize is weak

The Relative crowding coefficient (K) was calculated as:

iv) $\mathrm{K} = (\mathrm{Kmaize\ x\ Ktree})$ Equation 3-5

Where $\mathrm{Kmaize} = \mathrm{Ymi\ x} \frac{\mathrm{Zti}}{} / \left((\mathrm{Ym} - \mathrm{Ymi})\mathrm{xZmi}\right)$ Equation 3-6

$$\text{Ktree} = \text{Yti x} \frac{\text{Zmi}}{}((\text{Yt} - \text{Yti}) \text{ x Zti}) \qquad \text{Equation 3-7}$$

Then, the Competition Ratio (CR) index was calculated using the formula:

v) $\text{CRmaize} = \left(\frac{\text{LERmaize}}{\text{LERtree}}\right) \text{x} \left(\frac{\text{Zti}}{\text{Zmi}}\right)$ $\text{CRtree} = \left(\frac{\text{LERtree}}{\text{LERmaize}}\right) \text{x} \left(\frac{\text{Zmi}}{\text{Zti}}\right)$ Equation 3-8

In addition, partial Actual Yield Loss (AYL) represent proportionate yield loss or gain of each species when grown as intercrops, relative to their yield in sole planting (Dhima et al. 2007). The AYL (Banik, 2000) was calculated as.

vi) $\text{AYL} = \text{AYLmaize} + \text{AYLtree}:$

vii) Where $\text{AYLmaize} = \left(\frac{\frac{\text{Ymi}}{\text{Xmi}}}{\frac{\text{Ymi}}{\text{Xm}}}\right) - 1$ $\text{AYLtree} = \left(\frac{\frac{\text{Yti}}{\text{Xti}}}{\frac{\text{Yt}}{\text{Xt}}}\right) - 1$ Equation 3-9

3.3 RESULTS

The results of the chemical analysis indicated that the soil had 20% clay content and the soil pH (KCl) of 4.37. Soil chemical results showed that Nitrogen (%) was 0.06. Phosphorus and Potassium levels were 20.4 mg/L and 114.2 mg/L respectively while Organic carbon (%) was 0.65

(Table 3.2).

Table 3.2 Chemical soil characteristics for the study site

Parameter	Value
Nitrogen (%)	0.06
Phosphorus mg/L	20.4
Potassium mg/L	114.2
Calcium mg/L	488
Magnesium mg/L	95.6
Copper mg/L	2.98
Total Cations cmol/L	3.594
Organic Carbon (%)	60.65
pH (KCL)	4.37
Clay (%)	16

Source: Cedara soil laboratory 2016

3.3.1 Maize growth and development

Figure 3.1 shows the number of days to 90% to emergence, 50% flowering and 50% physiological maturity of sole maize and maize + tree intercrops.

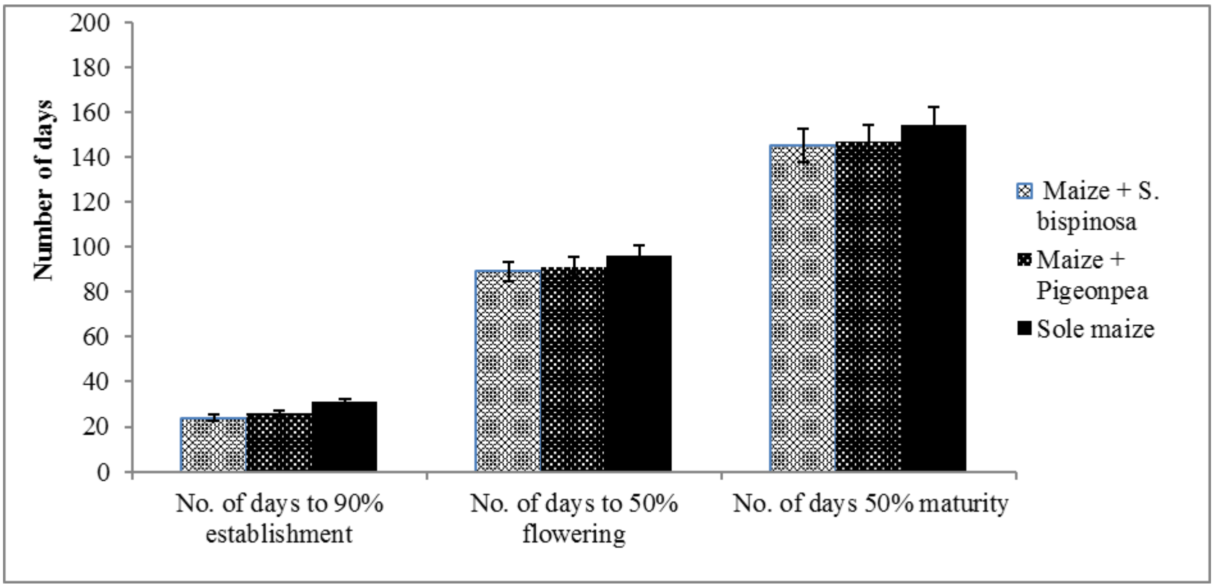

Figure 3.1 Growth stages of sole maize and intercrops at Fountainhill Estate in 2015/2016 growing season

The results showed that they were no differences on 90% establishment, 50% days to flowering and 50% days to physiological maturity on both sole maize and maize + tree intercrop Fig 3.1.

3.3.2 Tree growth and development

Figure 3.2 shows the number of days to 50% flowering, pod formation and physiological maturity. There were no marked differences noted on the following parameters: days to 90% establishment, days to 50% flowering, pod formation and physiological maturity between sole pigeonpea and pigeonpea + maize intercrop. Fig 3.2

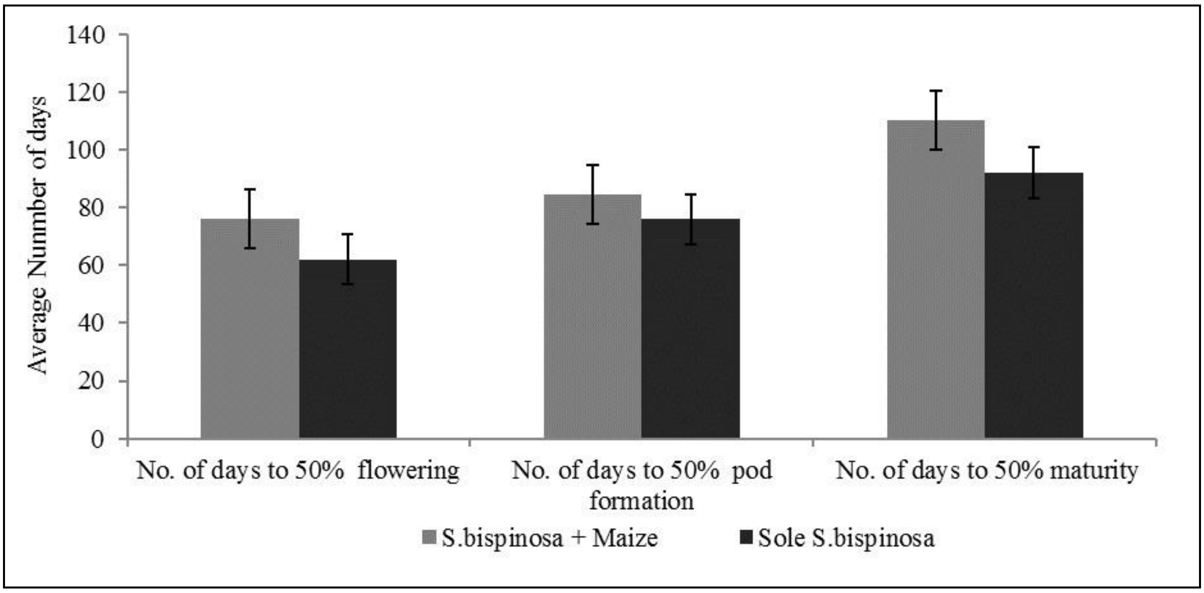

Figure 3.2 Growth rate of sole *S. bispinosa* and intercrop at Fountainhill in 2015/2016

The results indicate that there were no differences in terms of number of days to 90% establishment**,** days to 50% flowering, pod formation and physiological maturity on sole pigeon and intercrop (Fig 3.3).

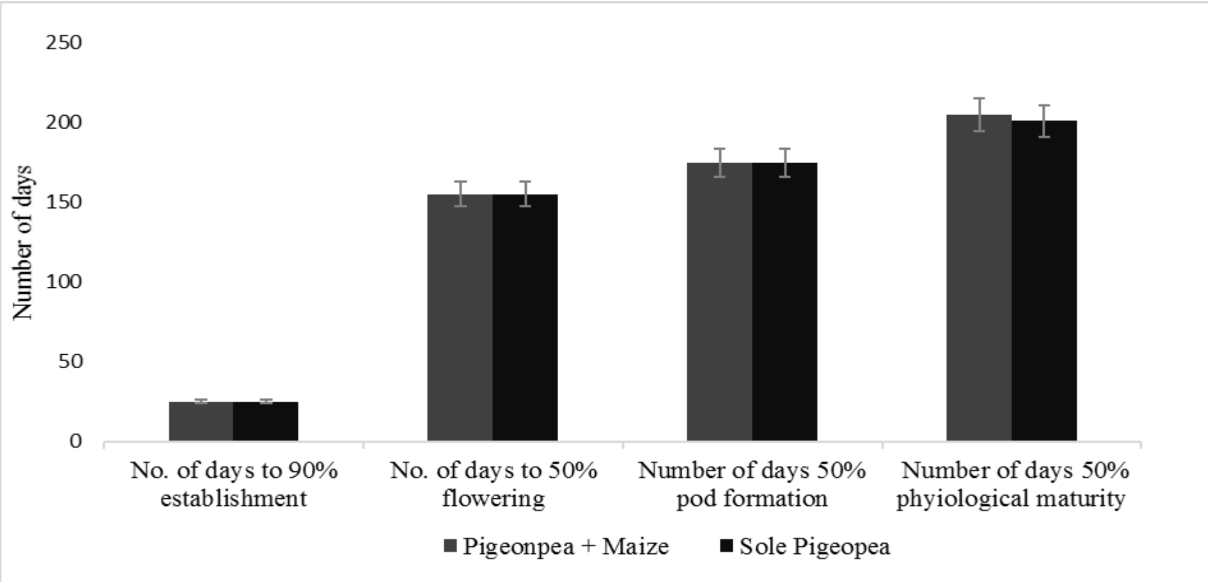

Figure 3.3 Growth rate of sole pigeonpea and intercrop at Fountainhill Estate in 2015/16 season

Results indicated that sole *S. bispinosa* canopy diameter, tree height and root collar differed significantly ($P < 0.05$: Table 3.3) between *S. bispinosa* intercrop and either sole pigeonpea or intercrop. Based on the results in Table 3.3. Sole *S. bispinosa* outperformed all treatments in all parameters which include canopy diameter (1.375 cm), height (1.89 cm) and root collar diameter of 22.17 mm whilst the least was observed on sole pigeonpea with canopy of 0.463 cm, height of 0.913 mm and root collar diameter of 9.65 mm.

Table 3.3 Canopy diameter, tree height and root collar at 110 days at Fountainhill Estate in 2015/16

Treatments	Canopy diameter (m)	Tree height (m)	Root collar diameter (mm)
Sole pigeonpea	0.6437**a**	0.913**a**	9.65**a**
Pigeonpea + maize	0.6293**a**	0.990**a**	10.14**a**
S. bispinosa + maize	0.9946**ab**	1.60**bc**	15.16**a**
Sole *S. bispinosa*	1.375**b**	1.89**c**	22.17**b**
LSD $_{(0.05)}$	0.524	0.4272	5.941

Numbers followed by same letters are not significantly different at P<0.05 according to Fisher`s Protected LSD

Data for aboveground dry cumulative biomass at 110 days after establishment of *S. bispinosa*, pigeonpea are present in Figure 3.4. There were significant differences (P<0.05) in relation to dry cumulative biomass, sole *S. bispinosa* outperformed all treatments which had 378 kg/ha. The least was attained on sole pigeonpea which had 82.3 kg/ha.

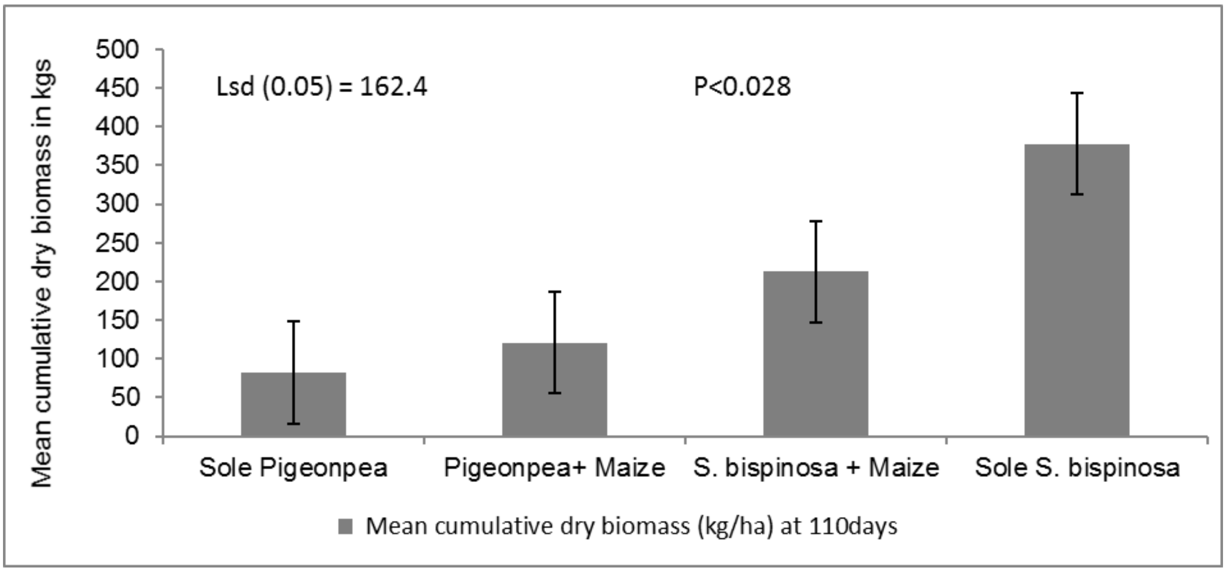

Figure 3.4 Cumulative aboveground dry biomass of trees at 110 days for different tree treatments during the 2015/16 season at Fountainhill

3.3.4 Tree seed yields

Results indicated that there was no significant (P<0.05) difference in the pigeonpea yield obtained in the sole and the yield obtained in the intercrop system (Table 3.4)**.** The two cropping systems involving sole pigeonpea (1073 kg/ha) and pigeonpea- maize intercrop (1029 kg/ha) had very close yield but differed significantly (P<0.05) with sole *S. bispinosa* and *S. bispinosa* maize intercrop which yielded 207.3 kg/ha and 58 kg/ha, respectively.

Table 3.4 Seed yields of *S. bispinosa* and pigeonpea at Fountainhill in 2015/2016 season

Treatments	Yield (kg)
S. bispinosa + Maize	58.3**a**
S. bispinosa	207.3**a**
Pigeonpea + Maize	1029.3**b**
Pigeonpea	1073.3**b**
LSD $_{(\mathbf{0.05})}$	206.9

Numbers followed by same letters are not significantly different at P<0.05 according to Fisher`s Protected LSD

3.3.5 Maize grain, cob and stover yields

Maize grain, cob mass and stover yields in both intercropping systems had lower values when compared with the monoculture configuration ($P>0.05$; Table 3.5)**.** There were significant differences ($P>0.05$) in terms of maize grain, cob mass and stover yields across all treatments. Grain yield, cob mass and stover mass were significantly higher in sole maize treatment as compared with the intercrop counterparts. The three parameters were statistically similar for maize intercropped with *S. bispinosa* and maize intercropped with pigeonpea.

Table 3.5 Maize grain, cob mass and stover yields at Fountainhill Estate in 2015/16 summer season

Treatments	Grain yield (kg/ha)	Cob mass (kg/ha)	Stover mass (kg/ha)
Maize + *S. bispinosa*	538**a**	742**a**	101.7**a**
Maize + Pigeonpea	604**a**	762**a**	107.9**a**
Sole Maize	1867**b**	2753**b**	314.2**b**
LSD ($_{0.05}$)	446.6	543.7	72.5

Numbers followed by same letters are not significantly different at $P>0.05$ according to Fisher`s Protected Lsd

3.3.6 Competition indices

Differences among intercropping systems and monocrops were significant P< 0.001 for LER. Pigeonpea + maize had higher LER value (1.23) as compared to *S. bispinosa* intercropped with maize (0.63). Combined LER for maize and *S. bispinosa* was even lower than sole pigeonpea although it had less than 1 LER. Partial LERs were generally lower in all monocultures. (Figure 3.5). Sole maize had the least LER followed by sole *S. bispinosa*.

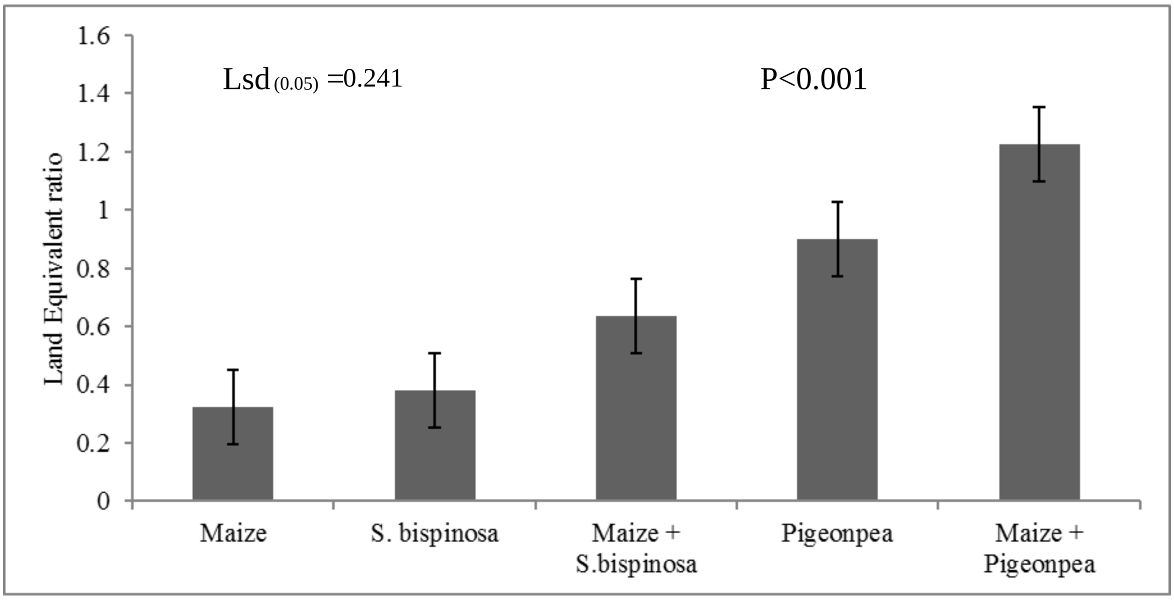

Figure 3.5 Land Equivalent ratio for different cropping systems at Fountainhill in 2015/16 season

Table 3.6 Shows competition indices which were used to determine competition in the simultaneous agroforestry system involving maize, pigeonpea and *S. bispinosa*. In terms of aggressivity in maize + pigeonpea intercrop positive value was noted on pigeonpea while maize had negative value. In maize + *S. bispinosa* intercrop positive value was recorded *S. bispinosa* while maize had negative. Higher relative crowding coefficient values were recorded on maize (1.4) intercropped with pigeonpea (4.8) as compared to low values on both maize (0.046) and *S. bispinosa* (0.228). S. *bispinosa* had a higher competition ratio of 9.42 while maize had 0.31, while pigeonpea had (1.71) and 0.61 for maize (Table 3.6).

Table 3.6 Competition indices for the intercropping cropping systems at Fountainhill Estate

	Aggresivity (A)			Relative Crowding coefficient (K)			Competition ratio (C)		
Treatment	Mz	Pp	S. b	Mz	Pp	S. b	Mz	Pp	S. b
Mz + Pp	-0.44	0.44		1.4	4.8		0.61	1.71	
Mz + S. b	0.23		-0.23	0.046		0.228	0.31		9.42
Lsd $_{(0.05)}$	0.789	0.387		8.88	0.5040			1.467	7.552

Mz=maize Pp=pigeonpea, S. b=*Sesbania bispinosa*

Actual Yield Loss (AYL) maize had positive value in maize + pigeonpea intercropping whilst negative value was observed in maize + *S. bispinosa* intercrop. Both pigeonpea and *S. bispinosa* trees had positive values when intercropped with maize (Table 3.7).

Table 3.7 Actual yield gain (+) or loss (-) in an agroforestry system at Fountainhill Estate in 2015/2016

Intercrop Combinations	Actual yield gain (+) or loss (-)
Maize + Pigeonpea	+0.09
Maize + *S. bispinosa*	-0.01
Pigeonpea + Maize	+0.02
S. bispinosa + Maize	+0.04
Lsd $_{(0.05)}$	0.24

3.4 DISCUSSION

3.4.1 Soil chemical properties on the study site

The analysis shows that the experimental site has a relatively low pH (KCH). Plant growth and most soil processes, including nutrient availability and microbial activity, are favored by a soil pH range of 5.5 – 8. Acid soil, particularly in the subsurface, will also restrict root access to water and nutrients. The optimum pH (KCl) for maize is 5 - 5.5 (ARC-Grain Crops Institute 2003), pigeonpea is 5-7 (Valenzuela and Smith 2002) and *S. bispinosa* is 5.8 - 7.5 (Orwa et al., 2009). The results of analysis clearly indicate that the pH was not within the range which supports the growth of both tree species (pigeonpea and *S. bispinosa*) and maize.

3.4.2 Maize growth, development and grain yield

Overall, higher numbers of days to 90% establishment across all maize treatments was observed due to replanting, which was done to counteract poor emergence. Erratic rainfall that was received during the early growing season might have contributed to poor emergence.

Maize grain, cob mass and stover yields were significantly higher in sole maize plots as compared to intercrops. This might have been caused by competition for available resources like water, light, space, and nutrients. This was for both *S. bispinosa* as well as pigeonpea although other studies have shown that pigeonpea grow slowly initially and do not compete for resources with the associate crop (Valenzuela and Smith 2002). These findings are in line with Mathews et al., (2001) who found that yields of both maize and pigeonpea in intercropping systems were generally lower than in monocropping systems in Mpumalanga. Singh and Sinha (1962) also found that maize intercropped with *S. bispinosa* has generally lower yields compared with sole maize. In another study in India sole crop of maize recorded significantly higher yield as compared to the intercropping (Lingaraju and Chandrasekhar 2008). Singh and Sinha (1962) also found that maize intercropped with *S. bispinosa* has generally lower yields as compared to sole maize. However, yield of maize intercropped with pigeonpea in semi-arid conditions is often less than that of sole cropped maize (Rao and Mathuva, 2000, Snapp et al., 2002, Chikowo et al., 2004, Myaka et al., 2006), indicating probable yield suppression due to competition for soil nutrients and/or moisture. This study also concurs with the results of Kwesiga et al., (1999) who found that intercropping maize with trees during the first year of the 2-year fallow has a negative effect on both maize yields. According to Ledgard and Giller (1995), the benefits of an intercrop system between a legume and cereal crop are more likely to occur to subsequent crops as the main transfer path-way is due to root and nodule senescence and fallen leaves. Although benefits may occur on subsequent crop a farmer, may have additional second crop which in this study was pigeonpea.

3.4.3 Tree growth, development and seed yield

The results from the study are consistent with results from a study by Kwesiga et al., (1994) who found that pigeonpea was slow in terms of growth as compared to *Sesbania sesban* in establishment. *S. bispinosa* growth was very rapid at initial establishment of the experiment that is why tree heights, root collar and canopy diameter was greater than for pigeonpea. Significant differences were noted on sole *S. bispinosa*, which had higher canopy diameter as compared to sole pigeonpea this is probably because of the erectile (upward) growth pattern of pigeonpea as compared to planophile (branching) growth pattern of *S. bispinosa*.

Highest total aboveground biomass yield was recorded from sole *S. bispinosa* and lowest on sole pigeonpea. The probable causes for getting higher dry biomass yield might be due to more vigorous growth and higher branching of *S. bispinosa* as compared to pigeonpea. This study concurs with Kamanga et al., (1998) who found that significantly high biomass was recorded from *S. sesbania* while pigeonpea produced low biomass.

No significant difference in terms seed yield was noted between intercropped pigeonpea and sole crop. In another similar study by Kumar et al., (2013) they found non-significant variation in yield between sole pigeonpea and pigeonpea + mungbean cropping system. This probably explained that pigeonpea can be grown in association for maximum utilization of resources.

Sole *S. bispinosa* produced higher seed yield as compared to *S. bispinosa* + maize plots, although statistically there was no difference. The adverse effect on yield of the tree seed due to intercropping occurred mainly due to competition among companion plants for light, space, nutrients, and water. In another similar study by Rana et al., (2013) it was discovered that sole *Sesbania rostrata* plots produced higher seed yield as compared to intercropping *S. rostrata* with rice.

3.4.4 Competition indices

The productivity of agroforestry system involving maize with pigeonpea or *S. bispinosa* in the present study was determined using LER and related attributes described in previous sections. The results of the study indicate high percent of partial Land Equivalent ratio of pigeonpea, maize and S. *bispinosa* but pigeonpea (90%) outperformed the *S. bispinosa* (38.1%) and maize (32.1%). Maize grown in association with pigeonpea had land equivalent ratio greater than 1, which indicated that agroforestry system was more beneficial than monocropping. Maize + pigeonpea intercrop was highly productive despite low yields of the main crop (maize).

The poor productivity of maize meant that there was reduced competition to the companion pigeonpea crop thus the high LER values were driven more by pigeonpea productivity. These results concur with Edje (2014), who found that intercropping maize with pigeonpea was more productive than either crop in monoculture in Swaziland. Egbe et al., (2010) have reported similar results in pigeonpea/sorghum intercrop. When maize was intercropped with *S. bispinosa* the ratio was less than 1, which means intercropping negatively affected the growth and yield of maize and *S. bispinosa* (Dhima et al., 2007; Workayehu 2014). The LER of 1.23 indicates 23% greater yield for maize + pigeonpea intercrop or 23% greater area required for monocropping system. These results concur with Ijoyah and Usman (2013) and Ijoyah et al., (2012), who found that LER of 1.25 can be interpreted as 25% greater yield for intercropping or as a 25% greater area requirement for the sole cropping system.

Combined LER values were higher than one indicating the advantage of intercropping over sole stands in relation to use of environmental sources for plant growth (Dhima et al., 2007). Similar results were reported for the pea + barley intercrop (Chen et al., (2004). The competition ratio values for maize and pigeonpea increased (0.61-1.71) indicating an absolute yield advantage of both maize and pigeonpea in intercropping systems. In a similar study, Egbe (2010) found that the competitive ratio of soybean in sorghum intercrop increased (0.76-1.15) indicating higher competitiveness of soybean than the sorghum component. The same author also found that the competitive ratio of sorghum had the opposite response (1.23-0.76). This suggests that cereal crops are less competitive than legumes when the two-crop species are grown in intercrop systems. In addition, (K) values for maize and *S. bispinosa* intercrop systems were generally very low, less than one, indicating yield disadvantage when grown in association.

Aggressivity values were negative on maize when intercropped with pigeonpea, which means pigeonpea was dominant species. While in maize *S. bispinosa* intercrop, maize had a positive value, which means maize was dominant species in that system. Matusso et al., (2014), argued that the main reasons for intercropping is to ensure that an increased and diverse productivity per unit area is realized as compared to monocropping. According to Muoneke et al., (2007), LER of 1.02-1.63 means efficient utilization of land resource. Most studies which involved different intercropping systems, none of them reported LER values less than one and this is evidenced in the studies conducted by Addo-Quaye et al., (2011) and Osman et al., (2011). These findings concur with maize + pigeonpea intercrop in the present study although different results were observed in maize + *S. bispinosa* intercrop.

A review carried out by Matusso et al., 2014 found that intercropping of cereal and legumes is widespread among small-scale farmers due to the ability of the legume to cope with declining levels of soil fertility and soil erosion. There is an incentive for the small-scale farmers to continue with integrating legume trees into their cropping systems because of improvement of soil fertility status, risk minimization against total crop failure, soil conservation, weed suppression and balanced human and livestock diet. Matusso et al., (2014) reviewed that several researchers have been working with cereal legume intercropping systems in sub-Saharan Africa and proved its combined success compared to the monocropping systems. Tsubo and Walker (2003) reported that intercropping technique is common for smallholder farmers worldwide. Gathumbi et al., (2003) suggested that mixing of leguminous plants with cereal crops helps to enhance subsoil nitrogen retrieval for the growing crops.

Banik et al., (2000) argued that, AYL index gave more accurate information than the other indices on inter and intraspecific competitions in intercropping systems. Thus, there was 9% (AYLmaize = + 0.09) increase in maize and 2% (AYLpigeonpea = + 0.02) increase in pigeonpea in the maize + pigeonpea intercropping system. However, there was 1% (AYLmaize = - 0.01) decrease of maize and 4% (AYL*S.bispinosa* + 0.04) increase in *S. bispinosa* in intercropping involving maize and *S. bispinosa* when compared to their sole crop yields when evaluating on plant basis. The magnitude of AYLmaize that is greater than AYLpigeonpea indicated that maize was resistant to yield loss than pigeonpea in maize + pigeonpea agroforestry system. AYLmaize had negative values when grown with *S. bispinosa* which means maize was prone to yield loss when intercropped with *S. bispinosa*.

3.5 CONCLUSION

Sole maize had higher grain yield, cob mass and stover as compared to intercrops. Maize + pigeonpea intercropping system increased the LER despite decreasing yield of the main component crop (maize), which can be compensated by yield of pigeonpea. The competition ratio values for maize and pigeonpea increased (0.61-1.71) and AYL had 9% maize and 2% pigeonpea increase indicating an absolute yield advantage of both maize and pigeonpea in intercropping systems. Although, pigeonpea was a dominant species as compared to maize in an intercropping system. Therefore, incorporation of pigeonpea into the sole-maize based cropping systems could boost overall productivity of the system in this environment of Wartburg, South Africa.

3.6 RECOMMENDATION

From the study, it follows that when smallholder farmers plan on cultivating both maize and legume tree, planting maize associated with pigeonpea is more beneficial than *S. bispinosa* with maize or sole cropping in terms of saving the shortage of arable land and promote the sustainable development of natural resources. Pigeonpea can thus be recommended in simultaneous agroforestry systems with maize due to its higher LER ratio and production of grain for human and livestock consumption. To minimize competition in the pigeonpea/maize intercropping and enhance profitability, reduction of the densities may be considered for investigation.

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CHAPTER FOUR

Water use and water use efficiency in simultaneous agroforestry systems in South Africa

Abstract

Due to global warming, there is a need to increase the water use efficiency of crops under rainfed agriculture, particularly under smallholder farming systems. Therefore, water use efficiency in agroforestry systems was determined at Fountainhill Estate in 2015/16 summer season. The hypothesis was that agroforestry systems have low water use, high water use efficiency compared to monocropping. The experiment had 5 treatments: sole maize; sole pigeon pea; sole *S. bispinosa*; maize + *S. bispinosa*; and maize + pigeonpea laid out in a randomized complete block design (RCBD) replicated three times. Time domain reflectometry (TDR) probes were placed at 20cm, 50 cm and 120 cm below ground level under maize or tree to measure volumetric soil water content. Significant ($P<0.001$) differences were observed among the treatments. Sole maize ≥ sole pigeonpea ≥ pigeonpea + maize > maize + pigeonpea ≥ maize + *S. bispinosa* > sole *S. bispinosa* ≥ *S. bispinosa* + maize. Sole treatments of maize and pigeonpea had significant ($P<0.001$) higher Water Use Efficiency of 6.28 kg/ha mm and 5.77 kg/ha mm respectively. While pigeonpea + maize recorded a significantly ($P<0.001$) higher WUE of 5.47 kg/ha mm. The lowest was recorded on *S. bispinosa* + maize (0.292 kg/ha mm) and sole *S. bispinosa* (0.425 kg/ha mm) subject to the provision that the calculations were based on changes in soil water content rather than actual measurements of water uptake by the trees and crops. A combination of pigeonpea + maize proved to be better agroforestry system since it has higher WUE efficiency although, there was no evidence of outcompeting the sole crops.

Key words: maize, monocropping system, pigeonpea, water use efficiency

4.1 INTRODUCTION

Agriculture is the major water user in most countries. Agriculture is facing enormous challenge of producing almost 50% more food by 2030 and doubling production by 2050 (Ingram 2000; Fischer et al. 2005). This will likely need to be achieved with less water, mainly because of growing pressures from climate change. In this context, it will be vital in future for farmers to receive the right information on how to increase water use efficiency and productivity to attain food security (AGRA; 2016: El Chami and El Moujabber 2016). The impacts from climate change have been hard on the South African agricultural sector, which is extremely sensitive to heat and uses over 60% of the total water resources of the country (DWA; 2013).

Traditional monocropping systems cannot fully utilize available rainfall due to losses by evaporation from the soil surface (Es), drainage and runoff (Ong et al. 2006, 2007). Es comprises 20–40 % of rainfall in sub-Saharan Africa (Wallace et al. 1999; Jackson and Wallace 1999; Wallace and Gregory 2002). This has major consequences for crop production. Black and Ong (2000) suggested that the benefits of intercropping in such environments may result primarily from improvements in water use efficiency (WUE). Several factors influence WUE. Morris and Garrity (1993) suggested that a key factor contributing to improvements in WUE in intercropping systems relative to sole crops is that their more rapid canopy expansion and greater groundcover reduces soil evaporation, with the result that transpiration forms a larger proportion of evapotranspiration. Secondly, the modified microclimatic conditions provided by the presence of two or more system components which differ in their above-ground canopy structure and growth dynamics may create an atmospheric environment which enhances WUE; for example, relative humidity may be increased and wind speed reduced within the canopy, thereby reducing evaporative demand (Wallace and Gregory 2002, Lin 2010). Significant complementarity of water use is obtained when the component species have different rooting patterns or exhibit contrasting temporal characteristics (Ong et al. 2000).

Developing cropping systems that use scarce resources such as water efficiently is important to improve food security as future climate change scenarios predict reduction or more erratic rainfall in sub-Saharan Africa (Wallace and Gregory 2002). Agroforestry systems were found to have greater WUE as compared to monocropping systems, although the estimates of water consumption used in the calculations were based on changes in soil water content rather than direct measurements of water uptake by the tree and crop components (Chirwa et al., 2007). A central biophysical agroforestry hypothesis is that trees and crops can efficiently grow together on the same area of land and at the same time. The spatial and/or temporal complementary exploitation of soil resources may optimize water use efficiency. In a situation of water scarcity, studies on the water use efficiency (WUE) are relevant. Therefore, understanding the water use processes that give rise to the observed levels of available soil water would provide suggestions for improved technologies for sustainable crop production in KwaZulu-Natal.

A study in KwaZulu-Natal was initiated to test a hypothesis that agroforestry systems have low water use, high water use efficiency compared to monocropping. The main objective was to evaluate seasonal water use and water use efficiency of *Sesbania bispinosa,* pigeon pea and maize as sole crops and in simultaneous agroforestry systems.

4.2 MATERIALS AND METHODS

4.2.1 Study site

The experiment was established at Fountainhill Estate (latitude 29°27'2" S; longitude 30°32'42" E and altitude 853 m above sea level) in the uMshwathi Local Municipality, near Wartburg approximately 30 km northeast of Pietermaritzburg in KwaZulu-Natal, South Africa. The site has an annual precipitation of 805 mm per annum. The mean minimum temperature is 3.3 °C and the maximum is 37.4°C,

4.2.2 Experimental design and treatments

The experiment was established during the 2015/16 summer season. The experiment had five treatments (1) sole maize, (2) sole pigeon pea, (3) sole *S. bispinosa* (4) maize + *S. bispinosa*, (5) maize + pigeon pea. The experiment was laid out in a randomized complete block design (RCBD) replicated three times.

4.2.3 Land preparation and establishment of the experiment

Two legume tree species (pigeon pea and *S. bispinosa*) were planted at s 1 m inter-row and 1 m intra-row spacing, while the mixed crop of trees and maize had 1 m inter-row and 0.4 m intra row spacing for the maize. Sole maize had 0.8 m inter-row and 0.5 m intra-row spacing with 120 plants per plot such that the same maize plant population as the mixed plots was maintained (i.e. 25 000 plants/hectare). Maize and pigeon pea seed were planted simultaneously on the second week of January, while the *S. bispinosa* plants were transplanted from trays. Maize was replanted again on third week January 2016 as the initial sowing failed due to the late arrival of the rains.

4.2.4 Soil water content measuring methods

Time domain reflectometry (TDR) probes at depth intervals of 20cm, 50cm and 120 cm below ground level were used to measure volumetric soil water content. Three depths (20, 50 & 120 cm) were chosen since they provide good indication of soil water status (and changes thereof) within the crop root zone for most agronomic crops. Gravimetric soil water content was evaluated each of the plots that had instruments for calibration purposes. The TDR probes were read on site, on weekly basis. To avoid crop damage, installations of instruments were done when trees and maize plants were small, early in the season. This also allowed time for the TDRs and sensors to acclimatize with the surrounding soil.

4.2.5 Calibration of the TDR probes

To enable volumetric water content (VWC) to be calculated from the TDR probe readings, soil samples were collected from undisturbed soil cores at each depth near the instruments. The samples were weighed and dried in an oven at 105 ^{o}C for 24 hours and then reweighed. Gravimetric values were converted to VWC using bulk density values determined for undisturbed soil cores of known volume sampled. This procedure was repeated several times during the 2015/2016 cropping season to span the range between extreme soil wetness and dryness. The figures were used to establish the relationship between VWC and probe reading or all sampling depths.

4.2.6 Statistical analysis

Data were analyzed using GenStat version 17 (VSN International Ltd, UK). ANOVA was carried out using general analysis of variance. Where significant differences were found, the multiple comparisons were made by Least Significant Differences (LSD) test ($p<0.05$).

4.3 RESULTS

4.3.1 Soil characteristics within the rooting depth

The results of the soil texture analysis are presented in Table 4.1. Generally, the top 20 cm of the soils at the experimental site comprised of loamy sand. A notable difference is on the 50cm and 120cm depth were the soil horizon is characterized by sandy clay loam.

Table 4.1 Soil physical characteristics within the rooting depth on the study site

Depth (cm)	Clay %	Silt %	Sand %	Texture
20	14.2	2.4	83	Loamy sand
50	24.3	3.6	72.2	Sandy clay loam
120	28.1	30	67.3	Sandy clay loam

4.3.2 Weather data

The following climatic variables were recorded from an automatic weather station in the immediate vicinity (1km radius) of the experimental plots: dry and wet bulb temperature, potential evaporation and rainfall. Measurements were taken at as hourly means. These values were used to compute daily values of potential evapotranspiration using FAO Penman's Monteith formula. The trend of weather during the period of the trial (Fig 4.1) indicates adequate moisture for crop growth. However, rainfall was slightly below the long-term mean of the area. Temperatures were also within the ranges necessary for adequate plant growth (Downes 1972).

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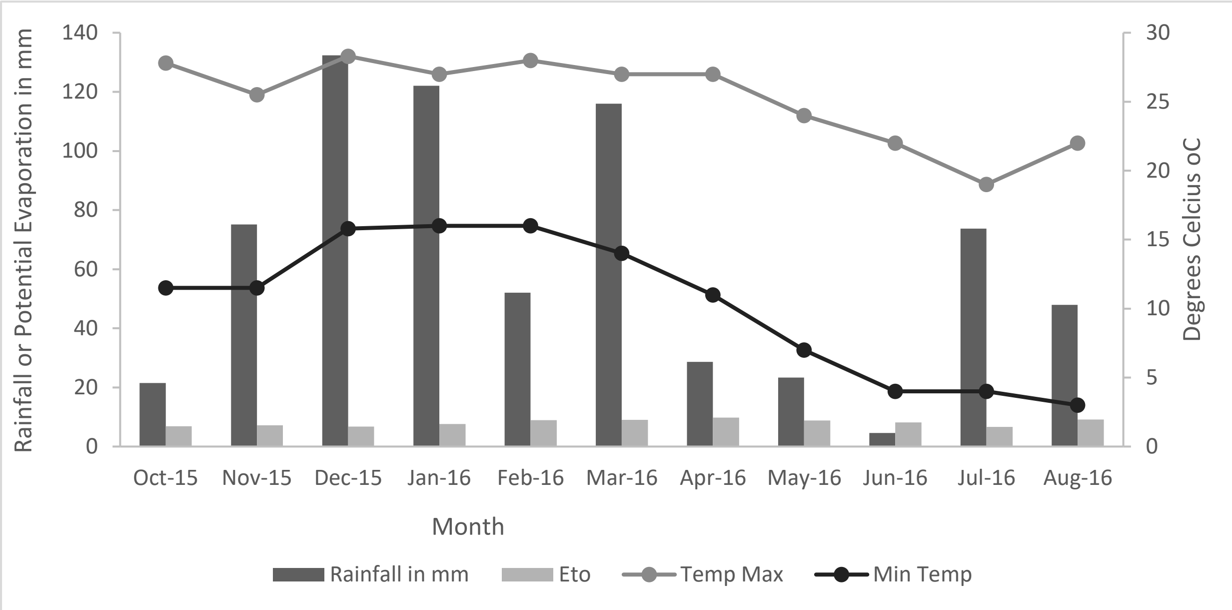

Fig 4.1 Climatic data recorded for the 2015/2016 at Fountainhill Estate.

4.3.3 Seasonal water use

Water use (WU) or evapotranspiration (ET) was calculated by solving the soil-water balance equation as follows. Water use (WU) in the various cropping systems was estimated for the period from maize planting until maturation of pigeonpea and *S. bispinosa*

WU was calculated as follows: $WU = R + SWCh \;\; Equation\; 4 - 1$

Where R denotes rainfall and SWCh represents the change in soil water content within the 0–120 cm soil profile between TDR probe measurements. Estimated total seasonal water use did not differ between treatments, ranging between 186.17mm and 487.79 mm (Table 4.2)

Table 4.2 Yield, water use and water use efficiency of the various cropping systems

Cropping systems	Yield (kg/ha)	Water Use (mm)	WUE (kg/ha mm)
Sole *S. bispinosa*	207.3**a**	487.79	0.42**a**
Sole Maize	1867**d**	297.19	6.28**c**
Maize + Pigeonpea	604**b**	203.75	2.96**b**
S. bispinosa + Maize	58.3**a**	199.88	0.29**a**
Pigeonpea + Maize	1029.3**c**	188.08	5.47**c**
Maize + *S. bispinosa*	538**b**	188.02	2.86**b**
Sole Pigeonpea	1073.3c	186.17	5.77**c**
Lsd $_{(0.05)}$	308.89		1.293

Numbers followed by same letters are not significantly different at P>0.05 according to Fisher`s Protected Lsd.

4.3.4 Water use efficiency (WUE)

Water-use efficiency (WUE) is simply grain yield (kg/ha) divided by water-use

$$\mathrm{WUEg} = \frac{\mathrm{Yg}}{\mathrm{ETt}} \quad Equation\ 4-2$$

$$Where\ WUEg\ is\ the\ WUE\ for\ grain\ yield\ Yg = grain\ yield$$

$$ETt\ is\ the\ total\ cumulative\ evapotranspiration\ (mm) over\ the\ growing\ season\ calculated\ from$$

$$Soil\ water\ balance (Et) = Rainfall - changes\ in\ soil\ water\ content\ Equation\ 4-3$$

This was the method employed by French & Schultz, who deliberately chose sites that were not prone to run-off, drainage, or lateral water movement so for this experiment runoff and drainage was assumed negligible and was not measured. This assumption was validated by the slope which was less than 2% and field was relatively flat. The final values of WUE (Table 4.2), derived as described by CSIRO in its WUE Benchmarking guide (Hunt and Kirkegaard, 2012) shows the various water use and corresponding use efficiencies of the various cropping systems.

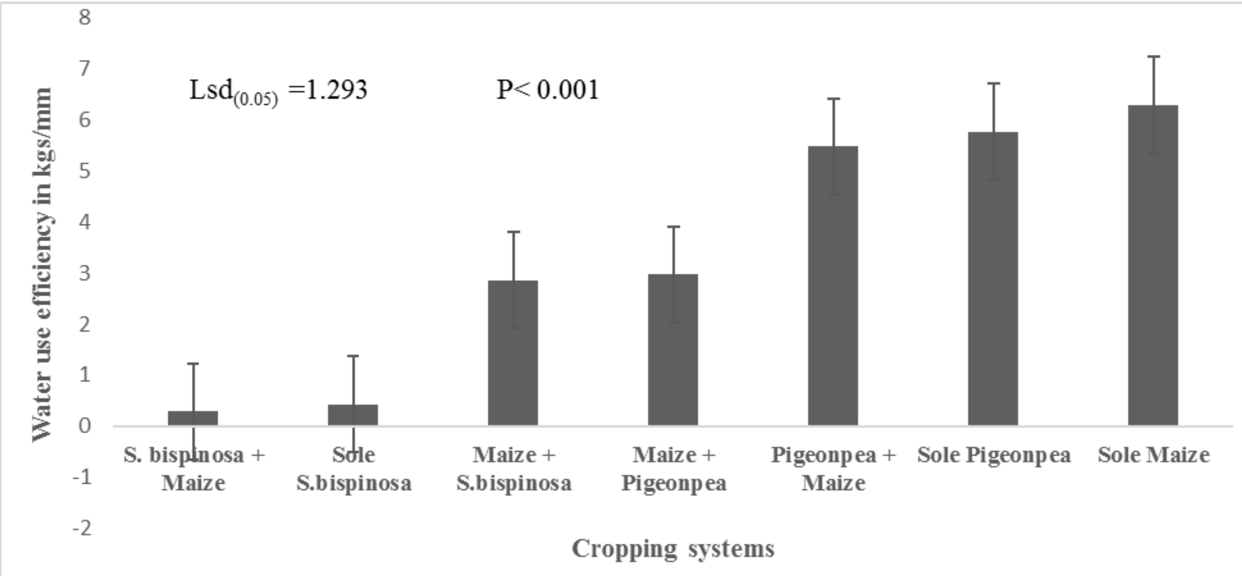

Figure 4.2 Water use efficiency of the various agroforestry systems

The effect of simultaneous agroforestry systems water use and water use efficiency is shown in Table 4.2. The results indicate significant differences (P< 0.001) in terms of water use efficiency, the sole maize cropping system outperformed all other treatments with 6.28 kg/ha mm while *S. bispinosa* + maize (0.292 kg/ha mm) had the least WUE. In terms of intercrops pigeonpea + maize (5.47 kg/ha mm) outperformed all other cropping systems while the least combination was *S. bispinosa* + maize. There were no differences noted on the maize intercropped with both trees (maize + pigeonpea = 2.97 kg/ha mm and maize + *S. bispinosa* = 2.86 kg/ha mm). Among the intercropping systems, highest value of WUE was recorded in pigeonpea + maize. Minimum WUE was recorded on *S. bispinosa* grown in association with maize (0.292 kg/ha mm) and sole *S. bispinosa* (0.425 kg/ha mm). In generally the results can be explained by the following sequence in terms of WUE in agroforestry systems which were evaluated. Sole maize ≥ sole pigeonpea ≥ pigeonpea + maize > maize + pigeonpea ≥ maize + *S. bispinosa* > sole *S. bispinosa* ≥ *S. bispinosa* + maize.

4.4 DISCUSSION

4.4.1 Water use (WU)

In the review of previous studies by Morris and Garrity (1993) they noted the differences in water use between intercrops and sole crops often range between (-6) % and + (7) % although these cropping systems did not have trees. The absence of notable treatment effects on seasonal soil water indicates that maize + pigeonpea/or *S. bisponsa* and sole treatments used similar quantities of water, this view is supported by estimates of seasonal water use (Table 4.2). The study agrees with Chirwa et al., (2007) who found no significant differences in WU on agroforestry systems involving maize, pigeonpea and *Gliricidia sepium*. Droppelmann et al., (2000) reported similar findings for an agroforestry trial in Northern Kenya involving *Acacia saligna* and *Sorghum bicolor*. However, this conclusion may not be valid for the present study in view of the fundamental differences in productivity between the tree-based and sole cropping systems; for example, grain yield of sole maize was 3-fold greater than in maize + tree (pigeonpea/*S.bispinosa*) intercrop (Table 4.2). A possible explanation is that, in areas of relatively high rainfall or poor drainage, the water table may remain close to or within the rooting zone for much of the cropping season, particularly during periods when significant deep percolation occurs. Under such condition, treatment differences in water use, and hence in calculated water use efficiency values, may be masked if significant quantities of water are extracted from the water table by deep rooting species. In such occurrences, measurements of water abstraction from profile above the water table, as in the present study, cannot give reliable estimates of total water use. However, this difficulty may be avoided in future studies by using sap flow gauges to determine water uptake by individual system components (Lott et al., 2003); this method provides direct, non-destructive measurements of the quantity of water used during the production of dry matter. Thereby providing undisputable estimates of WUE for individual system components.

4.4.2 Water use efficiency (WUE)

Morris and Garrity (1993) and Ong et al., (1996) concluded that, although total water use may not differ between sole and intercropping systems, the latter often use more water efficiently. Their studies partly agree with the present study where pigeonpea grown in association with maize proved to have higher WUE (Table 4.2). The values of WUE on sole cropping systems (maize and pigeonpea) and pigeonpea intercropped with maize were higher. These results corroborated with reports that season-long WUE values range between 2.1 kg/ha mm and 5.2 kg/ha mm in millet, a C4 species and 6.4 kg/ha mm in groundnut, C3 species, depending on the prevailing atmospheric saturation deficit (Black and Ong 2000). Lower values have been reported for castor bean grown in semi-arid conditions (0.88-1.31 kg/ha mm, Vijaya Kumar et al., 1996). These values are greater than those obtained for sole *S. bispinosa* and maize intercropped with maize in the present study. Meena et al., 2013 concluded that a crop with higher yield must also have higher WUE which might have contributed to higher WUE which might have contributed to the higher WUE values of sole maize, sole pigeonpea and pigeonpea intercropped with maize (Table 4.2). More transpiration due to good crop stand and soil evaporation may have contributed to high WUE in the sole maize as evaporative losses may be large in annual cropping systems (Wallace 1996). The high WUE value obtained from pigeonpea + maize reflects the intense shade provided by its dense canopy and the associated microclimatic changes which might have greatly reduced soil evaporation, ensuring that transpiration dominated evapotranspiration losses

4.5 CONCLUSIONS

The study provided no evidence that WUE was greater in the tree-based systems than sole maize only pigeonpea proved to have higher WUE when grown in association with maize due to its comparatively higher yields while maize had low WUE in that combination which was attributed to relatively low yields. The results can be explained by the following sequence sole maize ≥ sole pigeonpea ≥ pigeonpea + maize > maize + pigeonpea ≥ maize + *S. bispinosa* > sole *S. bispinosa* ≥ *S. bispinosa* + maize subject to the provision that the estimates of water consumption used in the calculation were based on changes in soil water content rather than direct measurements of water uptake by the tree and crop constituents.

The observed changes in soil water content may also have been influenced by evaporation from the soil surface. In future, it will be important to measure soil evaporation and water uptake by the component species of agroforestry system to provide the actual measurements of the quantity of water utilized in the production of yield and dry matter and thereby provide rigorous reliably estimates of the WUE for each system component. Under water scarce environment, the results suggest that the pigeonpea + maize agroforestry system may be beneficial among smallholder farmers since it proved to have higher water use efficiency. Although the maize yields may be compromised in that system but it is system which is more sustainably because there is soil water conservation and provision of other benefits to farmers like food and feed for consumption, improve soil fertility and firewood

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CHAPTER FIVE

5.0 GENERAL DISCUSSION

Agroforestry has been widely practiced in Sub-Saharan Africa because of its prominent effects in soil fertility improvement, reducing soil and water losses and improving land-use efficiency. The main reasons for higher yields in agroforestry system is that the component crop and tree can use natural resources differently and make better overall use of natural resources than grown separately. This was not the case in the present study as sole maize had higher yields as compared to agroforestry systems. This might have been caused by competition for resources. Similar studies conducted by Mathew et al., (2001) in Mpumalanga, South Africa found that sole maize had higher yields as compared to intercrops. Kwesiga et al., (1999) argued that intercropping maize with trees during the first year of the 2-year fallow has a negative on maize yield.

The yield obtained in the sole pigeonpea was numerically close to that of an intercrop. The close yield similarity obtained between the cropping systems would suggest that maize yield might be increased in the following season as a subsequent crop in the same field because of residual nutrients which would have been enhanced and set free for plant uptake during previous season. Giller et al., (1991) argued that the evidence of substantial benefits of N-transfer from grain legumes to the associated cereal crops is limited. Ledgard and Giller (1995) argued that the benefits of an intercrop between legume and cereal crop are more likely to occur to subsequent crops as the main transfer pathway is due to root and nodule senescence and fallen leaves.

The efficient use of basic resources in the cropping system depends partly on the inherent efficiency of the individual plants that make up the system and partly on complimentary effects between the crops. Availability of water in cropping system is vital to determine the growth of plant. Improvement of water use efficiency in agroforestry systems leads to increase in the use of other resources. Agroforestry systems have been identified to conserve water largely because of early high leaf area index and higher leaf area. The study indicated that sole maize, sole pigeonpea and pigeonpea + maize had greater WUE more than other treatments. The reason behind these higher WUE is the yield which was comparatively higher.

A combination of maize + pigeonpea was better in terms of WUE efficiency as compared to S. *bispinosa* + maize although there were similar values for maize in either tree legume but pigeonpea proved to have higher WUE when grown in association with maize which was different with *S. bispinosa*. In terms of land equivalent ratio maize + pigeonpea had higher values which clearly indicated benefits of intercropping. Although the maize yields were low in that system there are more benefits which can be accrued by smallholder farmers.

5.1CONCLUSIONS

Sole maize outperformed maize + tree intercrops in terms of grain yield. The maize grain yield among the treatments explained by the following sequence sole maize > maize + pigeonpea ≥ maize +*S. bispinosa*. The tree seed yield by the following order Sole pigeon ≥ pigeon + maize > Sole *S. bispinosa* ≥ *S. bispinosa* + maize. In generally the results can be explained by the following sequence in terms of WUE in agroforestry systems which were evaluated. Sole maize ≥ sole pigeonpea ≥ pigeonpea + maize > maize + pigeonpea ≥ maize + *S. bispinosa* > sole *S. bispinosa* ≥ *S. bispinosa* + maize.

5.2 RECOMMENDATIONS

Small-scale farmers may adopt a maize cropping system involving pigeonpea if they want to practice simultaneous agroforestry system, although the system produced low maize yields, these low yields may be compensated by pigeonpea yields. This combination is also supported by higher Land Equivalent ratio (LER) values which were recorded. The practice of agroforestry system involving pigeonpea saves a substantial (23%) land which can be subsequently be used for other crop production. Pigeonpea is recommended in agroforestry systems with maize due to its higher LER and combined production of grain for human and livestock consumption, soil fertility improvement and firewood. This cropping system proved to have higher WUE as compared to maize intercropped with *S. bispinosa*. In future studies sap flow gauges or lysimeters may be used to determine water uptake by individual system components this method provides direct, non-destructive measurements of the quantity of water used in the production of dry matter, thereby providing undisputable estimates of WUE for individual system components. Future more experiments should be established with the very first planting rains around mid-November and more testing sites should be used.

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APPENDIX

GenStat 64-bit Release 14.1 (PC/Windows 7) 14 August 2016 06:05:49
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GenStat Fourteenth Edition
GenStat Procedure Library Release PL22.1

Analysis of variance

Variate: Grain_yield_kg_ha

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	212948.	106474.	2.74	
Block. *Units* stratum					
Treatments	2	3366115.	1683058.	43.35	0.002
Residual	4	155288.	38822.		
Total	8	3734351.			

Tables of means

Variate: Grain_yield_kg_ha

Grand mean 1003.

Treatments	Maize + Pigeonpea	Maize + *S. bispinosa*	Sole Maize
	604	538.	1867.

Least significant differences of means (5% level)

Table	Treatments
rep.	3
d.f.	4
l.s.d.	446.6

Stratum standard errors and coefficients of variation
Variate: Grain_yield_kg_ha

Stratum	d.f.	s.e.	cv%
Block	2	188.4	18.8
Block.*Units*	4	197.0	19.

Analysis of variance

Variate: Mass_of_stover_kg_ha

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	285.	142.	0.14	
Block. *Units* stratum					
Treatments	2	87776.	43888.	42.85	0.002
Residual	4	4097.	1024.		
Total	8	92158.			

Tables of means

Variate: Mass_of_stover_kg_ha

Grand mean 175.

Treatments	Maize + Pigeonpea	Maize + S. bispinosa	Sole Maize
	108.	102.	314.

Least significant differences of means (5% level)

Table	Treatments
rep.	3
d.f.	4
l.s.d.	72.5

Analysis of variance

Variate: Mass_of_cob_kg_ha

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.

Block stratum	2	334223.	167112.	2.90	
Block. *Units* stratum					
Treatments	2	8010355.	4005177.	69.62	<.001
Residual	4	230118.	57529.		
Total	8	8574696.			

Tables of means
Variate: Mass_of_cob_kg_ha

Grand mean 1419.

Treatments	Maize + Pigeonpea	Maize + S. bispinosa	Sole Maize
	762.	742.	2753.

Least significant differences of means (5% level)

Table	Treatments
rep.	3
d.f.	4
l.s.d.	543.7

Stratum standard errors and coefficients of variation

Variate: Mass_of_cob_kg_ha

Stratum	d.f.	s.e.	cv%
Block	2	236.0	16.6
Block.*Units*	4	239.9	16.9

Analysis of variance

Variate: Canopy_diameter_m

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.19236	0.09618	1.40	

Block. *Units* stratum

treatments	3	1.11934	0.37311	5.43	0.038
Residual	6	0.41214	0.06869		
Total	11	1.72384			

Tables of means

Variate: Canopy_diameter_m

Grand mean 0.91

treatments Pp	Pp + Mz	S. b	Sb + Mz
0.64	0.63	1.37	0.99

Least significant differences of means (5% level)

Table	treatments
rep.	3
d.f.	6
l.s.d.	0.524

Stratum standard errors and coefficients of variation

Variate: Canopy_diameter_m

Stratum	d.f.	s.e.	cv%
Block	2	0.155	17.0
Block. *Units*	6	0.262	28.8

Fisher's protected least significant difference test
treatments

	Mean	
PP + MZ	0.6293	a
Pp	0.6437	a
S.b + MZ	0.9946	ab
S. b	1.3750	b

Analysis of variance

Variate: LER

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.051667	0.025833	4.43	

Block.*Units* stratum

Treatment	3	0.782500	0.260833	44.71	<.001
Residual	6	0.035000	0.005833		
Total	11	0.869167			

Tables of means

Variate: LER

Grand mean 0.458

Treatment	Sole maize	Maize + Pigeonpea	Maize + *S. bispinosa*
	0.3	1.23	0.63

Sole Pigeonpea	Sole *S. bispinosa*
0.9	0.4

Least significant differences of means (5% level)

Table	Treatment
rep.	3
d.f.	6
l.s.d.	0.241

Stratum standard errors and coefficients of variation

Variate: LER

Stratum	d.f.	s.e.	cv%
Block	2	0.0804	17.5
Block.*Units*	6	0.0764	16.7

Combined anova of maize, pigeonpea and *S. bispinosa* yield
Analysis of variance

Variate: Grain_yield_kg_ha

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	68193.	34097.	1.13	
Block.*Units* stratum					
Treatments	6	6818550.	1136425.	37.70	<.001
Residual	12	361773.	30148.		

Total	20	7248516.

Tables of means

Variate: Grain_yield_kg_ha

Grand mean 768.32

Treatments	Maize + Pigeonpea	Maize + S. bispinosa	Pigeonpea + Maize
	604.17	538.40	996.00

Treatments	S. bispinosa + Maize	Sole Maize	Sole Pigeonpea
	58.33	1867.36	1106.67

Sole S. bispinosa
207.29

Least significant differences of means (5% level)

Table	Treatments
rep.	3
d.f.	12
l.s.d.	308.888

Stratum standard errors and coefficients of variation

Variate: Grain_yield_kg_ha

Stratum	d.f.	s.e.	cv%
Block	2	69.792	9.1
Block. *Units*	12	173.631	22.6

Analysis of variance

Variate: WUE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.7147	0.8574	1.75	
Block.*Units* stratum					
Treatments	6	112.0776	18.6796	38.06	<.001
Residual	12	5.8889	0.4907		
Total	20	119.6813			

Tables of means

Variate: WUE

Grand mean 3.44

Treatments	Maize + Pigeonpea	Maize + S. bispinosa	Pigeonpea + Maize
	2.97	2.86	5.47

Treatments	S. bispinosa + Maize	Sole Maize	Sole Pigeonpea
	0.29	6.28	5.77

Treatments	Sole S. bispinosa
	0.42

Least significant differences of means (5% level)

Table	Treatments
rep.	3
d.f.	12
l.s.d.	1.293

Stratum standard errors and coefficients of variation

Variate: WUE

Stratum	d.f.	s.e.	cv%
Block	2	0.350	10.2
Block.*Units*	12	0.701	20.4

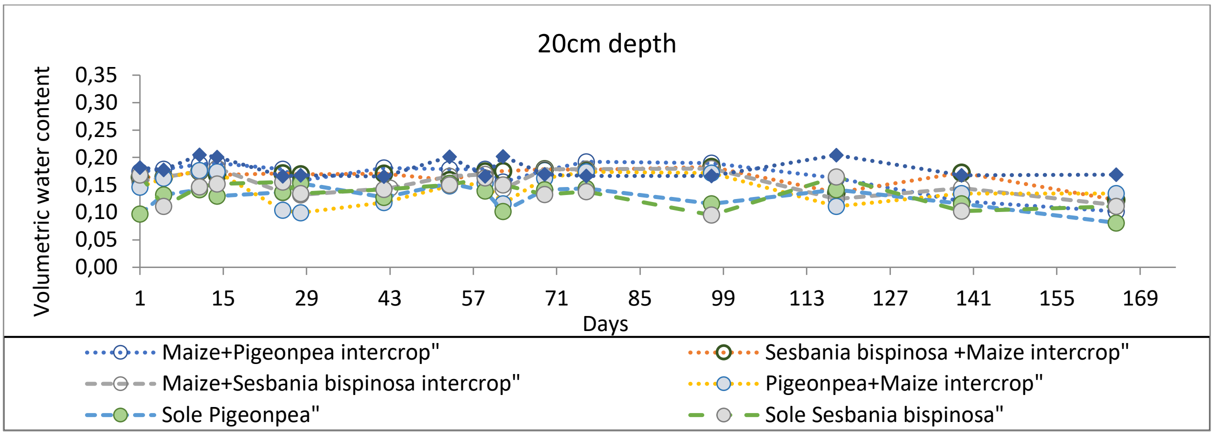

Fig 1 Average soil water content at 20cm depth

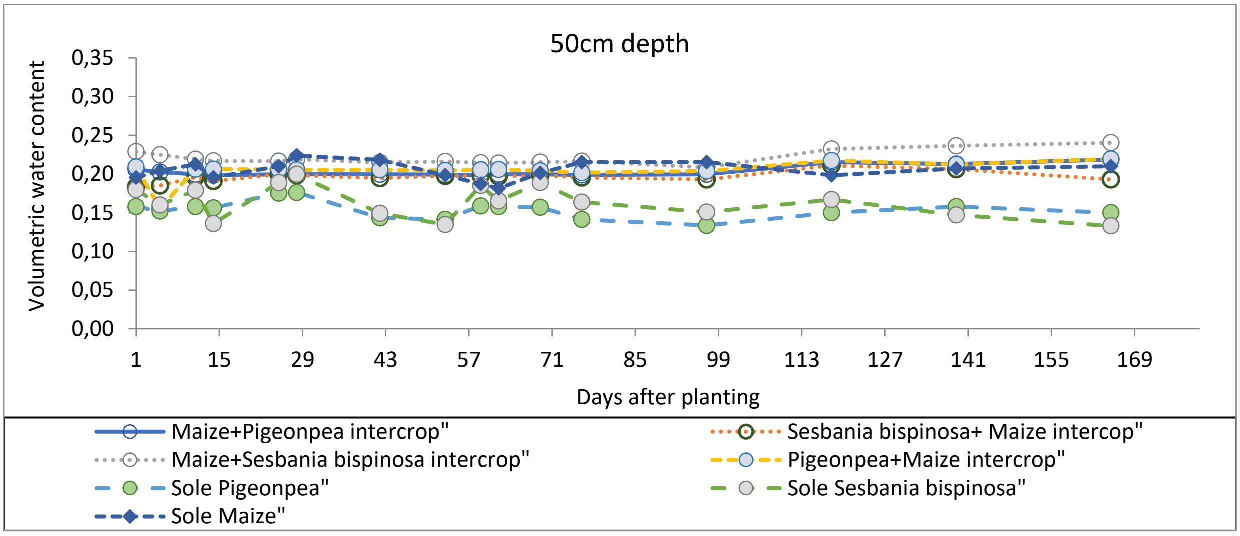

Fig 2 Average soil water content at 50cm depth

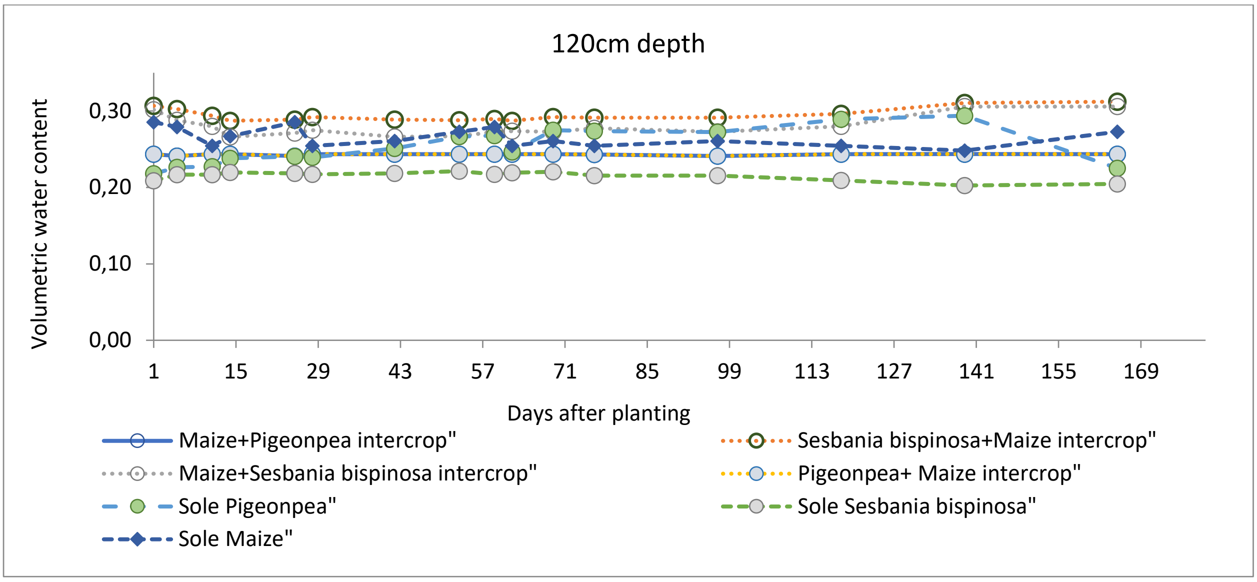

Fig 3 Average soil water content at 120cm depth