RAINWATER HARVESTING, LEUCAENA BIOMASS TRANSFER AND INTEGRATED NUTRIENT MANAGEMENT IN IMPROVING SORGHUM (*SORGHUM BICOLOR* [L MOENCH]) PRODUCTIVITY IN SEMI-ARID REGIONS OF ZIMBABWE

BY

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ABSTRACT

Yield decline in rain-fed agriculture is mainly caused by moisture stress and poor soil fertility in semi-arid areas. Current mineral fertiliser application rates cannot replenish soil fertility and improve yields. The aim of the study was to assess the role of rainwater harvesting; *Leucaena leucocephala* biomass combination with cattle manure and mineral fertiliser in improving sorghum productivity in semi-arid areas of Zimbabwe. Three experiments were arranged in split-split-plot designs with three rainwater harvesting techniques, nutrient management and two sorghum varieties (Macia and SV1) used as the sub-sub plot factor. The first experiment had rainwater harvesting as the main factor at three levels (tied contour, infiltration pit and standard contour) and Leucaena biomass was the sub-plot factor at five levels (0, 5, 10, 20 and 30 t ha^{-1}). The second experiment had rainwater harvesting techniques as main factor and Leucaena/cattle manure combinations as sub plot factor with five levels (0, 5, 10, 20 and 30 t ha^{-1}). The third experiment had rainwater harvesting as main factor, Leucaena + NPK fertiliser (7% N: 14%P_2O_5: 7%K_2O) as sub-plot factor at five levels (0, 2.5/25, 5/50, 10/100 and 15/150). Soil moisture content was higher ($p<0.05$) across all the seasons in the depth ranges of 0–20cm and 21–40cm for tied contours. Moisture content of 7.18 % was highest from 0-20 cm and 9.34 % from 20-40 cm under tied contour. Lowest moisture content from 0-20 cm was 6.69 % and 8.04% from 20-40 cm under standard contour treatments. Tied contour had significantly ($p<0.05$) higher sorghum grain and stover yields followed by infiltration pit and the least was under standard contour. Highest grain yield (1.15 t ha^1) obtained from SV1 under tied contour treatments amended with 30 t ha^{-1} biomass. Interaction of rainwater harvesting techniques and Leucaena biomass had significant ($p<0.05$) effect on stover yields with highest (4.47 t ha^{-1}) yield observed from tied contour + 30 t ha^{-1} Leucaena biomass in 2018/19 from Macia variety. Rainwater-use efficiency was significantly ($p<0.05$) affected by rainwater harvesting techniques with the highest efficiency of 3.28 kg ha^{-1} mm^{-1} from Macia and 3.24 kg ha^{-1} mm^{-1} for SV1 all under tied contours. The relationships between Rainwater use efficiency were positively correlated to Leucaena biomass (r^2= 0.76-0.99) for both sorghum varieties over three seasons. Results showed significant ($p<0.05$) increase in sorghum grain and stover yield with increased applications of Leucaena/cattle manure. Macia variety had statistically greater ($p<0.05$) grain yield than SV1 variety. Tied contour show considerably higher yield for both varieties in all seasons. Harvest Indices show significant differences ($p<0.05$) as influenced by rainwater harvesting technique, with tied contour and infiltration pit having comparably higher value than standard contour. Leucaena/cattle manure significantly influenced ($p<0.05$) sorghum net return in all seasons except at 5 t ha^{-1} where no significant effect was observed. Macia variety had higher (US$263.16) net return compared with SV1. Grain and stover yields show significant ($p<0.05$) difference among treatments under Leucaena/NPK fertiliser combination. Highest grain yield from Macia (1.146 t ha^{-1}) and 1.1 t ha^{-1} from SV1 were from tied contour with 15 t ha^{-1} biomass + 150 kg ha^{-1} NPK fertiliser. Agronomic efficiency was significantly ($p<0.05$) affected by rainwater harvesting, Leucaena/NPK fertiliser and their interaction. Highest (0.075kg kg^{-1}) agronomic efficiency was observed from treatments with tied contour + 2.5 t ha^{-1} Leucaena biomass + 25 kg ha^{-1} NPK fertiliser. It can be concluded that tied contours and infiltration pits have better yield benefits than standard contours when amended with organic and inorganic nutrient sources. Basing on results of this study, agriculture policy makers are encouraged to implement technologies which improve yields, net benefits and show agronomic efficiency. This will enable smallholder farmers in semiarid areas to improve food security and improve resilience to climate change.

Keywords: Rainwater harvesting; *Leucaena Leucocephala*; sorghum; soil moisture content; Leucaena/cattle manure; rainwater use efficiency; net returns

DECLARATION: PLAGIARISM

I, **Andrew Tapiwa Kugedera** declare that:

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The following publications are associated with the research presented in this thesis:

1. Kugedera, A.T., Nyamadzawo, G., Mandumbu, R., & Nyamangara, J. (2022). Potential of field edge rainwater harvesting biomass transfer and integrated nutrient management in improving sorghum (*Sorghum bicolor* (L.) Moench) productivity in semi-arid regions: a review. *Agroforestry Systems*, 96 (5-6), 909-924. https://doi.org/10.1007/s10457-022-00751-w

2. Kugedera A.T, Mandumbu, R., & Nyamadzawo, G. (2022). Rainwater harvesting and *Leucaena leucocephala* biomass rates effects on soil moisture, water use efficiency and sorghum (*Sorghum bicolor* [(L.) Moench]) productivity in a semi-arid area in Zimbabwe. *Journal of the Science of Food and Agriculture*, 102 (14), 6443-6453. https://doi.org/10.1002/jsfa.12011

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4. Kugedera, A. T., Nyamadzawo, G., & Mandumbu, R. (2022). Augmenting *Leucaena leucocephala* biomass with mineral fertiliser on rainwater use efficiency, agronomic efficiency and yields on sorghum (*Sorghum bicolor* [(L.) Moench]) under rainwater harvesting techniques in semi-arid region of Zimbabwe. *Heliyon*, 8(7) e09826. https://doi.org/10.1016/j.heliyon.2022.e09826

APPROVAL FORM

We, the undersigned certify that we have supervised and recommend to Bindura University of Science Education (BUSE) for acceptance a thesis entitled "RAINWATER HARVESTING, LEUCAENA BIOMASS TRANSFER AND INTEGRATED NUTRIENT MANAGEMENT IN IMPROVING SORGHUM (*SORGHUM BICOLOR* [L MOENCH]) PRODUCTIVITY IN SEMI-ARID REGIONS OF ZIMBABWE" for submission of the Doctor of Philosophy Degree in Agricultural Science.

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DEDICATION

This thesis is dedicated to my wife Letticia Kudzai, son Arnold, Emmanuel Taonashe and Anotidaishe Andrew (Jnr) and my parents for their support during this period. Thank you for taking me to this level of education.

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LIST OF ABBREVIATIONS

AE	Agronomic efficiency
FAO	Food and Agriculture Organisation
ha	hectare
HI	Harvest Index
INM	Integrated nutrient management
kg	kilogramme
mm	millimetre
N	nitrogen
NPK	Nitrogen, Phosphorous and potassium
NUE	Nutrient Use Efficiency
RWH	Rainwater harvesting
RWUE	Rainwater use efficiency
SOC	Soil organic carbon
SSA	Sub-Saharan Africa

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND TO THE STUDY

Food insecurity is high in semi-arid areas of Africa due to moisture stress and poor soil fertility. This contributes to poor crop growth causing low yields to be realised (Muchai et al., 2020; Kimaru-Muchai et al., 2021; Kubiku et al., 2022a). Soil moisture stress has been regarded as one of the major constraints in cereal production which contribute to poor food production in countries like Zimbabwe. Climate variability in semi-arid areas negatively affected crop yields contributing to food insecurity and poverty (Nyagumbo et al., 2019; Nciizah et al., 2020; Mandumbu et al., 2021). Semi-arid areas are associated with high evapotranspiration and frequent long season dry spells which reduce crop production under rainfed agriculture (Mupangwa et al., 2006; Nyamadzawo et al., 2013; Heard et al., 2014; Mahinda et al., 2018; Nyagumbo et al., 2019).

Rainfall in semi-arid areas of Zimbabwe has been very low over the past two decades and this negatively affected rainfed agriculture (Mupangwa et al., 2012a; Nyagumbo et al., 2020). This contributed to low crop productivity in semi-arid areas (Mupangwa et al., 2012b, 2016; Masaka et al., 2019). This is similar to semi-arid areas across the world (Mugwe et al., 2019; Chilagane et al., 2020; Sebnie et al., 2020; Kimaru-Muchai et al., 2021; Tsujimoto et al., 2021). To address issues of low erratic rainfall, irrigation schemes can be implemented but this has proved to be difficult for resources constrained countries (Nyamadzawo et al., 2013), hence the need to adopt climate smart agriculture in semi-arid areas to improve yields. Climate smart agriculture techniques and growing of drought tolerant crops such as sorghum can be a better option to reduce food insecurity and poverty in semi-arid areas.

Sorghum (*Sorghum bicolor* [L Moench]) is an important food crop widely grown in semi-arid and arid regions across the world, especially in Sub-Saharan Africa (SSA) (Williams and der Vries 2019; Masaka et al., 2019; Nciizah et al., 2020). Sorghum is ranked the fifth important cereal grain globally (Hakeem et al., 2018; Mahinda et al., 2018) and second to maize in SSA countries where it is mainly used for human consumption (Masaka et al., 2019; Kimaru-Muchai et al., 2021; Kubiku et al., 2022b). The crop is favoured in semi-arid areas because of its ability to thrive in harsh environmental conditions (Nyamudeza, 1993; Nyakatawa et al., 1996; Mwadalu and Mwangi, 2013; Hakeem et al., 2018; Mwadalu et al., 2022). Although sorghum has been widely adopted in semi-arid areas, its productivity is very low with smallholder farmers producing meagre yields (0.514 t ha^{-1}) which do not meet food demands requirements (Itabari, 199; Kpongor, 2007; Twomlow et al., 2008; Palé et al., 2009; Gebreyesus, 2012; Tsusaka et al., 2015; Marumbi et al., 2020). Sorghum production in semi-arid areas is constrained by moisture stress and poor soil fertility (Ndlangamandla et al., 2016; Enciso et al., 2019; Sebnie et al., 2020).

Challenges of low yields in semi-arid areas can be addressed by combining rainwater harvesting techniques with nutrient management options. Integrating rainwater harvesting and nutrient management options create synergies that improve rainwater use efficiency and crop yields in semi-arid areas (Kilasara et al., 2015; Nyamadzawo et al., 2015; Kimaru-Muchai et al., 2021). Use of better rainwater harvesting techniques such as tied contours and infiltration pits increase rainwater use efficiency and avert effects of mid-season dry spells (Nyamadzawo et al., 2015; Nyagumbo et al., 2019). Infiltration pits and tied contours have risk mitigatory capacities, harvest runoff water, store it and reduce soil moisture stress in arable lands (Kilasara et al., 2015; Nyamadzawo et al., 2015; Kubiku et al., 2022a). These techniques minimise soil erosion through reduced water velocities; improve water availability to crops and groundwater recharge (Mupangwa et al., 2012a, 2012b; Wuta et al., 2018; Nyagumbo et al., 2019). The benefits of using infiltration pits on sorghum have been demonstrated in semi-arid areas of Africa (Kilasara et al., 2015; Kubiku et al., 2022a). The benefits of using tied contours in improving sorghum grain yields has not been fully evaluated, although Nyamadzawo et al.

(2015) and Kubiku et al. (2022a) show positive benefits but there is need for further evaluation. Several authors reported positive benefits of using infiltration pits in semi-arid areas of Zimbabwe (e.g., Motsi et al., 2004; Mugabe, 2004; Mutekwa and Kusangaya, 2006; Mupangwa et al., 2012b; Nyakudya et al., 2014; Nyamadzawo et al., 2015; Nyagumbo et al., 2019).

Infiltration pits and tied contours alone cannot achieve higher yields, especially in low input systems, hence the need to integrate them with organic and inorganic nutrient sources. Organic nutrient sources such as cattle manure and *Leucaena leucocephala* biomass can be cheap nutrient sources for smallholder farmers together with reduced rates of mineral fertilisers. Biomass transfer of *L. leucocephala* is one of the sustainable ways of improving soil fertility for smallholder farmers in semi-arid areas (Mafongoya and Dzowela, 1999; Mugwe, 2007; Kebede et al., 2012). Leucaena biomass is rich in nitrogen which is the major limiting nutrient in soil and improves crop production (Mafongoya and Nair, 1997; Mafongoya et al., 1998; Mafongoya et al., 2006a; Mucheru-Muna et al., 2007; Mugwe, 2007). Several authors reported improved soil fertility and crop yield after use of Leucaena biomass in semi-arid areas of Kenya, Malawi and Zambia (e.g. Kang et al., 1981; Mafongoya and Dzowela, 1999; Mugendi et al., 1999; Mugendi et al., 2003; Kazombo-Phiri, 2005; Mafongoya et al., 2006b; Murovhi and Materechera 2006; Mugwe et al., 2007; Kebede et al., 2012; Getu and Teshager, 2015; Opala et al., 2020). Combining Leucaena biomass with field edge rainwater harvesting techniques has the potential to increase water retention, improve soil fertility and sorghum yields.

Furthermore, Leucaena biomass can be integrated with cattle manure to determine compatibility level which can be adopted by smallholder farmers in improving sorghum and other cereal crop yields. Combining Leucaena biomass with cattle manure in equal quantities can increase soil organic carbon (SOC) due to higher rate of mineralisation and faster decomposition of Leucaena increasing availability of nutrients in the soil for crops (Timsina, 2018). Organic nutrient sources have potential to improve soil health, N mineralisation, decrease soil bulk density and increase yields (Mafongoya et al., 2006; Mugwe et al., 2019; Gram et al., 2020). The use of Leucaena/cattle manure combination reduces soil acidity and increases base saturation, cation exchange capacity and population of microbes which are responsible for mineralisation in the soil (Bayu et al., 2006; Bekunda et al., 2010; Bekeko 2013; Vanlauwe et al., 2015; Srinivasarao et al., 2021). However, organic nutrient sources alone take time to decompose and release nutrients. There is need to augment Leucaena biomass with mineral fertiliser which quickly releases nutrients. In addition to that, use of mineral fertiliser rich in major nutrients can increase yields in many intensified rainfed agricultural systems (Kimaru-Muchai et al., 2021; Srinivasarao et al., 2021).

Combining Leucaena biomass with mineral fertiliser has been demonstrated to increase yields in other cereal crops due to positive interactions and complementarities between Leucaena biomass and mineral fertiliser (Timsina, 2018). All these nutrient sources can be combined with rainwater harvesting to simultaneously reduce soil moisture stress, increase soil fertility and sorghum yields. Since infiltration pits and tied contours require much labour in their construction, there is need to evaluate economic benefits realised when integrated with organic and inorganic nutrient sources.

1.2 PROBLEM STATEMENT

Moisture and nutrient stress are major constraints limiting crop production in semi-arid areas including drought resistant crops such as sorghum. Low and erratic rainfall which is unreliable contributed to moisture stress in Sub-Saharan Africa (SSA) and this is supported by inadequate application of nutrient sources which is below quantities harvested by crops. Low crop production has been attributed to poor soil and water conservation practices which have been used by smallholder farmers in semi-arid areas. Several soil and water management practices are available but farmers are not able to utilise them due to lack of technical knowledge.

Farmers also apply these methods separately hence they need to be used simultaneously to improve crop production. This brings in the need to evaluate the effects of rainwater harvesting techniques and biomass transfer of *Leucaena leucocephala* on sorghum productivity.

1.3 JUSTIFICATION OF STUDY

Sorghum is mainly grown in stressful environments with high temperatures, unpredictable water supply, fragile soils with low nutrient status and limited growing season length which negatively affect its productivity. Moisture stress and climatic variability are major limiting factor to crop production in semi-arid areas (Nyamadzawo *et* al., 2013; Ayanlade et al., 2018; Chilagane et al., 2020; Sebnie et al., 2020; Tsujimoto et al., 2021) such as Chivi in Zimbabwe. Water deficit has been triggered by low rainfall, high surface runoff and high evapotranspiration in semi-arid areas (Heard et al., 2014; Mahinda et al., 2018; Masaka et al., 2019).

Recurrent droughts, mid-season droughts and premature cessation of the growing season are the major causes of moisture stress and are responsible to widespread food shortages in semi-arid areas in Sub-Saharan Africa (SSA) (Derese, 2017; Bosire, 2019). Low soil fertility of the dominant sandy soils in semi-arid regions also contributed to low sorghum production, hence the need to adopt climate smart agriculture options. The use of climate smart options for rainfed agriculture such as field edge rainwater harvesting techniques, biomass transfer of Leucaena, cattle manure and mineral fertiliser in integration has the potential to reduce soil moisture stress, poor soil fertility and improve sorghum production (Kebede et al., 2012). Infiltration pits and tied contours harvest surface runoff water, store it and reduce soil erosion leading to improved crop yields (Mupangwa et al., 2012a, Kilasara et al., 2015; Nyamadzawo et al., 2015; Wuta et al., 2018; Nyagumbo et al., 2019; Kubiku et al., 2022a). Infiltration pits have demonstrated their benefits in improving soil moisture and cereal grain yield (Motsi et al., 2004; Mugabe, 2004; Gumbo et al., 2012; Kilasara et al., 2015). Tied contours can be one of the cheapest options for smallholder farmers due to its ability to store large volume of water, recharge groundwater, reduce soil erosion and improve crop yields (Nyamadzawo et al., 2015; Wuta et al., 2018; Nyagumbo et al., 2019).

Biomass transfer of Leucaena serves as soil moisture conservation and soil fertility replenishment option which has the potential to improve crop yields (Mafongoya and Dzowela, 1999; Mugendi et al., 1999; Kazombo-Phiri, 2005; Mafongoya et al., 2007; Mugwe, 2007; Kebede et al., 2012). Furthermore, combining organic nutrient sources has the ability to improve soil cation exchange capacity, soil moisture, nutrient availability and crop yields (Bekunda et al., 2010; Bekeko, 2013; Vanlauwe et al., 2015; Wolka et al., 2018; Srinivasarao et al., 2021). Therefore, combining field edge rainwater harvesting, Leucaena biomass, cattle manure and/or mineral fertiliser can be one of the best climate smart agriculture approaches to address effects of climate variability, improve moisture availability to crops, soil fertility and sorghum yields and economic benefits in semi-arid areas of Zimbabwe and beyond.

1.4 AIM OF THE STUDY

The aim of the study was to determine the integrated effects of tied contours and infiltration pits, Leucaena biomass; Leucaena/cattle manure combination and Leucaena/NPK fertiliser on soil moisture content, rainwater use efficiency, agronomic efficiency, sorghum yields and economic benefits in Chirinda village of Chivi District.

1.4.1 OBJECTIVES OF THE STUDY

The specific objectives of the study were to:

i. Evaluate the effects of rainwater harvesting and use of different *L. Leucocephala* biomass rates on soil moisture content, rainwater use efficiency, and grain and stover yields of sorghum varieties (Macia and SV1).

ii. Assess the compatibility of *Leucaena leucocephala* biomass mixed with equal amounts of cattle manure on grain and stover yields, rainwater use efficiency and net returns of two sorghum varieties (Macia and SV1) under rainwater harvesting techniques in a semi-arid region in Zimbabwe.

iii. Determine the effects of augmenting *Leucaena leucocephala* biomass with mineral fertiliser on grain and stover yields, rainwater use efficiency and agronomic efficiency, and of two sorghum varieties (Macia and SV1) under rainwater harvesting techniques.

1.5 HYPOTHESIS

The hypotheses tested in the study were:

i. The use of rainwater harvesting and different *L. Leucocephala* biomass rates improve soil moisture content, rainwater use efficiency, and grain and stover yields of two sorghum varieties (Macia and SV1).

ii. The effects of *Leucaena leucocephala* biomass mixed with equal amounts of cattle manure improves grain and stover yields, rainwater use efficiency and net returns of two sorghum varieties (Macia and SV1) under rainwater harvesting techniques in a semi-arid region in Zimbabwe.

iii. Augmenting *Leucaena leucocephala* biomass with mineral fertiliser improves grain and stover yields, rainwater use efficiency and agronomic efficiency of two sorghum varieties (Macia and SV1) under rainwater harvesting techniques.

1.6 CONCEPTUAL FRAMEWORK

Water deficit which leads to water stress causes poor sorghum productivity and food insecurity in SSA particularly Zimbabwe (Mudatenguha et al., 2014). However, field edge rainwater harvesting techniques such as tied contours and infiltration pits can be a solution to address soil moisture stress in semi-arid areas as they can increase plant available water for crop growth. Improved rain water harvesting (tied contours) may result in improved crop yields, food security and better livelihood among households (Nyamadzawo et al., 2015; Nyagumbo et al., 2019; Kubiku et al., 2022a). However, increasing water availability alone may not be enough as there is need to address the issue of low soil fertility. The use of Leucaena biomass transfer, cattle manure and/ mineral fertiliser can help to address soil fertility in semi-arid areas.

However, the integration of field edge rainwater harvesting techniques, Leucaena biomass transfer, cattle manure and/ mineral fertiliser as climate smart agriculture option has the potential to improve sorghum productivity for smallholder farmers in semi-arid areas (Figure 1.1).

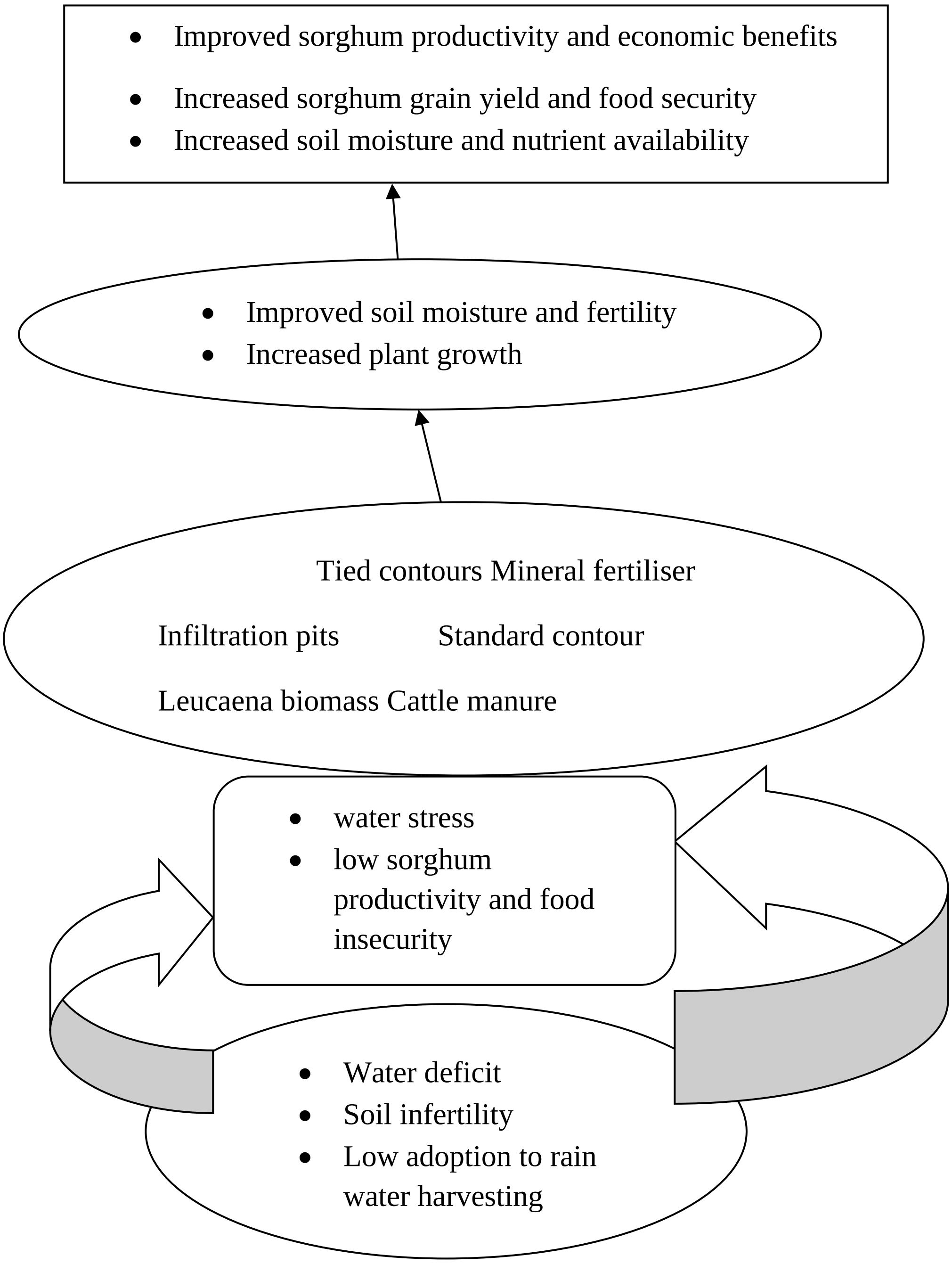

Figure 1.1: Conceptual framework

1.7 THESIS OUTLINE

This thesis is based on paper format with 7 chapters. Chapter 1 consists of general introduction, objectives, hypothesis, conceptual framework and thesis structure. Chapter 2 consists of literature review that synthesises the potential of field edge rainwater harvesting, biomass transfer and integrated nutrient management in improving sorghum productivity. Results from related experiments are also indicated in this chapter. Chapter 3 covers site description and general methodology. Chapter 4 is based on experiment that determined the effects of rainwater harvesting and *Leucaena leucocephala* biomass rates on soil moisture, water use efficiency and *Sorghum bicolor* [(L.) Moench] productivity in semi-arid areas of Zimbabwe. Chapter 5 covers field experiments designed to evaluate the compatibility of *Leucaena leucocephala* biomass and cattle manure combination under rainwater harvesting on sorghum (*Sorghum bicolor* [(L.) Moench]) productivity and economic benefits in semi-arid areas of Zimbabwe. Chapter 6 describes field experiments that determined the effects of augmenting *Leucaena leucocephala* biomass with mineral fertiliser on rainwater uses efficiency, agronomic efficiency and yields on sorghum (*Sorghum bicolor* [(L.) Moench]) under rainwater harvesting techniques in semi-arid region of Zimbabwe. Chapter 7 covers synthesis of chapters 4 to 6 giving major discussions and conclusions of the whole project covering all three objectives. It also outlined recommendations, societal benefits from study and suggestions for future research and studies.

CHAPTER 2: POTENTIAL OF FIELD EDGE RAINWATER HARVESTING, BIOMASS TRANSFER AND INTEGRATED NUTRIENT MANAGEMENT IN IMPROVING SORGHUM (*SORGHUM BICOLOR* (L.) MOENCH) PRODUCTIVITY IN SEMI-ARID REGIONS: A REVIEW

ABSTRACT

Sorghum has been promoted in arid and semi-arid areas due to its drought tolerance which makes it survive under harsh environmental conditions, but grain yields are very low, e.g., averaging 514 kg ha^{-1}. The use of field edge rainwater harvesting techniques of tied contours and infiltration pits can be suitable options to capture rainfall and reduce runoff on the soils. Furthermore, integration of field edge rainwater harvesting with appropriate soil fertility management practices can potentially increase sorghum yields. The use of biomass transfer of nitrogen fixing trees such as *Leucaena leucocephala* is an agroforestry practice which can improve soil fertility through increasing mineral nitrogen, cation exchange capacity; porosity, water retention, and reduce soil bulk density. Other appropriate soil fertility management options include integrated nutrient management (INM) where organic fertilisers such as cattle manure are mixed with inorganic fertilisers. These technologies are examples of climate smart agricultural practices that have the potential to increase sorghum yields. The integration of rainwater harvesting techniques and INM show improved sorghum yields ranging from 750-2100 kg ha^{-1} with potential of increasing yields in clayey soils. However, currently there is little data available on the implementation of these technologies in semi-arid areas. This paper reviews and analyses the potential effect of integration rainwater harvesting, biomass transfer and INM on sorghum yields in semi-arid areas of Zimbabwe.

Keywords: *Field edge, rainwater harvesting, biomass transfer, sorghum productivity, semi-arid*

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2.1 INTRODUCTION

Low crop productivity is common in most smallholder farming areas of Zimbabwe located in Masvingo, Matabeleland Provinces, Mudzi, Mbire, Chipinge and Buhera which receive less than 450 mm rainfall per annum (Nyakudya and Stroosnijder, 2015). Climate variability has affected crop production especially in smallholder farming environments in marginalised areas. Semi-arid areas in Zimbabwe are more vulnerable to climate vulnerability causing erratic rainfall which is unevenly distributed and cannot sustain crop production (Nyagumbo et al., 2019), which sometimes causes crop failure and food shortages (Nyamadzawo et al., 2013; Kubiku et al., 2022a). Most smallholder farmers in marginal areas of Zimbabwe are now growing sorghum to supplement low maize yields which average of 500 kg ha^{-1} $year^{-1}$.

These regions are associated with a very short growing season and dry spells (Mudatenguha et al., 2014; Ayanlade et al., 2018; Muchai et al., 2020). Most soils in smallholder farming areas of Zimbabwe have poor fertility (Masvaya et al., 2017) because they are derived from granite rocks (Masaka et al., 2019). The soils have low clay content, low organic matter content, poor biological activity, high acidity, few weatherable minerals and are susceptible to erosion (Chikowo, 2004; Kimaru-Muchai et al., 2021). Low crop productivity is due to moisture stress (Muchai et al., 2020; Kimaru-Muchai et al., 2021), high surface runoff and inherently poor soil fertility, prolonged droughts and monoculture (Njeru et al., 2013; Coulibaly, 2015). Farmers are recommended to use intercropping and crop rotation to improve soil fertility. In semi-arid areas farmers are encouraged to grow sorghum (*Sorghum bicolor* L) because its drought tolerant (Masaka et al., 2019). However, sorghum production has been negatively affected by inherent poor soil fertility leading to low grain and stover yields in Zimbabwe (Chiduza et al., 1995; Masaka et al., 2019), Kenya (Kimaru-Muchai et al., 2021), West Africa (Zougmoré et al., 2014) and Sudan (Hakeem et al., 2018). Most farmers now grow sorghum on small pieces of land. Sorghum is ranked the fifth most important cereal crop in the world following maize (*Zea mays*), rice (*Oryza sativa*), wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) (FAO, 2018). Sorghum has the ability to solve food insecurity crisis and to boost animal feed production thereby reducing pressure on maize which is a major staple food in Africa (Muzerengi and Tirivangasi, 2019; Kimaru-Muchai et al., 2021). Although sorghum is an important cereal, its production is very low in most African countries with grain yield ranges of 500-1500 kg ha^{-1} in Kenya (Mwadalu 2014; Kisinyo et al., 2019), 329-850 kg ha^{-1} in Sudan

(Noureldin et al., 2012), 202-671 kg ha^{-1} Burkina Faso (Palé et al., 2009), 320-1387 kg ha^{-1} in Tanzania (Kilasara et al., 2015) and 400-900 kg ha^{-1} Zimbabwe (Twomlow et al., 2008).

Grain and stover yields of sorghum can potentially be increased by improving soil moisture availability through the use of field edge rainwater harvesting techniques and improving the soil fertility through the use of integrated nutrient management (INM) and use of agroforestry system of biomass transfers e.g., using Leucaena biomass (Jama et al., 2000; Mucheru-Muna et al., 2007; Mugwe, 2007; Neba et al., 2015). Rainwater harvesting techniques are low-cost options to reduce soil moisture stress, soil erosion and increase sorghum growth. Tied contours and infiltration pits can be best option for smallholder farmers once constructed since they harvest surface runoff, increase infiltration and water retention (Mutekwa and Kusangaya, 2006; Nyagumbo et al., 2019).

The use of INM can improve soil fertility and a low N dose of ≤17 kg ha^{-1} can reduce immobilisation of N in the soils. INM improves availability of secondary nutrients and micronutrients as well in the plant root zone throughout the growing season (Vanlauwe et al., 2010; Mugwe et al., 2019) and increase crop yields. The use of INM reduces soil acidity and increases base saturation, cation exchange capacity and population of microbes which are responsible for mineralisation in the soil (Bayu et al., 2006; Bekunda et al., 2010; Bekeko 2013; Vanlauwe et al., 2015). Integrated nutrient management is environmentally friendly, have the potential to increase crop productivity and farm profitability in semi-arid areas (Vanlauwe et al., 2010).

Leucaena leucocephala is a leguminous tree which can be used for several years supplying biomass and improving soil fertility (Mafongoya et al., 2006a; Mafongoya et al., 2006b; Mugwe, 2007) since it produces high quality biomass with high N content (Mafongoya and Nair, 1997; Mafongoya et al., 1998; Mafongoya et al., 2006b; Mucheru-Muna et al., 2007).

According to Mugendi et al., (1999). Incorporation of Leucaena prunings improves soil fertility and maize yields e.g., 4.1 t ha^{-1} of maize was recorded in Embu, Kenya. In Malawi it was reported that the use of 10 t ha^{-1} Leucaena biomass is similar to use of 100 kg N ha^{-1} (approximately 300 kg ha^{-1} of ammonium nitrate) (Kazombo-Phiri, 2005). Mulching of maize crop fields using Leucaena biomass increased maize yield from 1.9 t ha^{-1} to 3.5 t ha^{-1} in Nigeria (Kang et al., 1981). Incorporation of Leucaena prunings which have high N content, supplying phosphorous and other trace elements when twigs decompose, replenish soil fertility and increase maize yields compared with that applied as mulch in Kenya (Young 1986; Delve et al., 2000; Mwangi 1997; Mugwe, 2007). According to Kimaru (2017) and Kimaru-Muchai et al. (2021), land users have shown high level of adoption of agroforestry in semi-arid areas of Kenya because they are unable to buy large quantities of mineral fertilisers. This contributed to adoption of agroforestry systems like biomass transfer and improved fallow in southern African countries like Zambia and Zimbabwe (Mafongoya et al., 2006b).

The use of rainwater harvesting, INM and biomass transfer can potentially improve soil moisture and soil fertility, leading to improved crop productivity. However, few studies have evaluated the impacts of integrating field edge rainwater harvesting, INM and agroforestry practice of biomass transfer on the yields of sorghum in semi-arid areas where rainfall is very low and erratic. Thus, this review synthesises and analysis the potential of rainwater harvesting, INM and agroforestry (biomass transfer) as sustainable methods of improving sorghum productivity in semi-arid areas in Zimbabwe.

2.2 METHODOLOGY

Zimbabwe is a southern African country located between 19º and 30º S, 25° and 34° E of the equator. Zimbabwe has a total land area of 39 million ha and receives 500-1500 mm rainfall per annum (Nyamadzawo et al., 2012b). Most soils in marginal areas of the country range from sands to loamy sands which are inherently infertile with low weatherable minerals (Chikowo, 2004). Dry regions of the country receive less than 500 mm rainfall (Mugandani et al., 2012, Mugandani and Mafongoya, 2019) and cover the largest area of the country. These are the regions where small grains such as sorghum, pearl millet (*Pennisetum glaucum*) and finger millet (*Eleusine corocana*) are grown. Agriculture is the major economic activity of Zimbabwe with the study area depending mainly on rainfed maize and sorghum production as their economic activity. Agriculture in the study area is mainly influenced by poor soil fertility due to soil erosion and nutrient mining which can be controlled using agroforestry systems such as improved fallow and biomass transfer.

Comprehensive literature search was done from July 2019 to August 2020 using Google, Researchgate and Google scholar for peer reviewed published papers on INM, rainwater harvesting, biomass transfer and sorghum production in semi-arid areas of Africa including Zimbabwe. The search was restricted to papers published between 1990 and 2020 inclusive and the following criteria were used to select papers; experiments showing effects of RWH, INM, biomass transfer and their combinations on sorghum productivity in semi-arid areas regionally or internationally. Papers selected for the review meet the following criteria: (1) Paper published in peer review journals. (2) Paper show experiments done in semi-arid areas at research stations or farmer fields, (3) Original field experiments showing research on rainwater harvesting techniques, biomass transfer/ agroforestry technologies and INM. Peer reviewed publications from several countries were selected; especially those countries which have similar climatic conditions with Zimbabwe or from sub–Saharan Africa (SSA). A total of 100 published papers were retrieved and selected. After selecting the related publications, duplicates were removes leaving a total of 80 publications. Screening was done removing all papers not relevant to studies on sorghum leaving a total of 60 publications. Eligibility was done on 60 publications and five (5) full texts were removed leaving a total of 55 studies included in the review. Then the selected papers were screened and assessed their eligibility.

The next step was to synthesize the data of those eligible papers, including extraction and classification of treatments and results. The final step was evaluation of the synthesized data, making discussion, indicating the way forward and inferring conclusions.

2.3 RESULTS AND DISCUSSIONS

2.3.1 Field edge rainwater harvesting techniques options for smallholder farming in semi-arid areas of Zimbabwe

2.3.1.1 History of the standard contours

Contour ridges are common in most fields of smallholder farmers across semi-arid areas of Zimbabwe and dispose precious water from the fields (Nyamadzawo et al., 2012a; Wuta et al., 2018). Contour ridges are graded ridges with upstream channels in a cross-slope direction (Nyakudya and Stroosnijder, 2015). Contour ridges were designed to safely discharge water without causing much erosion or with no erosive power in high rainfall areas. Dimensions of standard contours vary according slope, soil types and other factors considered by farmers (Nyakudya and Stroosnijder, 2015). However, in the 1950s, after witnessing high levels of soil erosion in the native areas (areas occupied by African and mainly located in semi-arid areas), contour ridges were enforced as a way of controlling rill and gulley erosion in arable lands.

Colonial government intervened to control land degradation using the Native Land Husbandry Act of 1952 which enforced compulsory construction of contour ridges (Hagmann and Murwira, 1996). Contour ridges were seen as inappropriate in semi-arid areas which receive low rainfall, that are affected by frequent droughts, as they dispose-off water from fields instead of retaining it (Nyamadzawo et al., 2013). Therefore, contour ridges have been modified to dead level contour ridges (Mupangwa et al., 2006), tied contours (Nyamadzawo et al., 2013; Nyagumbo et al., 2019) and others construct infiltration pits inside contour ridges (Mutekwa and Kusangaya, 2006) to increase water storage and infiltration of water. Contour ridges with infiltration pits harvest more water due to their depth.

2.3.1.2 Field-edge RWH structures in Zimbabwe

These are modified structures of standard contours at the edge of the field. These are used to capture runoff water and store it and allow it to infiltrate, improve infiltration rates, water retention, reduce surface runoff, and increase surface storage of water for example infiltration pits (Motsi et al., 2004).

a. Infiltration pits

Infiltration pits are water holding pits also known as locally in Zimbabwe as "Chibatamvura", Fig 2.1 (Motsi et al., 2004; Nyamadzawo et al., 2015). These are pits dug along contour drainage to trap runoff in order to increase infiltration of water (Mutekwa and Kusangaya 2006). Infiltration pits are deep trenches dug along the contour ridge to trap run-off and increase infiltration (Nyamadzawo et al., 2013; Mhizha, 2017), most of them are rectangular trenches of varying dimensions dug at various intervals in channels of contour ridges (Motsi et al., 2004). They can be filled with grass or stover to enhance decomposition (Mugabe, 2004; Mupangwa et al., 2011), thus ideal for composting. This technique originated in Zimbabwe from a farmer called Mr. Zephaniah Maseko Phiri, in Zvishavane (Maseko, 1995). The pits developed measured 4 m long, 2 m wide and 1 m deep in loamy sands on gentle slopes (Motsi et al., 2004). According to Mugabe (2004) infiltration pits used were 7 m long and 1 m deep at 20 m intervals in loam soils.

Figure 2.1: Infiltration pit used during the experiment. Photo by Kugedera AT (2017)

Infiltration pits were promoted from 1991-1997 and they were found to increase yields of crops (Motsi et al.,2004; Mutekwa and Kusangaya, 2006; Mhizha, 2017). According to Mupangwa et al. (2006) infiltration pits within contour ridges are still being used as a soil water management and they replenish soil water on the up and down slope sides of the pit. Infiltration pits are beneficial to farmers as they reduce surface runoff, improve soil moisture and crop yields. The use of infiltration pits in Zimbabwe recorded maize yields of 2400 kg ha^{-1} on sandy loams in Mudzi (Motsi et al., 2004), 1250 kg ha^{-1} maize on sands in smallholder farming areas of Shurugwi (Nyagumbo et al., 2019). Use of infiltration pits in Ikhanoda, Tanzania was reported to produce 1234 kg ha^{-1} of sorghum (Wahi variety) and 1387 kg ha^{-1} (Hakika variety) on sandy loam soils (Kilasara et al., 2015, Table 2.1).

Table 2.1: Yield benefits of different rainwater harvesting structures on sorghum

Rainwater harvesting technique	**Soil type**	**Area**	**Sorghum variety**	**Season**	**Experimental layout**	**Grain yields (kg ha^{-1})**	**Reference**
Tied contour	Sandy loam	Zimbabwe (Marange)	Macia SC Sila	2016/17 - 2018/19	Split-split plot	200 1200	Kubiku et al. (2022a)
Infiltration pit	Sandy loam	Zimbabwe (Marange)	Macia SC Sila	2016/17 - 2018/19	Split-split plot	1800 640	Kubiku et al. (2022a)
Standard contour	Sandy loam	Zimbabwe (Marange)	Macia SC Sila	2016/17 - 2018/19	Split-split plot	760 540	Kubiku et al. (2022a)
Contour ridge	Sandy loam to loamy	Kenya	Gadam	2011/12	Randomised Complete Block Design (RCBD)	410 (first harvest) 900 (Ratoon)	Kathuli and Itabari (2013)
Contour ridge	Sandy	Mali	Segulfa	2012	RCBD	620	Traore et al. (2017)
Contour ridge	Sandy	Mali	Jacumbe	2012	RCBD	381	Traore et al. (2017)
Infiltration pits	Sandy loam	Tanzania (Ikhanoda)	Wahi	2010/11	Split-split plot	1234	Kilasara et al. (2015)
	Sandy loam	Tanzania (Ikhanoda)	Hakika	2010/11	Split-split plot	1387	Kilasara et al. (2015)
	Sandy loam	Tanzania (Mbande)	Wahi	2010/11	Split-split plot	320.3	Kilasara et al. (2015)
	Sandy loam	Tanzania (Mbande)	Hakika	2010/11	Split-split plot	312.5	Kilasara et al. (2015)
Ripper	Sandy	Zimbabwe	Macia	1984/85, 1985/86	5 x 2 factorial x 3 reps (30 treatments)	532 732	Chiduza et al. (1995)

Planting pits, Basin, Ripper	Sandy loam	Zimbabwe (Chipinge)	Macia	2010/11	RCBD	1700 1200	Marumbi et al. (2020)
Tied ridges	Sandy clay loam; strong clay	Zimbabwe (Chiredzi and Gwebi)	Macia, SV4	2006/07	RCBD in split-plot arrangemen t	1331; 1012 1445; 407	Soko (2012)
Tied ridges,	Sandy	Zimbabwe	Macia	1990/91	3 x 4 factorial x 3 reps	850	Nyakatawa (1996)
Tied ridges	Sandy	Zimbabwe	Macia	1987/88 - 1989/90	3 x 3 factorial x 3 reps	670	Nyakatawa et al. (1996)
Tied ridges	Sandy	Zimbabwe	Macia	1995/96; 1996/97	3 x 4 factorial x 3 reps	920	Nyakatawa et al. (2001)
Ripper, Basins	Silty clay loam	Zimbabwe (Matopos)	Macia	2006/07	3 x 7 factorial x 3 reps	1890 1390	Mupangwa et al. (2012)
Tied contours	Sandy loam	Zimbabwe (Chivi)	Macia, SV1	2017/18 - 2019/20	Split-split plot (90 treatments)	967 957	Kugedera et al. (2022)
Infiltration pits	Sandy loam	Zimbabwe (Chivi)	Macia, SV1	2017/18 - 2019/20	Split-split plot (90 treatments)	967 906	Kugedera et al. (2022)
Planting pits, tied ridges	Sandy loam	Zimbabwe	Macia	2017/18	RCBD (27 treatments)	1900; 1820	Kugedera et al. (2018)
Tied ridges	Cambisol	Ethiopia	Ase	2013/14	RCBD in split-plot	2437	Madalcho and Sido (2015)
Tied ridges	Euritic Fluvisol	Ethiopia	n/a	2010/11	Split plot (24 treatments)	4922-5197	Wubet (2012)
Tied ridges	Silt loam	Ethiopia (Alamanta)	Gobiye	2005/06, 2006/07	Split plot in 3 x 4 factorial	1320	Mesfin et al. (2009)
Tied ridges	Clay	Ethiopia (Abergele)	Woitozi ra	2005/06, 2006/07	Split plot in 3 x 4 factorial	1470	Mesfin et al. (2009)

Tied ridges	Silty loam	Ethiopia (Melkassa)	Meko-1	2005/06, 2006/07	Split plot in 3 x 4 factorial	3110	Mesfin et al. (2009)
Tied ridges, Manual/Mechanised zai	Sandy loam	Burkina Faso	IRAT9, ICSV1001	2002/03 - 2004/05	RCBD (5 x 4 treatments)	881-1392	Palé et al. (2009)
Tied ridges	Loam	Mali		2010/11	RCBD	890	Kouyaté et al. (2012)
Tied ridges	Clay	Swaziland	PAN8625	2014/15	CRD (12 treatments)	8202	Ndlangamadhla et al. (2016)
Zai pits	Clay loam	Kenya	Gadam	2013/14	RCBD (12 treatments, 3 reps)	1960	Kimaru-Muchai et al. (2021)
Planting basins	Chromic-Leptic Cambisol	Zimbabwe (Matopos)	Macia	2014/15; 2015/16	CRBD in split-plot (27 treatments)	1700 2400	Masaka et al. (2019)
Tied ridge	Sand clay loam	Tanzania	n/a	2015/16	Split plot design	2350	Mahinda et al. (2018)
				2016/17		1600	
Ripping	Sand clay loam	Tanzania	n/a	2015/16	Split plot design	2390	Mahinda et al. (2018)
				2016/17		1170	
Tied ridge	Clay	Sudan	n/a	2006/07	RCBD	228.7	Karrar et al. (2012)
				2007/08		264	
Ridge furrow				2006/07		214	
Contour ridge				2007/08		239	
				2006/07		227.7	
				2007/08		238.5	
Grass strips infield	Ferric Lixisol	Burkina Faso	n/a	1999/00	RCBD	932	Zougmoré et al. (2003)
				2000/01		1537	
				2001/02		1411	
Terraces ties	Clay	Sudan	Dwarf Milo	2015/16	Strip plot design	4100	Naim et al. (2018)
				2016/17		3200	

b. ***Tied contours***

This is a system of modification of contour ridges found in most parts of semi-arid areas of Zimbabwe (Nyamadzawo et al., 2013; Nyamadzawo et al., 2015). Tied contours are constructed by modifying standard contour ridges by adding ties at specified intervals (Figure 2.2). Tied contours provide the cheapest options for improving availability of water for crop production in semi-arid areas (Kubiku et al., 2022a). Tied contours can be reinforced with infiltration pits to increase water holding capacities and where fertiliser application rates are increased to increase crop yields. This system impedes the loss of water from fields and increase water retention in the fields which can be used by crops during dry season (Nyagumbo et al., 2019).

Tied contours sustain crop production during mid-season dry spells and this reduces crop failure (Nyamadzawo et al., 2013). According to Nyamadzawo et al., (2015) tied contours increased maize production from 0.6 t/ha to between 1.5 and 2 t/ha compared with standard contours where N fertiliser application rates of 120 kg ha^{-1}. This is a semi-permanent water harvesting technology (Nyamadzawo et al., 2013) which, if supported have a big promise in increasing crop yields since these have an ability of storing water for long period of time. The technique requires less labour since it utilises contour ridges which had already been used by farmers.

Figure 2.2: Construction of Tied contours in Marange. Photo by Nyamadzawo G. (2012.)

2.3.2 Agroforestry systems for smallholder farmers in semi-arid areas in Zimbabwe

Agroforestry is a collective name for land use systems in which trees and shrubs are grown in association with agricultural crops and/ or livestock in spatial arrangement, rotation or both in which each of the component benefits from one another (Dwivedi, 1997). Over the past decades, food production levels in Sub-Saharan Africa including Zimbabwe have been declining partly explained by low levels of inputs such as chemical fertilizers, improved seeds and pesticides (Opala, 2020). Agroforestry has been seen as a viable option for fertility restoration and land degradation control. The emphasis of agroforestry in developing countries is on alleviating poverty, securing food nutrition and arresting land degradation, particularly under resource-limited conditions and lower-input situations, which cover an estimated 1.9 billion hectares of land and 800 million people (Mugwe, 2007; Nair, 2007). Agroforestry options which are viable for smallholder farmers include improved fallows, biomass transfer and fertiliser tree systems. Environmental benefits of agroforestry include soil erosion control (Nair, 2007; Mugwe, 2007), improvement of soil quality through increased nitrogen input, improved soil hydraulic conductivity, structure, porosity and improvement of water dynamics (Nyamadzawo et al., 2008), and increased activity of soil biota (Sileshi and Mafongoya, 2006). In Zimbabwe there has been limited research where agroforestry was used on sorghum and there are few studies across the world (e.g., Kebede et al., 2012; Getu and Teshager, 2015; Kimaru-Muchai et al., 2021). However, in semi-arid areas of India the use of agroforestry on sorghum produces grain yield ranging from 1.557 to 1.582 t ha^{-1} (Patil and Sheelavantar, 2004). In Burkina Faso the use of agroforestry alone produced sorghum ranging from 0.2 to 0.8 t ha^{-1} (Coulibaly et al., 2014; Table 2.2).

Table 2.2: Yield benefits of sorghum from different Agroforestry technologies

Techniques	**Country/ area**	**Season**	**Soil Type**	**Crop**	**Mean Grain yield (kg/ha)**	**Source**
2.5 t/ha Leucaena biomass +50 % Recommended Rate of fertiliser (RDF)	Ethiopia	2010	Clay	Sorghum	2160	Kebede et al. (2012)
5 t/ha Leucaena biomass +50 %RDF	Ethiopia	2010	Clay	Sorghum	2540	Kebede et al. (2012)
Agroforestry parkland	Burkina Faso	2012	Clay	Sorghum	575	Coulibaly et al. (2014)
Agroforestry parkland	Burkina Faso	2012	Sand y	Sorghum	250	Coulibaly et al. (2014)
Leucaena biomass	Ethiopia	2010	Clay	Sorghum	774	Getu and Teshager (2015)
Tithonia biomass	Ethiopia	2010	Clay	Sorghum	1240	Getu and Teshager (2015)
Tephrosia	Ethiopia	2010	Clay	Sorghum	2342	Getu and Teshager (2015
Tithonia diversifolia (biomass transfer) + Zai pits	Kenya	2014	Ferra sol	Sorghum	4300	Kimaru-Muchai et al. (2021)
Tithonia + conventional tillage	Kenya	2014	Ferra sol	Sorghum	3750	Kimaru-Muchai et al. (2021)

2.3.3 Biomass transfer system of *Leucaena leucocephala*

Biomass transfer refers to cutting and carrying ("transferring") nutrient-rich leaves of agroforestry plant species to fertilize fields for the production of high value vegetable crops and cereal crops such as maize and sorghum (Kwesiga et al., 2003; Murovhi and Materechera, 2006). This is usually done in areas where the soils are losing nutrients at a faster rate (Murovhi and Materechera, 2006). Biomass transfer system may be practiced carrying biomass produced from one farm to another or by transferring biomass produced outside the farm but within the same catchment area (Mafongoya et al., 2003). This system can also be done through recycling nutrients using livestock manure and pruning from Leucaena and other N fixing species (Mugwe, 2007). Biomass from legume species is rich in nitrogen compared with that from non-legume species (Mugendi et al., 2003). Biomass in form of leafy and tender twigs is cut and transferred from the area where the leguminous trees are grown to the garden or crop field and is incorporated to improve soil fertility (Katanga et al., 2007a; Opala, 2020). Leafy material from legume species such as *L. leucocephala* accumulates huge quantities of nutrients (N, P, K, Mg, and Ca) which improve soil fertility upon decomposition when incorporated into the soil.

Leucaena is one of the most widely used legume species for soil fertility experiments in Africa to improve soil fertility and crop yields as it is rich in nitrogen and other macro-nutrients. Leucaena produces large quantities of biomass ranging from 10 to 25 t ha^{-1} $year^{-1}$ which replenish soil fertility (Murovhi and Materechera, 2006) and improves crop yields when incorporated in the soil well (Delve et al., 2000; Katanga et al., 2007a). Leucaena fixes approximately 300 kg N ha^{-1} $year^{-1}$. This makes it suitable for biomass transfer due to high N content in leaves and twigs (Mafongoya et al., 2006b; Katanga et al., 2007b). Leucaena biomass was reported to contain 2.0 to 4.0 % nitrogen from its leaves (Mucheru-Muna et al., 2007; Mugwe, 2007), and it is adequate to meet plant demands if leaves are to be incorporated in soil in time to allow decomposition. The use of biomass from Leucaena has been reported to increase maize grain yield in Kenya (Mugwe, 2007) and if applied in field where sorghum is grown there is high potential of increasing both grain and stover yields. Leucaena leaves decompose quickly releasing nutrients into the soil and are available for absorption by plant roots.

Biomass transfer of Leucaena can be used by a variety of crops including vegetable and become more profitable than any other technology (Mafongoya et al., 2006b). Biomass transfer does not occupy land for crops and does not compete with crops (Kuntashula et al., 2004; Kazombo-Phiri, 2005; Mafongoya et al., 2006b) compared with other technologies such as alley cropping, improved fallow and fertiliser tree system. Biomass transfers have the potential to offer farmers an opportunity to supplement farm income through growing cash crops which fetch higher prices on town markets. Results from various biomass transfer studies show that it has the potential of increasing grain yields regardless of soil type and region. Kebede et al. (2012) recorded 2160 kg ha^{-1} of sorghum after using 2.5 t ha^{-1} of Leucaena biomass + 50 % Recommended amount of fertiliser (RDF). Results on sorghum grain yields from different studies were in the range of 250 to 4300 kg ha^{-1} for Kenya, Ethiopia and Burkina Faso (Table 2.2).

2.3.4 Effects of INM on sorghum production

Integrated nutrient management (INM) is a set of soil fertility management approaches that include the use of inorganic and organic nutrient sources aiming at improving agronomic use efficiency and crop productivity (Mugwe et al., 2007; Vanlauwe et al., 2010; Mugwe et al., 2019). INM has been seen as a sustainable way of restoring soil fertility through combining both organic and inorganic sources of nutrients (Mugwe et al., 2007).

Use of INM recorded higher sorghum grain yields from various experiments compared to sole application of mineral or organic fertiliser in most African countries. Use of 1 t ha^{-1} of cattle manure + 15 kg NPK ha^{-1} (1.05 N + 2.1 P_2O_5 + 1.05 K_2O kg ha^{-1}) in Nigeria recorded 1740 kg ha^{-1} sorghum grain yield. In another study, use of 2 t ha^{-1} of cattle manure + 45 kg NPK ha^{-1} (3.15 N + 6.3 P_2O_5 + 3.15 K_2O kg ha^{-1}) recorded 4040 kg ha^{-1} (Shuaibu et al., 2018; Table 2.3). Grain yield of 5187 kg ha^{-1} was obtained in Kenya after using 5 t ha^{-1} cattle manure + 50 kg ha^{-1}NP (3.5 N + 7 P_2O_5 kg ha^{-1}) fertilisers (Mwadalu 2014). These results were higher than those obtained in Zimbabwe due to low quantities of N fertiliser applied, with most farmers applying less than 17 kg N ha^{-1} (<50 kg AN) and low cattle manure at a rate of less than 4 t ha^{-1} instead of 20-40 t ha^{-1} to achieve higher yields (Twomlow et al., 2008).

Integrated nutrient management is the sustainable way of improving nutrient availability in the soils, promoting soil health and improving crop yields. Efficiency of nutrient use is improved, reduced land degradation and improves yields through the use of INM (Bayu et al., 2006; Njeru et al., 2013; Njeru et al., 2015). Improved nutrient use efficiency can be achieved compared with small incremental of inorganic or organic nutrient sources in sole applications (Ayoola and Makinde 2008; Mugwe et al., 2019). Smallholder farmers need to adopt INM as it mitigates risks against climate (Nezomba et al., 2018). Integrated nutrient management is the best smallholder farmers need to adopt because it increases crop yields, reduce losses caused by pests (Negassa and Sileshi, 2018), reduces loss of organic carbon from the soil (Mugwe et al., 2019) and reduce food insecurity. Integrated nutrient management can enhance soil fertility which can improve total soil productivity and increases farm profitability and maintain ecosystems sustainably. To improve sorghum yields in semi-arid areas of Zimbabwe farmers can adopt the use of 20-30 t ha^{-1} cattle manure or Leucaena biomass amended with 100-150 kg ha^{-1} NPK (7-10.5 N + 14-21 P_2O_5 + 7-10.5 K_2O kg ha^{-1}) fertiliser. However, cattle manure used by most smallholder farmers varies in quality due to poor quality of feeds in these areas (Mafongoya et al., 2006b; Mucheru-Muna et al., 2007). Smallholder farmers are resource poor and unable to procure required quantities of mineral fertiliser. Hence this may affect the success of INM in crop production.

Table 2.3: Yield benefits of sorghum from different INM options

Techniques	Country/area	Season	Soil Type	Mean Grain yield (kg/ha)	Source
Cattle manure (1t ha^{-1}) + NPK (15 kg/ha)	Nigeria	2017	n/a	1740	Shuaibu et al. (2018)
Cattle manure (2t ha^{-1}) + NPK (45 kg/ha)	Nigeria	2017	n/a	4040	Shuaibu et al. (2018
$90N+15P_2O_5$ $+20K_2O$ +15S +2.5 Zn +10Mg +0.5B kg ha^{-1}+ 5t ha^{-1} Cattle manure	Burkina Faso	2014	Silt loamy	2221	Quattara (2015)
4 t ha^{-1} Farm yard manure + 26 kg P-75 kg N ha^{-1}	Kenya	2017	Sandy clay loam	3040	Kisinyo et al. (2019)
5 t ha^{-1} Cattle manure + 170 kg ha^{-1} N fertiliser	Zimbabwe	2016/17-2018/19	Sandy loam	1390	Kubiku et al. (2022a)
5 t ha^{-1} Farm Yard Manure + 30N+13 P_2O_5 +25 K_2O	India	2000/01	Clay	1771	Blaise et al. (2003)

2.3.5 Effects of field edge rainwater harvesting, biomass transfer, organic and inorganic fertilisers on sorghum yields in smallholder farming systems

Field edge rainwater harvesting techniques can work better for smallholder farmers as these do not need to be prepared yearly but only need to be reconstructed, saving on labour requirements. These techniques include tied contours and infiltration pits which can store water for a long period during the rainy season where the water can be used by crops during dry spells (Mugabe, 2004). Infiltration pits can increase crops yields especially maize grain yields (e.g. Mosti et al., 2004; Nyamadzawo et al., 2013)

The use of agroforestry plant species alone resulted in lower sorghum yields ranging between 200 and 400kg ha^{-1} (Coulibaly et al., 2014; CIAT, 2014). However, the use of RWH increased yields to 500 kg ha^{-1}, and 1000 kg ha^{-1} when micro dose of inorganic fertiliser was used in combination with RWH (CIAT, 2014). Combining infiltration pits and farm yard manure produced between 523 kg ha^{-1} and 3223 kg ha^{-1} of sorghum grain in Mbande village, Tanzania (Kilasara et al., 2015).

Biomass transfer is a traditional method used by smallholder farmers to restore soil fertility in fields and gardens with the objective of improving crop yields. In Burkina Faso, application of tree pruning as biomass transfer in sorghum fields increased sorghum biomass and grain yields (Bayala et al., 2012; Coulibaly et al., 2014). Biomass transfer from *Tithoni*a *diversifolia* has been reported to increase soil fertility and grain yields (Kimaru-Muchai et al., 2021).

The use of Leucaena biomass was also reported to increase crop yields due to high content of nitrogen and easy decomposition of the leaves. Application of Leucaena lopping at 2.5 t ha^{-1} in India resulted in 1582 and 1557 kg ha^{-1} sorghum grain during 2001/02 and 2002/03 cropping seasons respectively (Patil and Sheelavantar, 2004). Biomass transfer alone cannot increase grain yields to high levels. Combination of biomass transfer and organic or inorganic fertiliser has been reported to increase sorghum and maize grain yields. *Tithonia* biomass + 30 kg N ha^{-1} showed an increase in sorghum grain and stover yields (Kimaru-Muchai et al., 2021). There are few studies where field edge RWH, INM and biomass transfer were used at the same time to boost sorghum productivity. However, Kubiku et al. (2022a) and Kugedera et al. (2022) indicated that the technique has a potential to improve sorghum production in smallholder farming systems. This can be constrained by high labour requirements in construction of RWH techniques. Palé et al. (2009) reported that the use of water management such as tied ridges and addition of inorganic fertiliser at reduced rates can increase sorghum grain yields from 0.112 t ha^{-1} to 0.78t ha^{-1}. Few studies were done on field edge RWH and INM to assess the potential of these techniques on sorghum production.

2.3.6 RWH, biomass transfer and, INM in improving sorghum yields as a climate smart option

The integration of RWH, biomass transfer and INM together can be a great solution to alleviate poverty, increase crop yields and reduce food insecurity for smallholder farmers in semi-arid areas. Combining the three innovations together brings in potential for smallholder farmers to increase yields from various food crops due to improved soil moisture, reduced soil erosion, improved soil fertility and reduced pest and diseases incidences due to nutrient deficiency (Mugwe et al., 2019). The use of RWH increases moisture content in the soils (Mupangwa et al., 2011; Kilasara et al., 2015; Nyagumbo et al., 2019; Muchai et al., 2020), with biomass transfer improving soils organic matter, total N, microbial population (Mugendi et al., 1999; Mafongoya et al., 2006a, 2006b; Mugwe, 2007; Coulibaly et al., 2014), reduce soil bulk density and increase base saturation from decomposition of leaves and twigs. This may create a win-win situation with the use of INM which improves nutrient availability in the plant root zone (Jat et al., 2013; Muchai et al., 2020; Kimaru-Muchai et al., 2021). All these three innovations cause soils to have a better structure which improves plant growth rate, reduce leaching, increase moisture retention and improved grain yields.

The integration of rainwater harvesting, biomass transfer and mineral fertiliser has been reported to be compatible where 30-100 kg ha^{-1} mineral fertiliser was used (Kimaru-Muchai et al., 2021). The adoptability of these technologies was also reported to be increasing in semi-arid areas of Kenya (Kimaru-Muchai et al., 2021). Although adoption of Agroforestry was reported to be increasing in some parts of Kenya, some countries have low adoption in smallholder farming areas due to land tenure issues and long period of time to receive benefits. There are few studies where there three innovations have been integrated in Africa.

Therefore, combining RWH, biomass transfer and INM together can create a climate smart agriculture which reduces food insecurity, mitigate climate risks, economic recovery

(Nezomba et al., 2018) and avert environmental degradation (Mupangwa et al., 2011; Gebremeskel et al., 2018). Adoption of these three technologies together have the capacity to improve food security for smallholder farmers in semi-arid areas and increase farm profitability (Erkossa et al., 2018; Mugwe et al., 2019) compared with the use of RWH, INM or biomass transfer alone. Combining these technologies together can have yield benefit to farmers because the techniques reduce soil and nutrient loss, increase plant growth and reduce moisture stress which are the major limiting factor of crop production in semi-arid areas. Farmers can grow agroforestry plant species such as Leucaena on degraded lands to restore the land at the same time providing biomass for use in biomass transfer. Leucaena provides high quality fodder for cattle and this improves quality of manure which farmers can use as organic source for INM.

The integration of RWH, biomass transfer and INM can be a better option to boost sorghum grain yields in semi-arid areas of Zimbabwe. These three technologies improve soil nutrient status, soil organic matter and moisture needed by sorghum to grow well since rainfall received is very low to sustain crops. RWH techniques harvest runoff water which will be used by crops during dry spells and improve nutrient absorption although the practices are labour intensive, they are cheap in the long run as they only need maintenance. Biomass transfer and INM enhance mineralisation leading to availability of nutrients and improving microbial population which decompose soil organic matter releasing nutrients. Combination of these three technologies can have high chances of success since semi-arid areas of Zimbabwe mainly depend on sorghum as their staple crop. For adoption rates to be high, farmers need to implement the technologies on small piece of land and expand with time.

2.4 CONCLUSION

Rainwater harvesting techniques are some of climate risk adaptations which can be adopted by farmers in semi-arid areas especially those who depend on rain fed agriculture with a potential to improve livelihoods, income and reduce poverty in smallholder farming sector. The challenge is that RWH alone cannot increase crop yields to significant levels due to low soil fertility, so combining it with strategies such as biomass transfer and INM creates climate smart agriculture which increased soil fertility and grain yields, and in turn it improves food security. Biomass transfer from nitrogen fixing trees such as Leucaena, Calliandra and Glirisidia improves soil fertility through increased total N, soil carbon, exchangeable Ca, Mg, P and K which increases plant nutrient availability in the plant root zone. Biomass transfer does not compete with crops for nutrients, water, space and sunlight as reported from other technologies such as alley cropping. However, biomass transfer needs to be integrated with inorganic nutrient sources (INM) as means of increasing soil fertility and crop productivity. Since it takes years for agroforestry species to give larger quantities of biomass at harvest, there is need to support it with INM of organic and inorganic fertilisers to boost grain yields and improve livelihoods. Combining RWH, biomass transfer and INM together create a strong soil and water conservation strategy which adapt to climate changes and brings in climate smart agriculture in smallholder farming areas. The three innovations are environmentally friendly and can be best option to reduce poverty, improve economy and remedy environmental problems faced by farmers. I can conclude that combination of RWH, biomass transfer and INM have the potential to boost sorghum grain yields though improved soil fertility, soil moisture and nutrient availability in the plant root zone. These options can have the potential to improve economic benefits of sorghum and its adoption in semi-arid areas as their staple crop. Since semi-arid areas are affected by long frequent droughts, there is need to adopt the use of irrigation to supplement rainfall and create sustainability in the use of INM and Leucaena biomass to increase sorghum production.

2.5 Areas for Further Study

Evaluation of RWH of tied contours need to be further studied to come up with their effects on soil moisture on various distances from the contour and to test their suitability in different soil types in Zimbabwe and elsewhere. There is need to carry out various experiments using tied contours, biomass transfer and INM in smallholder farming areas and even on commercial sector to evaluate their suitability in different regions as climate smart agriculture innovations. Various studies using RWH, biomass transfer and INM were done using maize and few were done using sorghum so there is need for further studies to come up with benefits from combining these three innovations on sorghum productivity in semi-arid areas. Semi-arid areas are associated with long and frequent droughts; there is need to research on the use of irrigation combined with INM and Leucaena biomass on sorghum production. This can increase sustainability in the use of soil fertility management strategies since the major problem is water scarcity in these areas. There is also need for more researches to determine the compatibility, adaptability, adoptability and sustainability of the three innovations in semi-arid areas.

CHAPTER 3: GENERAL MATERIALS AND METHODS

3.1 Experimental site

The experimental site was in ward 11 of Chivi District at approximately 20º13′S, 30º28′E at an altitude of 900 m (Fig 3.1). Three experiments conducted were on the following locations: experiment 1 (20º13.375′ S and 30º28.628′ E, 867 masl), experiment 2 (20º13.42′S and 30º28.565′E, 900 masl) and experiment 3 (20º13.441′ S and 30º28.656′ E, 775 masl). The experimental site has sandy loam soils derived from Granite rocks with poor fertility. The site is in agroecological zone V where average annual rainfall is 335 mm (Mugandani et al., 2012). Average rainfall received during the duration of the experiment was <450 mm and was erratic, but usually received from November to April. The site has been under alternate cultivation of cereal and legume crops whilst other fields have been under maize monoculture. The site is dominated with sparse *Mopane* woodlands mixed with other tree species like *Faidherbia albida*, *Dichrostachys cinerea Sclerocarya birrea* and *Julbernadia globiflora*. Smallholder farmers in the area practice livestock and crop production growing specifically maize (*Zea mays*), cowpeas (*Vigna aungiculata*), groundnuts (*Arachis hypogea*), sorghum (*Sorghum bicolor*) and Bambara nuts. Maize and sorghum are the main staple food crops in the area with few farmers growing Pearl millet (*Pennisetum glaucum*). The experimental site is shown in Figure 3.1.

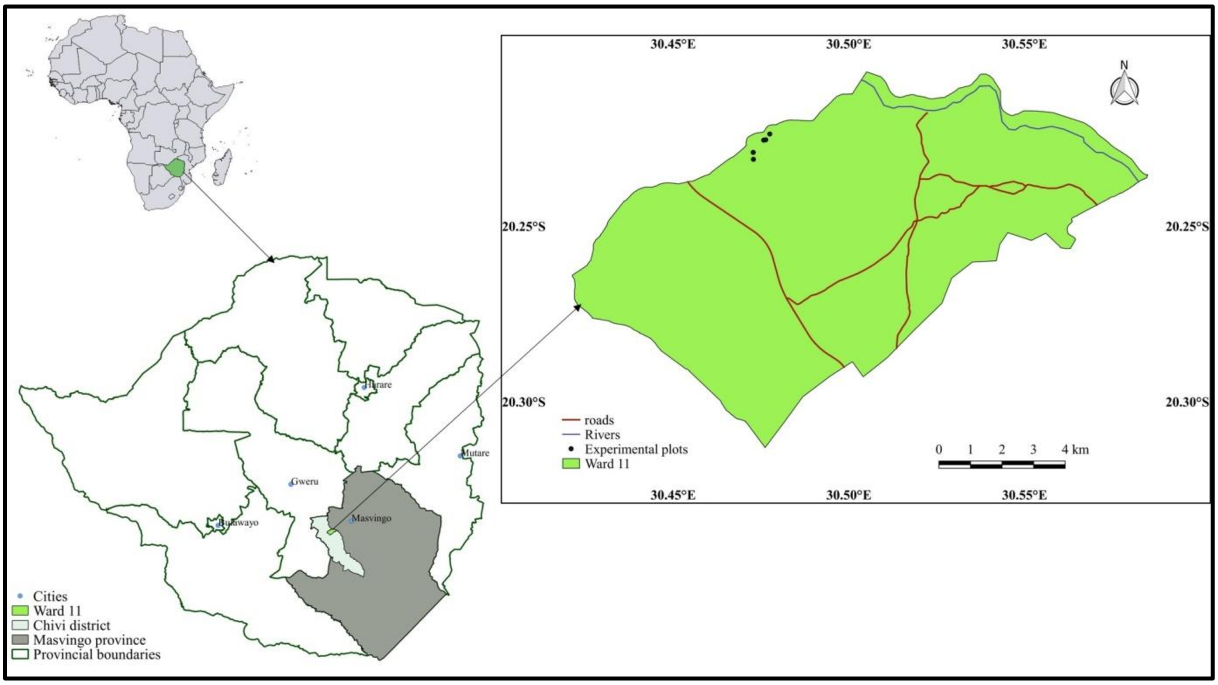

Figure 3.1: Study site location in Chivi District, Zimbabwe

3.2 Leucaena Leucocephala acquisition

Leucaena leucocephala used in the experiment was collected from local farmers who had been previously involved in *its* production for a local non-governmental organisation (NGO) which used for fodder. Leucaena biomass was cut in July to August 2017, 2018 and 2019 when it was still green. Leucaena biomass was also supplemented with Leucaena collected from Makoholi Research Station in Masvingo. Leucaena collected was under alley cropping (Figure 3.2).

Figure 3.2: ***Leucaena leucocephala*** **where biomass used for the experiment was collected. Photo by Kugedera A.T (2017)**

3.3 Cattle manure acquisition

Cattle manure was collected from local farmers' kraals in Chirinda Village during the experimental period (2017, 2018 and 2019). Manure consisted of cattle dung which was collected in July and August from cattle kraals. Kraals used by farmers had no roofs hence manure was subject to N loss.

3.4 Mineral fertiliser acquisition

Mineral fertilisers comprised Ammonium nitrate (34.5 % nitrogen) (0-0-34.5N) and Compound D fertiliser (7%N; 14%P_2O_5:7%K_2O) used in the experiment. The fertilisers were procured from N-Richards Hurudza Shop in Masvingo town in 2017, 2018 and 2019. Ammonium Nitrate (AN) procured was 200 kg and 200 kg for NPK fertiliser. Other quantities

(400 kg AN, and 400 kg compound D fertiliser) were supplied through Presidential Input Scheme.

3.5 Sorghum Seed acquisition

Two open pollinated sorghum varieties, Macia and SV1 were used in the experiment. Macia variety used was supplied through Presidential Input Scheme and SV1 variety was bought from N-Richards Hurudza Shop in Masvingo. Macia variety attains its physiological maturity with an average of 115-120 days and an average yield of 0.3 to 3 t ha^{-1} (Gasura et al., 2015). SV1 is an open pollinated semi-dwarf variety with an average of 115-125 days to maturity with yield potential of 0.3 to 2.5 t ha^{-1} under smallholder farmer conditions.

3.6 Land preparation

The field was manually cleared using axes to remove shrubs. Land was ploughed using ox-drawn plough to a depth of 20 cm. Tied contours, infiltration pits and standard contours were prepared using pick and shovel to dimensions described in each specific chapter.

3.7 Experimental design and treatments

The experiment was conducted during three rainy seasons (2017/18 to 2019/2020) with same experimental layout for each experiment. Split-split-plot design was used with three replications for each experiment. Rainwater harvesting was the main plot factor for experiments 1 and 3 with Leucaena/cattle manure combination being main plot factor for experiment 2. For experiment 1, Leucaena biomass at different rates was sub-plot factor. Two sorghum varieties, Macia and SV1 were used as sub-sub plot factors for all experiments. In experiment two rainwater harvesting with three factors (tied contour, infiltration pits and standard contours) were sub-plot factor. Leucaena/NPK fertiliser was used as sub-plot factor at five (5) different rates. The experiments were laid out as shown in Figure 3.3.

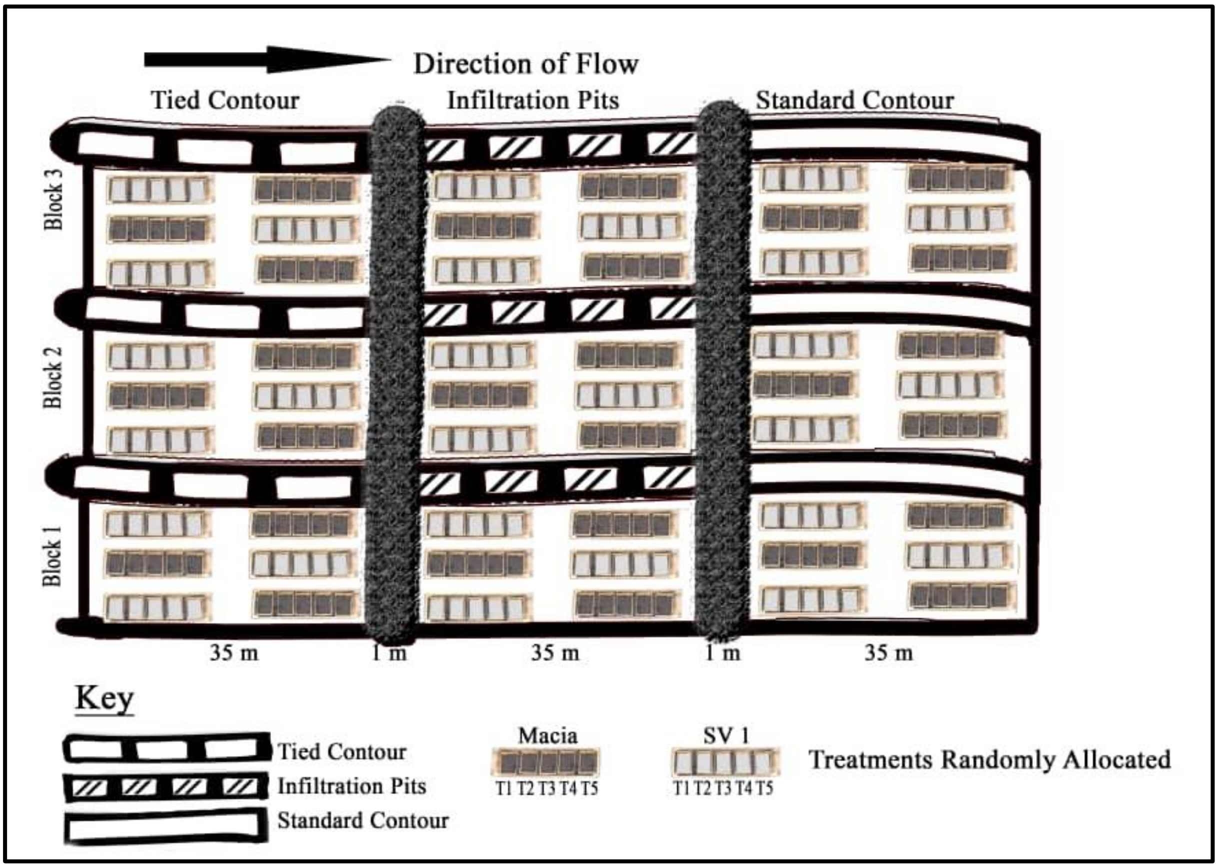

Figure 3.3: Showing experimental arrangements of treatments

3.8 Data collection

Data collected included sorghum grain and stover yields, soil moisture, rainwater use efficiency, harvest index, agronomic efficiency and economic benefits. Sorghum grain and stover were harvested at the end of each cropping season after attaining physiological maturity. Sorghum grain was adjusted to a moisture content of 12.5%. Stover was cut closer to the ground after removing sorghum heads. Detailed methodologies of all collected data are given in their respective chapters.

CHAPTER 4: RAINWATER HARVESTING AND *LEUCAENA LEUCOCEPHALA* BIOMASS RATES EFFECTS ON SOIL MOISTURE, WATER USE EFFICIENCY AND SORGHUM (*SORGHUM BICOLOR* [(L.) MOENCH]) PRODUCTIVITY IN A SEMI-ARID AREA IN ZIMBABWE

ABSTRACT

Sorghum is one of the major staple crops in Sub Saharan Africa but its production is mainly limited by moisture stress, frequent droughts and poor soil fertility, especially in the smallholder farming systems. This raises the need to develop climate smart options to improve sorghum production. The objective was to assess the effects of rainwater harvesting and use of different Leucaena biomass rates (0, 5, 10, 20 and 30 t ha^{-1}) on soil moisture content, rainwater use efficiency, and stover and grain yields in two sorghum varieties (Macia and SV1). The experiment was laid as a randomised complete block design in split-split plot arrangement from 2017/18 to 2019/20 season. The results showed that tied contour (TC) and infiltration pits (IP) significantly ($p<0.05$) increased soil moisture content than standard contour (SC). Tied contour had the highest soil moisture content at all depth with mean average of 7.09% from 0-20 cm and 9.21% for 20-40 cm compared with IP which had 6.91% (0-20 cm) and 9.15% (20-40 cm) and 6.89 % (0-20 cm) and 8.54% (20-40 cm) from SC over three seasons. Soil moisture content increased gradually with the increase in soil depth (20-40 cm>0-20 cm), with 2018/19 season having the maximum soil moisture content. Soil moisture content also increased with the increase in application rates of Leucaena biomass. Highest soil moisture content from 0-20 cm was 8.3 % and 9.97 % for 20-40 cm at 30 t ha^{-1} Leucaena biomass during 2018/19 season. Grain and stover yield were significantly ($p<0.05$) increased by all Leucaena biomass application rates with higher yield observed in 2018/19 season. Macia had higher sorghum grain yields compared with SV1 under different rainwater harvesting techniques. SC had significantly lower grain and stover yield at all Leucaena biomass application rates. TC and IP had comparable rainwater use efficiency compared with SC. Rainwater use efficiency increased with application rates of Leucaena biomass across all seasons and varieties. TC and IP are better adaptive mechanisms against drought spells in semi-arid areas and can be combined with 10 t ha^{-1} of Leucaena biomass due to better yield increments realised.

Keywords: Rainwater harvesting; Leucaena; soil moisture; rainwater use efficiency; sorghum; semi-arid regions.

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4.1 INTRODUCTION

Sorghum is a C4 grass that is importantly used for food and feed on a global scale especially in developing countries of Africa (Williams and der Vries, 2019; Masaka et al., 2019). Despite its importance, sorghum productivity has been low in most dry regions yielding an average of 0.5 t ha^{-1} (Mwadalu and Mwangi, 2013). In Sub Saharan Africa, food security is mainly affected by water scarcity which is one of the most pressing issues confronting the region. The major driver for low yields in semi-arid areas is moisture stress due to erratic and unreliable rainfall (Chilagane et al., 2020). Inadequate quantities of nutrient sources used in semi-arid areas also causes nutrient depletion, loss of organic matter and poor infiltration of rainwater leading to yield decline (Drechsel et al., 2015; Bunde 2017; Nyagumbo et al., 2019). Moisture stress and environmental degradation are threatening agricultural sustainability in the larger part of Sub-Saharan Africa (Nyamadzawo et al., 2015).

According to ZIMVAC (2020) very long dry spells of 20 – 30 days are sometimes experienced in semi-arid districts of Zimbabwe. The Zimbabwe Climate Change Response Strategy (2016) reported that Zimbabwe's national agricultural production largely relies on rain-fed agriculture which is very vulnerable to climate change and variability. Water supply in rainfed cropping systems is highly variable and adaptation strategies for crop plants to dry environments become increasingly important to increase yields. The production technologies that can respond to climate change are now a requirement to improve yields. Studies in Zimbabwe by Mupangwa et al. (2006), Mandumbu et al. (2021) and Nyamadzawo et al. (2013) show the efficiency of tied ridges, infiltration pits and other moisture conservation strategies in capturing rainwater and concentrating it in the plant root zone. Research by Nyamadzawo et al. (2012) found 50 % loss in soil moisture content when rainwater harvesting strategies are not used.

Therefore, there is need to adopt various soil and water conservation techniques to improve soil fertility, soil moisture content and crop production. Various integrated nutrient management options such as combining organic manure with mineral fertiliser and/ or legume tree biomass can be adopted to improve soil fertility and sorghum grain yields (Mugwe et al., 2019). The use of rainwater harvesting techniques has the potential to increase soil moisture content and crop production (Nyamadzawo et al., 2015). Infiltration pits were reported to be more effective in semi-arid areas of Zimbabwe where rainfall is low (Mugabe, 2004; Mupangwa et al., 2012b; Nyagumbo et al., 2019). Use of tied contours can be a cheaper option for farmers to improve water availability and crop production in semi-arid regions (Nyamadzawo et al., 2015; Mandumbu et al., 2021). Rainwater harvesting techniques retain water which crops can use during dry spell to promote growth and increase yields (Mupangwa et al., 2012a). However, the use of rainwater harvesting techniques alone cannot improve sorghum production because poor soil fertility is another limiting factor in semi-arid regions, hence the need to integrate rainwater harvesting techniques with soil fertility amendments.

The use of legume biomass transfer is potentially cheaper and a climate smart agriculture option for resource poor smallholder farmers to improve soil fertility and crop yields. The leguminous tree, Leucaena is able to fix nitrogen (2.5 to 4.0 %) and helps in nutrient recycling (Mugendi et al., 2003; Mafongoya et al., 2007; Mugwe, 2007). The use of nitrogen rich tree prunings as a substitute of inorganic fertilizer has proven to be a viable alternative source for soil fertility replenishment (Kebede et al., 2012). The use of Leucaena biomass improves soil nitrogen levels (Mugendi et al., 1999; Mugwe, 2007), microbial population, soil structure and crop productivity (Mafongoya and Dzowela, 1999; Patil and Sheelavantar, 2004). Application of 2.5 t ha^{-1} Leucaena loppings recorded 1582 kg ha^{-1} sorghum grain yields in India (Patil and Sheelavantar, 2004). Similarly, Mugwe (2007) reported 7.5 t ha^{-1} maize grain yield after using Leucaena biomass compared with cattle manure alone which yielded 6.1 t ha^{-1} and 5.8 t ha^{-1} from inorganic fertiliser at a rate of 60 kg N ha^{-1}.

Most existing research has assessed the effects of moisture stress and paid less attention on the combined effects of water harvesting and biomass. Therefore, the objective of the study was to assess the effects of rainwater harvesting and different rates of Leucaena biomass on soil moisture content, water use efficiency and sorghum yield.

4.2 MATERIALS AND METHODS

4.2.1 Study site

The experiment was conducted at Chirinda village (20º13.375' S and 30º28.628' E, 867 metres above sea level) in Chivi district, Masvingo Province, Zimbabwe during the three (2017/18-2019/20) cropping seasons. The experimental area is in agroecological zone V according to the Zimbabwean classification system (Mugandani and Mafongoya, 2019). Agroecological zone V is characterised with low rainfall which is unevenly distribution. The rainfall pattern is unimodal, starting from mid-November and ends in late March. Rainfall received over three seasons ranged from 295-305 mm which was below the long-term seasonal average of 335 mm per annum. The experimental site is predominated by sandy-loam soil with an average pH of 5.3 and associated with low nitrogen content. Monthly temperature ranges from 18 ºC to 32 ºC. Rainfall was recorded using a standard rain gauge. The experimental site is dominated with sandy loam soils which are inherently infertile. The soils have been under conventional cultivation for many years with little organic and inorganic fertiliser amendments. The experimental field had a general slope of 5 %. The area is dominated with Mopane woodlands and main farming activities include cereal and animal production. Crops grown include sorghum (*Sorghum bicolor*), maize (*Zea mays*), groundnuts (*Arachis hypogea*), cowpeas (*Invirgina unguiculata*). Farmers in this area also rear cattle and donkeys for draught power together with poultry, goats and sheep.

4.4.2 Soil sampling and analysis

A total of fifteen (15) soil samples were collected prior to planting from the experimental field measuring 105 m x 45 m using soil auger from a depth of 0-30 cm for soil characterization. A composite soil sample was prepared by mixing soil samples in a plastic bucket. Composite soil sample was air dried, grounded and sieved through a 2 mm sieve. Soil texture was determined by Bouyoucos hydrometer method (Henderson and Bui, 2002), total nitrogen by Kjeldahl method (Cottenie, 1980), soil pH by Calcium chloride ($CaCl_2$) method (Henderson and Bui, 2002), soil organic carbon by wet digestion method and available phosphorous by Olsen method (Olsen, 1954). Potassium, calcium and magnesium was determined Inductivity Coupled Plasma-Optical Emission Spectrometry Instruments (ICP-OES) (Mamuye et al., 2021).

4.2.3 Experimental design and treatments

The experiment was distributed in a randomised complete block design (RCBD) in a split-split plot arrangement in which three rainwater harvesting techniques were the main plots, with sorghum variety as the sub plot factor at two levels and biomass as the sub-sub plot factor at five levels. Treatments were randomly assigned to experimental units (plots). The experiment was replicated three times and repeated over three seasons. First season (2017/18) started from 17 December 2017 and ended on 30 April 2018, second season (2018/19) started on 15 December 2018 and ended on 25 April 2019 and third season (2019/20) started on 10 December 2019 and ended on 27 April 2020. In each rainwater harvesting (RWH), fives rates of biomass (0, 5, 10, 20 and 30 t ha^{-1}) were tested. Two sorghum varieties (Macia and SV1) were used in the experiment as test crop. RWH techniques used were: tied contour and infiltration pits. Tied contours were made of cross ties at an interval of 5 m along the contour making small dams measuring 5 m long x 0.5 m wide x 0.5 m deep. Infiltration pits were dug along the contour measuring 3 m long x 0.5 m wide x 0.5 m deep spaced at 0.5 m along the contour. Standard contour measuring 35 m long was used as a control and a distance of 1 m was separated the RWH techniques from each other (Figure 4.1).

Land was prepared and ploughed using oxen-drawn mouldboard plough to a depth of 15 -20cm and dry Leucaena biomass was encooperated at a rate of 0, 5, 10, 20 and 30 t ha^{-1} at a moisture content of 12%. Planting was done on 17 December 2017, 15 December 2018 and 10 December 2019 for 2017/2018, 2018/19 and 2019/20 seasons respectively. Row spacing of 0.75 m and in-row spacing 0.2 m was used to achieve a plant population of 66666 plants ha^{-1}. Weed control was done using hand hoes in all plots. Ammonium nitrate (AN) fertiliser (34.5 % N) was applied in two splits at 300 kg ha^{-1} (103.5 kg N ha^{-1}). First split of AN was applied three weeks after seed emergence and first hoeing at a rate of 150 kg ha^{-1} (51.75 kg N ha^{-1}) and second split of was done at day 49 from crop emergence using a rate of 150 kg ha^{-1} (51.75 kg N ha^{-1}).

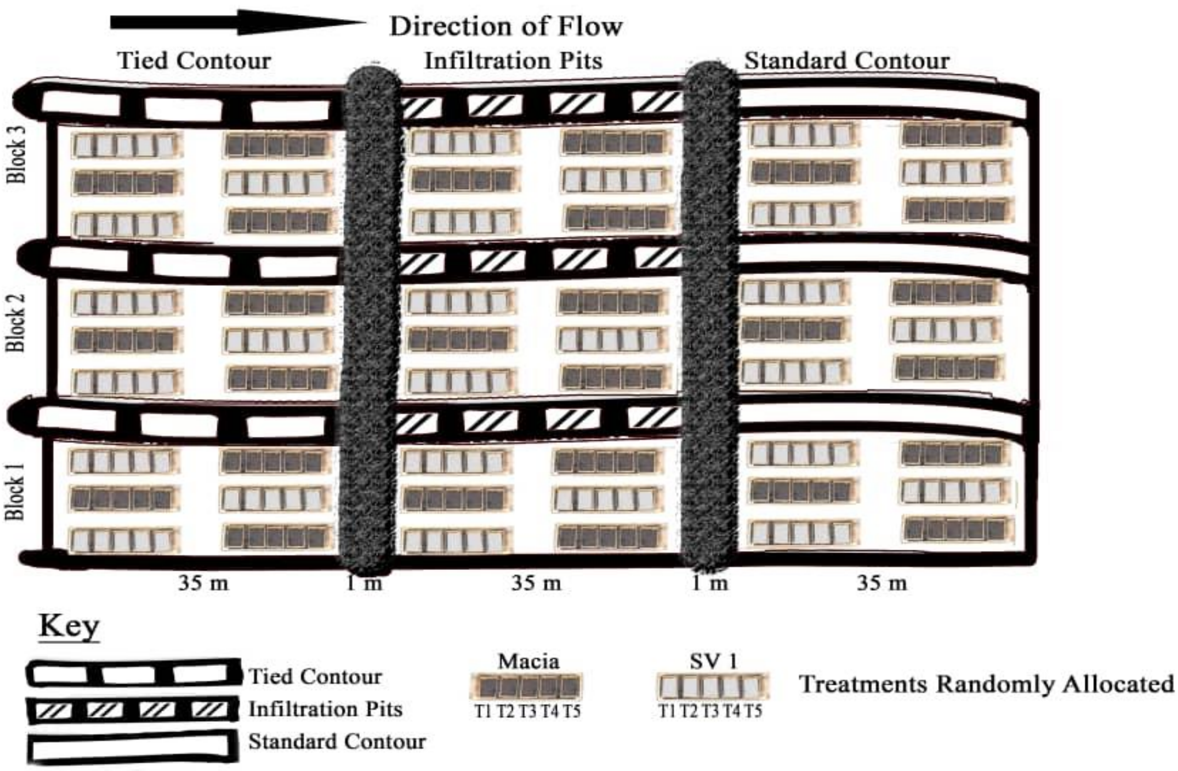


Figure 4.1: Experimental layout

4.3 DATA COLLECTION

4.3.1 Soil moisture content

Soil moisture content was determined using gravimetric moisture method. Three soil samples were collected from a depth of 0-20 cm and 20-40 cm from each subplot using an auger on monthly basis and means were calculated. Gravimetric moisture content was determined using method by Marshall and Holmes (1988). Soil samples were collected from plots under infiltration pits, tied contours and standard contours amended with different levels of Leucaena biomass. Ten (10) grams of soil was added in a pre-weighed container (A_1) and then combined weight of soil and container (A_2) was recorded. Soil and container were oven dried at 105 ºC for 48 hrs. Oven dried soil was cooled, weighed and recorded (A_3); the difference between fresh soil and oven dried weight was calculated.

Calculation:

$$\Theta m\ (\%) = \frac{wet\ soil\ mass - oven\ dry\ soil\ mass}{Oven\ dry\ soil\ mass} \times 100$$ (Marshall and Holmes, 1988) …equation 1

4.3.2 Grain and stover yield

Sorghum grain and stover yields were determined after harvesting at physiological maturity from a net plot (3 m x 3 m) from all experimental plots. Sorghum heads were separated from stover at harvesting using sharp knives and were sun dried for manual threshing. Manual winnowing was used to remove trash from grains. Grain yield was adjusted to 12.5 % moisture content after measuring moisture using digital moisture meter (Dickey-John model). The weights were converted to tonnes per hectare for statistical analysis. The following formula was used to convert grain yield to tonnes per hectare.

$$\text{Grain (t ha}^{-1}) = \frac{Yield\ in\ the\ net\ plot \times 10000 m^2}{net\ plot\ area}$$ ………………… equation 2

Where: 10000 m^2 is an area of 1 hectare and net plot area is 9 m^2.

$$\text{Adjusted yield} = \text{Actual yield} \times \frac{(100-M)}{(100-D)}$$ ……………………………… equation 3

Where M is the measured moisture content and D is the designated moisture content (12.5%).

Stover was cut at ground level and then cut into smaller pieces per treatments together with its replicates, sun dried and weighed. Stover yield was converted to tonnes per hectare using the following formula.

$$\text{Stover (t ha}^{-1}) = \frac{Yield\ in\ the\ net\ plot \times 10000m^2}{net\ plot\ area} \text{ .... equation 4}$$

Where: 10000 m^2 is an area of 1 hectare and net plot area is 9 m^2.

4.3.3 Rain Water Use Efficiency (RWUE)

This is the efficiency in which rainfall is converted to grain. This was calculated after harvesting of grain using the total grain yield per treatment and total rainfall received per season. It was calculated using the following formula (GRDC, 2009; equation 5).

$$\text{RWUE (kg ha}^{-1}\text{ mm}^{-1}\text{ rainfall)} = \frac{Total\ grain\ yield\ (kg\ ha^{-1})}{Total\ rainfall\ (mm^{-1})} \text{ .... equation 5}$$

4.4 Statistical data analysis

Data were subjected to normality test and two-way analysis of variance (ANOVA) using GenStat 14th edition. The least significance differences (LSD) were used to separate means at 0.05 significant levels. The general linear model used was:

$$Y_{ijk} = \mu + \alpha_i + \gamma_k + \eta_{ik} + \beta_j + (\alpha\beta)_{ij} + (\alpha\gamma\beta)_{ijk} + \varepsilon_{ijk}$$

Where: Y_{ijk} is the yield of the i^{th} variety under the k^{th} water harvesting technique in the j^{th} replication; μ is the overall mean; α_i is the fixed effect of variety ; α_i is the fixed effect of sorghum variety; γ_k is the fixed effect of rainwater harvesting technique; η_{ik} is the whole plot error; β_j represent fixed effect of Leucaena biomass; $(\alpha\beta)_{ij}$ represent fixed interaction between variety and Leucaena biomass treatment; $(\alpha\gamma\beta)_{ijk}$ represent fixed interaction between variety, rainwater harvesting and Leucaena biomass treatment; i=variety index (Marcia, sv1), k=water harvesting technique index (TC,SC,IP); k=replication index(1,2,3) and ε_{ijk} is the random error.

4.5 RESULTS

4.5.1 Soil characterisation

Initial soil characterisation classified the soil from experimental site as loamy sand (medium grained loamy sand), Fersiallitic 5G or Nitisols/Luvisols soil with 800 g kg^{-1} sand, 150 g kg^{-1} silt and 50 g kg^{-1} clay. The soil had an average pH of 5.3 with a total Nitrogen content of 1.5 g kg^{-1}, 13.4 g kg^{-1}, soil organic carbon, 0.006 g kg^{-1} available phosphorous and 0.21 $cmol_c$ kg^{-1} exchangeable potassium. The exchangeable cations were 0.81 $cmol_c$ kg^{-1} calcium and 0.35 $cmol_c$ kg^{-1} magnesium.

4.5.2 Rainfall

Total rainfall received during the three cropping seasons ranged from 295 to 305 mm which was below a long-term average of 450 mm for agroecological zone V. Highest rainfall (305 mm) was received in 2017/18 and 2019/20 cropping seasons and a lowest of 295 mm was recorded in 2018/19 season (Figure 4.2). The cropping seasons were associated with dry spells ($\leq$ 5 mm rainfall) with an average of 18 days in November, December and January. The longest dry spell (24 days) occurred in March during the 2018/19 season.

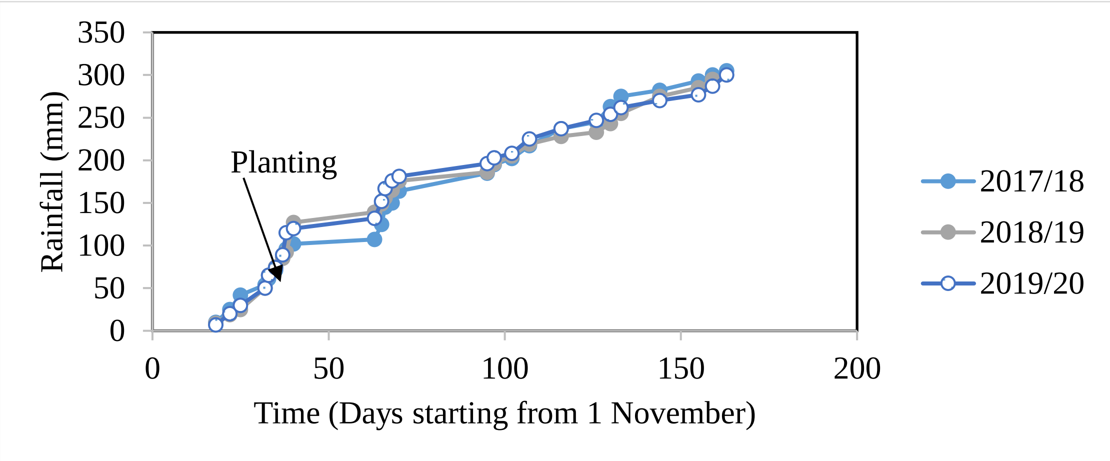


Figure 4.2: Cumulative rainfall distribution during the three cropping seasons at the experimental site.

4.5.3 Soil moisture content

Rainwater harvesting techniques show significant ($p<0.05$) effect on soil moisture content. Soil moisture content from tied contours (TC) and infiltration pits (IP) was significantly higher than that in standard contours (SC) (Table 4.1). Soil moisture content increased significantly with depth and higher soil moisture content was observed from 20-40 cm (Table 4.1). Tied contour and IP had comparable soil moisture content throughout the three cropping seasons. Soil moisture content was significantly ($p<0.05$) influenced by Leucaena biomass and a gradual increase in soil moisture content with increased application rate of Leucaena biomass was observed (Table 4.2). Application rate of 30 t ha^{-1} Leucaena biomass had the highest soil moisture content (9.81 %) from a depth of 20-40 cm while the least (5.88 %) was observed from the control at 0-20 cm depth (Table 4.2). Significant ($p<0.05$) perfect positive correlations were indicated between soil moisture content and Leucaena biomass at different depths (0-20 and 21-40 cm) for all three cropping seasons (Figure 4.3). The interactive effects of RWH and Leucaena biomass significantly influenced ($p<0.05$) soil moisture content (Table 4.3). Soil moisture content significantly increased with soil depth and varied with season (Table 4.3).

Table 4.1: Effects of rainwater harvesting techniques on soil moisture content

	Soil moisture content (%)					
Rainwater harvesting	**2018**		**2019**		**2020**	
	0-20cm	**20-40**	**0-20cm**	**20-40**	**0-20cm**	**20-40cm**
Standard contour	6.69^b	8.04^a	6.93^a	8.63^a	7.04^a	8.94^a
Infiltration pits	6.49^a	9.12^b	7.11^b	9.24^b	7.14^b	9.08^b
Tied contour	6.97^b	9.28^c	7.18^c	9.34^c	7.13^b	9.06^b
P-value	*<0.001*	*<0.001*	*0.001*	*0.001*	*<0.001*	*<0.001*
Lsd (0.05)	*0.0445*	*0.028*	*0.0345*	*0.0479*	*0.0359*	*0.0308*

Means in the same column followed by the same superscript are not significantly different at $p \leq 0.05$.

Table 4.2: Effects of Leucaena biomass on soil moisture content

Leucaena biomass (t ha^{-1})	Soil moisture content (%)					
	2018		2019		2020	
	0-20cm	20-40cm	0-20cm	20-40cm	0-20cm	20-40cm
0	5.88^{a}	8.09^{a}	5.98^{a}	8.10^{a}	6.04^{a}	8.15^{a}
5	6.08^{b}	8.55^{b}	6.42^{b}	8.65^{b}	6.63^{b}	8.52^{b}
10	6.66^{c}	8.73^{c}	7.06^{c}	9.03^{c}	7.17^{c}	9.07^{c}
20	7.14^{d}	9.24^{d}	7.61^{d}	9.59^{d}	7.61^{d}	9.57^{d}
30	7.86^{e}	9.46^{e}	8.30^{e}	9.97^{e}	8.08^{e}	9.81^{e}
P value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Lsd (0.05)	*0.0574*	*0.0361*	*0.0446*	*0.0618*	*0.0463*	*0.0397*

Means in the same column followed by the same superscript are not significantly different at $p \leq 0.05$.

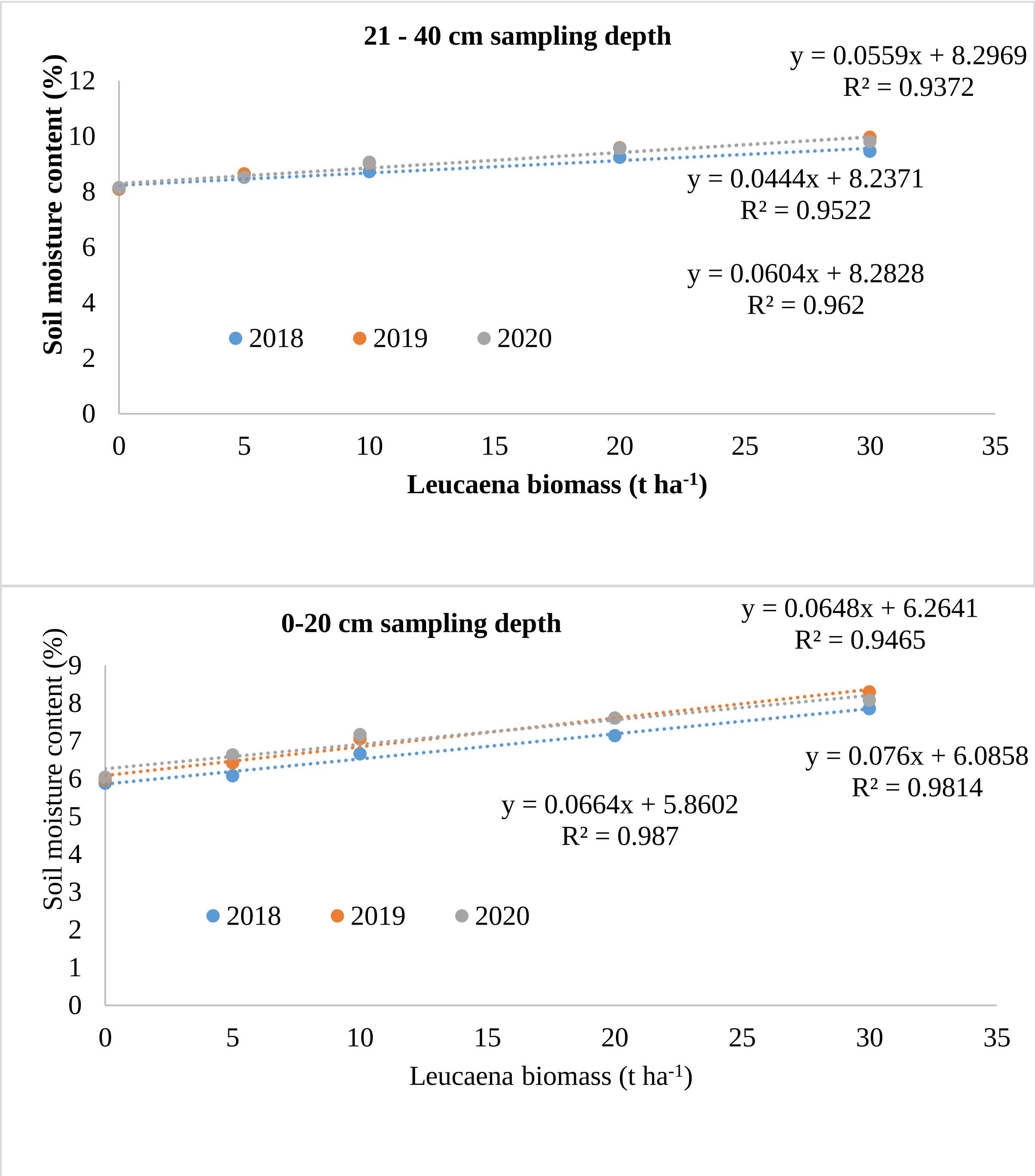


Figure 4.3: The relationship between soil moisture content and Leucaena biomass at the 21 – 40 cm depth

Table 4.3: Interaction effects of rainwater harvesting techniques and Leucaena biomass on soil moisture content

Soil moisture content (%)

Treatment combinations		**2018**		**2019**		**2020**	
Rainwater harvesting techniques	**Leucaena biomass level (t ha^{-1})**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**	**0-20cm**	**20-40cm**
Infiltration pits	0	5.88^{b}	8.11^{d}	5.99^{b}	8.12^{c}	6.07^{b}	8.19^{b}
	5	5.93^{b}	8.92^{g}	6.42^{e}	8.99^{e}	6.64^{c}	8.58^{d}
	10	6.39^{c}	8.88^{g}	7.09^{g}	9.12^{f}	7.22^{e}	9.12^{f}
	20	6.88^{e}	9.80^{ij}	7.67^{i}	9.87^{g}	7.68^{g}	9.66^{h}
	30	7.43^{h}	9.90^{j}	8.39^{k}	10.08^{h}	8.10^{h}	9.86^{j}
Tied contour	0	5.97^{b}	8.43^{e}	6.07^{c}	8.43^{d}	6.06^{ab}	8.20^{b}
	5	6.42^{c}	8.91^{g}	6.49^{e}	8.97^{e}	6.66^{c}	8.54^{d}
	10	7.02^{f}	9.42^{h}	7.11^{g}	9.94^{gh}	7.23^{e}	9.10^{f}
	20	7.38^{h}	9.77^{i}	7.69^{i}	9.80^{g}	7.58^{f}	9.62^{h}
	30	8.14^{j}	9.86^{j}	8.52^{l}	9.99^{h}	8.10^{h}	9.82^{ij}
Standard contour	0	5.78^{a}	7.73^{a}	5.86^{a}	7.75^{a}	5.98^{a}	8.05^{a}
	5	5.88^{b}	7.81^{b}	6.34^{d}	7.99^{b}	6.58^{c}	8.43^{c}
	10	6.56^{d}	7.89^{c}	6.99^{f}	8.48^{d}	7.04^{d}	9.01^{e}
	20	7.22^{g}	8.16^{d}	7.46^{h}	9.09^{f}	7.57^{f}	9.42^{g}
	30	8.01^{i}	8.62^{f}	7.98^{j}	9.83^{g}	8.04^{h}	9.78^{i}
	P-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.049*	*0.047*
	Lsd (0.05)	*0.0994*	*0.0626*	*0.0772*	*0.1071*	*0.0802*	*0.0688*
	CV (%)	*0.9*	*0.4*	*0.7*	*0.7*	*0.7*	*0.5*

Means in the same column followed by the same superscript are not significantly different at $p \leq 0.05$.

4.5.4 Sorghum grain and stover yield

Table 4.4 summarises the analysis of variance (ANOVA) of grain and stover yield of two sorghum varieties (Macia and SV1) under RWH techniques and varying Leucaena biomass application rates over three seasons (2017/18 to 2019/20). Grain and stover yield were significantly influenced ($p<0.05$) by RWH techniques, variety, Leucaena biomass and season (Table 4.4). The interactive effects of RWH techniques and season significantly influenced ($P<0.05$) grain yield of sorghum (Figure 4.4). In all three seasons, TC and IP had significantly higher ($p<0.05$) grain yield than SC (Figure 4.4). Macia variety had significantly higher grain yield compared with SV1 variety throughout the three cropping seasons under different RWH techniques (Figure 4.4). Sorghum stover yield was considerably influenced ($p<0.05$) by interaction of RWH and season for both varieties (Figure 4.5). TC and IP had comparable sorghum stover yield across all seasons and varieties. Highest stover yield (3.347 t ha^{-1}) was observed from tied contours and the lowest (2.668 t ha^{-1}) from the standard contour (Figure 4.5).

Table 4.4: Summary of ANOVA of soil moisture content, RWUE, sorghum grain and stover yield under RWH methods and Leucaena leucocephala application rates across three seasons (2017/18 to 2019/20).

Factor	**Significance**			
	Soil moisture content	**Grain yield**	**Stover yield**	**RWUE**
RWH method	*	*	*	*
Variety	-	*	*	*
Leucaena (L)	*	*	*	*
Season	*	*	*	*
RWH method x variety	-	*	*	*
RWH method x L	ns	ns	ns	*
Variety x L	-	*	*	*
RWH method x season	*	*	*	ns
Variety x season	-	*	*	ns
L x season	*	*	*	*
RWH method x variety x L	-	ns	ns	ns
RWH method x L	*	ns	ns	ns
RWH method x variety x season	-	*	*	ns
Variety x L x season	-	*	*	ns
RWH method x variety x L x season	-	ns	*	ns

***** Significant at $p \leq 0.05$; ns- not significant; RWUE- rainwater use efficiency; RWH- rainwater harvesting; L-*Leucaena leucocephala* biomass

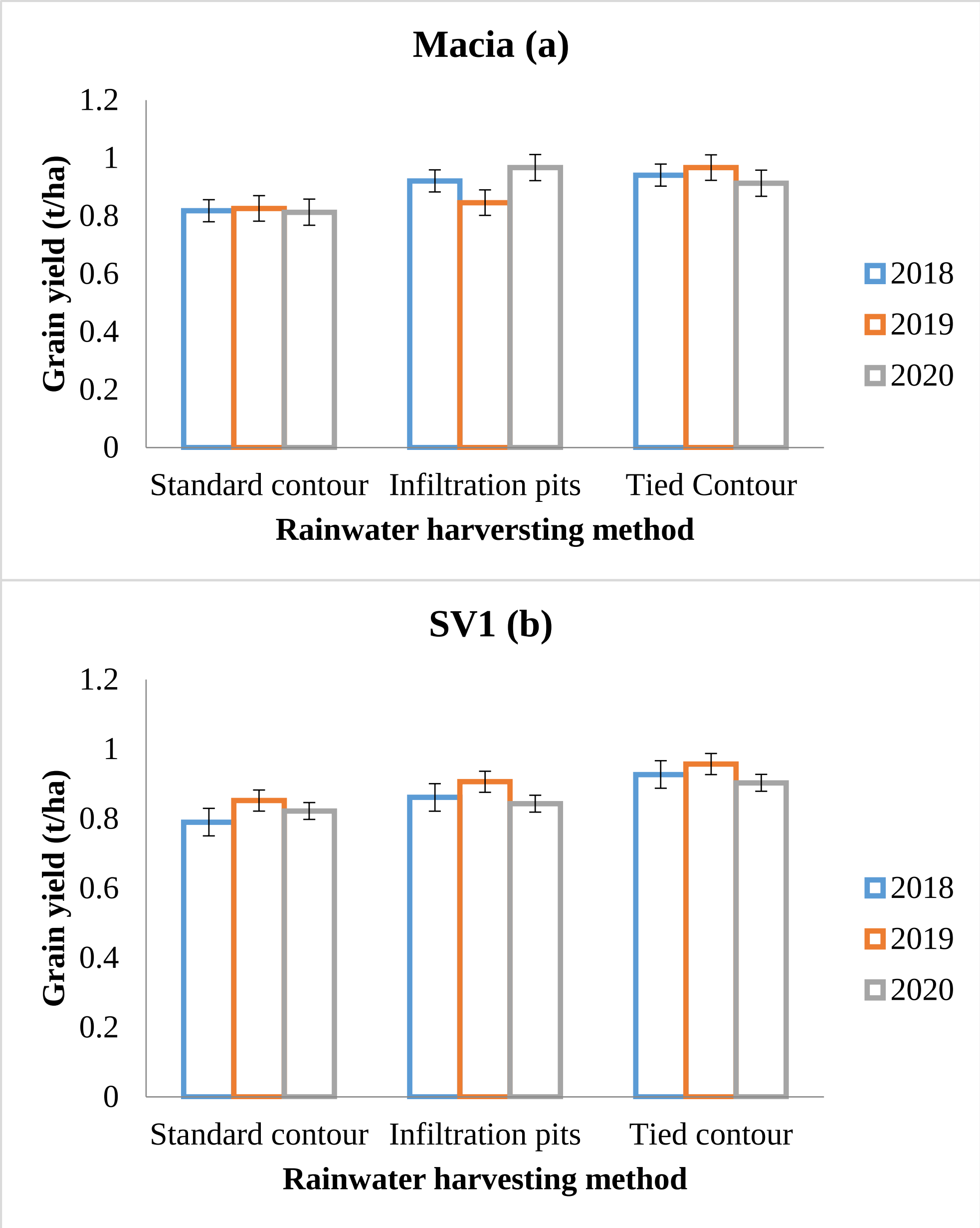
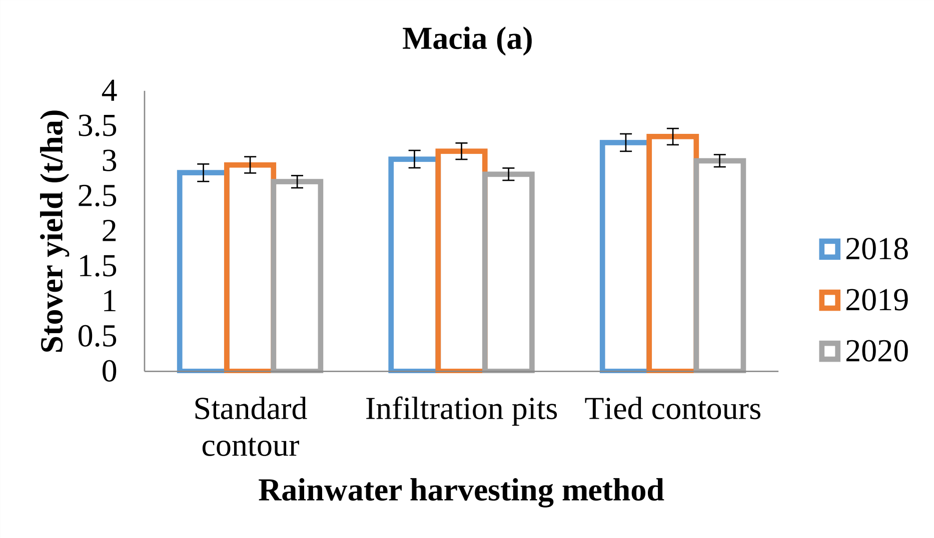


Figure 4.4: Effect of water harvesting methods on yield of Macia and SV1 grain yield over the three seasons



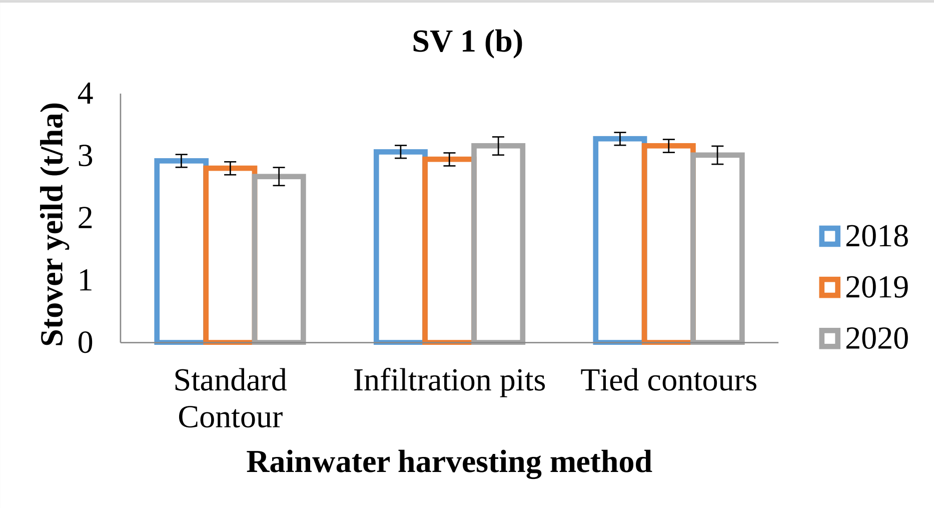


Figure 4.5: Effects of rainwater harvesting method on Macia and SV1 stover yield.

Grain yield was significantly influenced ($p<0.05$) by interaction of Leucaena biomass and season (Table 4.5). Sorghum grain yield increased with increase in application rate of Leucaena biomass. Sorghum variety Macia had higher grain yield than SV1 at 5 and 10 t ha^{-1} of Leucaena biomass in all seasons. Sorghum grain yield was higher from SV1 variety than Macia at 20 and 30 t ha^{-1} of Leucaena biomass (Table 4.5). Treatments with 0 t ha^{-1} had considerably low sorghum grain yield than treatments applied Leucaena biomass in all three cropping seasons (Table 4.5). Application rate of 30 t ha^{-1} showed higher yield from both varieties during all seasons with highest grain yield (1.083 t ha^{-1}) observed from SV1 variety in 2018/19 season (Table 4.5).

Stover yield was significantly affected ($p<0.05$) by interaction of Leucaena biomass and season (Table 4.5). Stover yield varied with application rate of Leucaena biomass, season and variety. Highest (4.023 t ha^{-1}) stover yield was observed from Macia at 30 t ha^{-1} Leucaena biomass in 2018/19 season (Table 4.5). On average, stover yield was higher from Macia variety compared with SV1 variety. Stover yield significantly increased with increase in application rate of Leucaena biomass every season for both varieties (Table 4.5).

Interactive effects of rainwater harvesting, variety and Leucaena biomass significantly ($p< 0.05$) affected stover yield over three seasons (Table 4.5) such that tied contours and 30 t ha^{-1} of Leucaena biomass had the highest (4.47 t ha^{-1}) stover yield from Macia variety. The lowest stover yield of 2.1 t ha^{-1} was observed from SV1 under standard contour with no biomass during 2019/20 season. Integrating TC and IP with Leucaena biomass gave higher stover yield for both varieties in all three seasons compared with Standard Contours combined with Leucaena biomass treatments (Table 4.6).

Table 4.5: Effects of Leucaena biomass on sorghum grain and stover yields

Leucaena biomass (t/ha)	Mean Macia grain yield (tha^{-1})				Mean SV1 grain yield (tha^{-1})			
	2018	**2019**	**2020**	**Mean**	**2018**	**2019**	**2020**	**Mean**
0	0.746^{a}	0.748^{a}	0.759^{a}	0.750	0.677^{a}	0.720^{a}	0.702^{a}	0.700
5	0.832^{b}	0.827^{b}	0.816^{b}	0.827	0.776^{b}	0.829^{b}	0.799^{b}	0.801
10	0.912^{c}	0.917^{c}	0.853^{bc}	0.892	0.826^{c}	0.899^{c}	0.863^{c}	0.864
20	0.958^{cd}	0.962^{cd}	0.892^{cd}	0.936	0.942^{d}	0.994^{d}	0.923^{d}	0.953
30	1.019^{e}	1.008^{e}	0.959^{e}	0.999	1.076^{e}	1.083^{e}	0.988^{e}	1.049
P value	*<0.001*	*<0.001*	*<0.001*		*<0.001*	*<0.001*	*<0.001*	
Lsd (0.05)	0.0555	0.0429	0.0222		0.0401	0.0293	0.0258	
	Mean Macia stover yield (tha^{-1})				**Mean SV1 stover yield (tha^{-1})**			
0	2.307^{a}	2.226^{a}	2.172^{a}	2.246	2.261^{a}	2.258^{a}	2.188^{a}	2.236
5	2.633^{b}	2.673^{b}	2.414^{b}	2.573	2.549^{b}	2.502^{b}	2.35^{b}	2.467
10	3.019^{c}	3.164^{c}	2.782^{c}	2.988	3.066^{c}	2.914^{c}	2.766^{c}	2.915
20	3.426^{d}	3.629^{d}	3.168^{d}	3.408	3.611^{d}	3.297^{d}	3.059^{d}	3.322
30	3.816^{e}	4.023^{e}	3.66^{e}	3.833	3.94^{e}	3.838^{e}	3.719^{e}	3.832
P value	*<0.001*	*<0.001*	*<0.001*		*<0.001*	*<0.001*	*<0.001*	
Lsd (0.05)	*0.0642*	*0.0453*	*0.043*		*0.0467*	*0.0393*	*0.0388*	

Means in the same column followed by the same superscript are not significantly different at $p \leq 0.05$.

Table 4.6: Interaction effects of RWH and Leucaena biomass on Macia and SV1 stover yields

Treatment combinations		**Macia** Mean stover yield (t ha^{-1})			**SV1** Mean stover yield (t ha^{-1})		
Rainwater harvesting techniques	**L. leucocephala biomass level (t ha^{-1})**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
Infiltration pits	0	2.247^{a}	2.177^{a}	2.17^{a}	2.257^{a}	2.26^{a}	2.173^{b}
	5	2.607^{d}	2.69^{cd}	2.387^{b}	2.523^{b}	2.41^{c}	2.223^{b}
	10	3.07^{f}	3.227^{f}	2.777^{e}	3.047^{e}	2.97^{f}	2.727^{e}
	20	3.457^{h}	3.663^{h}	3.107^{g}	3.647^{h}	3.20^{g}	3.01^{g}
	30	3.75^{i}	3.937^{i}	3.613^{i}	3.850^{i}	3.873^{j}	3.717^{j}
Tied contour	0	2.313^{ab}	2.193^{a}	2.16^{a}	2.313^{a}	2.313^{b}	2.293^{c}
	5	2.773^{e}	2.71^{d}	2.52^{c}	2.673^{c}	2.727^{d}	2.623^{d}
	10	3.237^{g}	3.43^{g}	2.947^{f}	3.260^{f}	3.033^{f}	2.887^{f}
	20	3.737^{i}	3.927^{i}	3.44^{h}	3.817^{i}	3.66^{i}	3.293^{h}
	30	4.25^{j}	4.473^{j}	3.943^{j}	4.30^{j}	4.06^{k}	3.957^{k}
Standard contour	0	2.36^{b}	2.307^{b}	2.18^{a}	2.213^{a}	2.20^{a}	2.097^{a}
	5	2.52^{c}	2.62^{c}	2.337^{b}	2.450^{b}	2.37^{bc}	2.203^{b}
	10	2.75^{e}	2.837^{e}	2.623^{d}	2.890^{d}	2.82^{e}	2.683^{de}
	20	3.083^{f}	3.297^{f}	2.957^{f}	3.370^{g}	3.03^{f}	2.873^{f}
	30	3.447^{h}	3.66^{h}	3.423^{h}	3.670^{h}	3.58^{h}	3.483^{i}
P-value		*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Lsd (0.05)		*0.1112*	*0.0785*	*0.0744*	*0.081*	*0.068*	*0.0672*
CV (%)		*2.2*	*2.1*	*1.6*	*1.6*	*1.4*	*1.4*

Means in the same column followed by the same superscript are not significantly different at $p \leq 0.05$.

4.5.5 Rain Water Use Efficiency (RWUE)

Rainwater use efficiency was significantly influenced ($p<0.05$) by RWH, variety, Leucaena biomass and season (Table 4.4). Interaction of Rainwater harvesting techniques and variety significantly affected ($p<0.05$) rainwater use efficiency during the three cropping seasons. TC and IP had significantly higher ($p<0.05$) RWUE compared with SC for both varieties across all seasons except in 2019/20 when IP and SC showed no significant difference (Table 4.7). TC had higher RWUE across all seasons for both varieties with highest RWUE (3.28 kg ha^{-1} mm^{-1}) observed for Macia in 2018/19 (Table 4.7).

Table 4.7: Effects of RWH and variety on sorghum RWUE

RWH Techniques	Macia RWUE (kg ha^{-1} mm^{-1})				SV1RWUE (kg ha^{-1} mm^{-1})			
	2018	2019	2020	Mean	2018	2019	2020	Mean
Standard contour	2.68^{a}	2.78^{a}	2.67^{a}	2.72	2.59^{a}	2.89^{a}	2.76^{a}	2.76
Infiltration pits	3.02^{b}	2.87^{a}	2.76^{b}	2.89	2.82^{b}	3.07^{b}	2.76^{a}	2.89
Tied contour	3.09^{b}	3.28^{b}	2.99^{c}	3.12	3.04^{c}	3.24^{c}	2.95^{b}	3.08
P-value	<0.001	<0.001	<0.001		<0.001	<0.001	0.0875	
LSD (0.05)	0.1419	0.1121	0.0561		0.1008	0.0773	0.1968	

Means in the same column followed by the same superscript are not significantly different at $p \leq 0.05$.

Significant interaction effects ($p<0.05$) of Leucaena biomass and season influenced RWUE (Figure 4.6). The highest RWUE was observed in 2018/19 season at all Leucaena biomass application rates, while the lowest RWUE was in 2019/20 season for Macia variety. The lowest RWUE for SV1 variety was observed in 2017/18 and highest was from 2018/19 cropping seasons (Figure 4.6). Interaction effects of Leucaena biomass and season show significant correlation (R^2

= 0.76-0.99), with perfect positive correlation (R^2 = 0.99) observed from SV1 variety in 2017/18 season (Figure 4.6). Furthermore, SV1 had the lowest correlation (R^2 = 0.76) between rainwater use efficiency and Leucaena biomass in 2019/20 while Macia variety had the highest (R^2 = 0.96) in the same season.

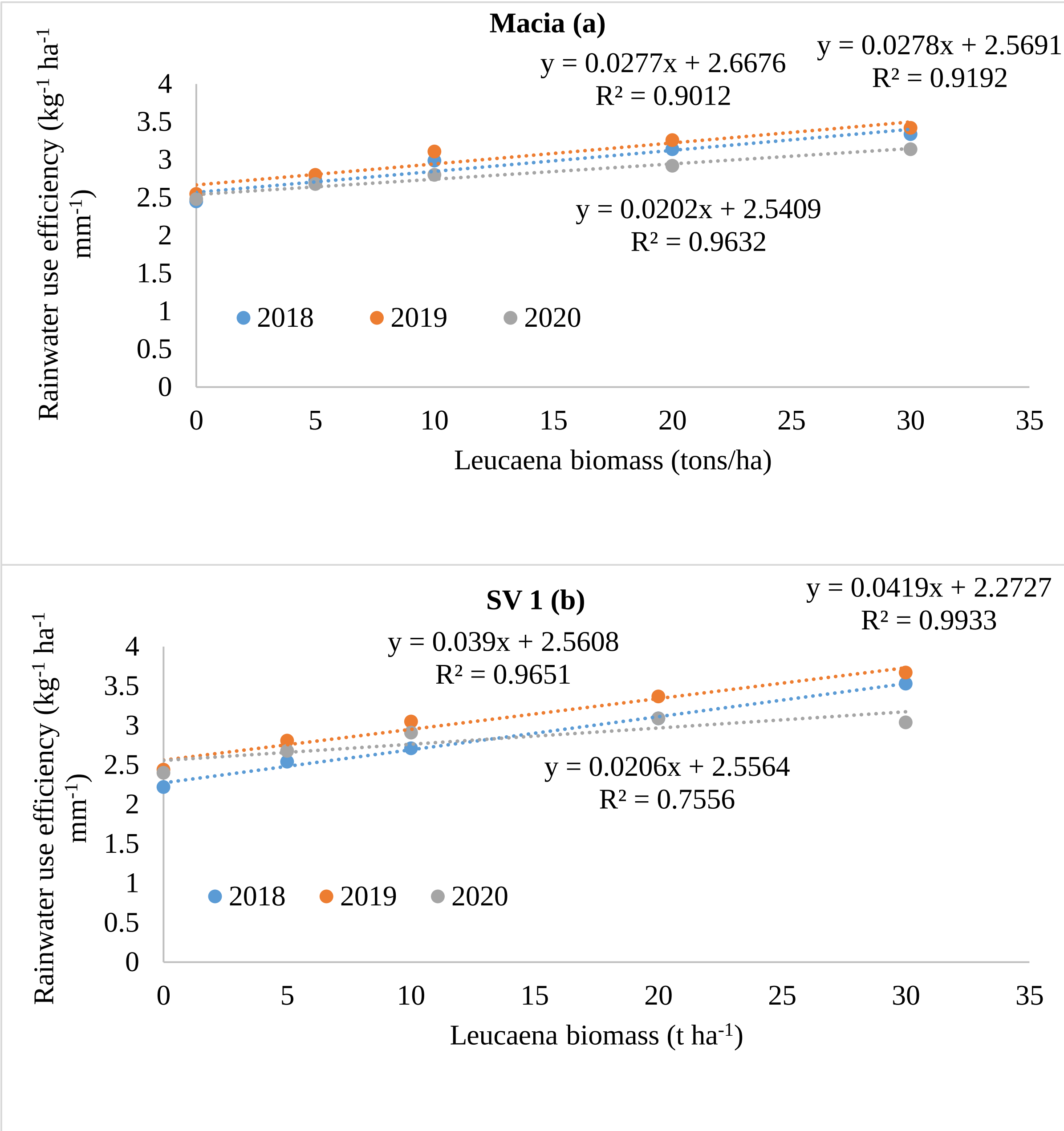


Figure 4.6: The relationship between rainwater use efficiency and Leucaena biomass for three seasons.

4.6 DISCUSSION

4.6.1 Rainfall

The total rainfall received over three cropping seasons was below the long-term average of 450 mm per annum. The total rainfall received irrespective of distribution can hardly take sorghum crop to maturity hence the need to manipulate moisture availability in the plant root zone. Rainfall totals were below the long-term average confirming the assertion by Nyagumbo et al. (2019) that Zimbabwe has been affected by climate change. These totals call for rainfed systems that are highly adaptable in their response to stress factors. Mugandani et al. (2012) and Nyagumbo et al. (2019) confirmed that climate change has affected the southeastern and southern parts of Zimbabwe causing a huge decrease in grain yield.

4.6.2 Soil moisture content

The RWH techniques of TC and IP improved soil moisture content over three cropping seasons because of their capacity to collect runoff water and store it. Tied contour and IP have comparable soil moisture content because they designed to impound water. Tied contour and IP have the capacity to reduce surface runoff from fields, holding water for longer period, allowing it to infiltrate and recharging the root zone to greater depths. This caused higher soil moisture content at a depth of 20-40 cm. The standard contour had the least soil moisture content because it is designed to discharge runoff water from field. These results concur with findings by Nyamadzawo et al. (2013), Mupangwa et al. (2006) and Mandumbu et al. (2021) who found that TC and IP retain moisture which crops eventually use during the dry spells. Results from this study support findings by Mugabe (2004), Gumbo et al. (2012) and Nyagumbo et al. (2019) who reported improved soil moisture content using infiltration pits, *Fanya juus* and contour ridges with cross ties in semi-arid areas of Zimbabwe. The 2018/19 season had higher soil moisture content than other seasons irrespective of soil depth. This may have been caused by residual soil moisture content from previous season. Decreased soil moisture content in 2019/20 cropping season might be attributed to rainfall variability and high intensity rainfall which caused surface runoff. Seasonal variation of soil moisture content was also reported by Nyakudya (2014), Nyagumbo et al. (2015) and Nyamadzawo et al. (2015b) who indicated that rainfall variability and intensity largely contributed to this variation.

Soil moisture content was increased with increase in application rates of Leucaena biomass. This might have been attributed to reduction in evaporation loss from the biomass cover as well as enhanced water infiltration. This concurs with findings by Mapa and Gunasena (1995) who reported increase in soil moisture content with addition of legume tree-based biomass. This might be because Leucaena biomass improves soil physical properties such as lowering bulk density, increasing soil total porosity and water infiltration rates. Nyamadzawo et al. (2007) also found that Sesbania and Glirisidia mixed with Dolichos increased infiltration rates significantly compared with fertilised plots. Therefore, investment in soil fertility using Leucaena biomass directly improves soil moisture content. Application of Leucaena biomass increased soil moisture content (Patil and Sheelavantar, 2004; Ramamoorthy et al., 2002; Mugwe, 2007). Interaction of RWH techniques, Leucaena biomass and season improved soil moisture content with soil depth. Rainwater harvesting techniques of TC and IP collects runoff and store it, but when integrated with Leucaena biomass which improves soil physical properties may lead to improved soil water retention which support crops for longer periods. Residual effects of Leucaena biomass also contributed to increased soil moisture content when combined with TC and IP compared with SC which dispose-off runoff.

4.6.3 Sorghum grain and stover yield

Tied contours and infiltration pits show grain yield benefits compared with standard contour in all three seasons. This may have been caused by variation in soil moisture content between TC, IP and SC. The RWH techniques of TC and IP collected runoff water, stored it and allowed it to flow laterally into the field. This water increased soil moisture availability to crops during dry spell, improving crop growth and sorghum grain yield. This was similar to findings by Mupangwa et al. (2006); Nyamadzawo et al. (2015), Nyagumbo et al. (2019) and Kubiku et al. (2022b) who reported higher grain yield from TC and IP compared with SC using different varieties from those used in this study. Higher yields from TC and IP could be attributed to improved water retention which increase soil moisture, increasing crop growth and sorghum grain yield. The same effect was observed in stover yield. Availability of soil moisture increased nutrient uptake which improved sorghum growth causing heavier stover to be produced. These results support findings by Mupangwa et al. (2012b), Kilasara et al. (2015), Traore et al. (2017), Chilagane et al. (2020) and Kubiku et al. (2022a) who reported increased sorghum grain and stover yield with the use of IP. Differences in total rainfall received across semi-arid areas in Africa greatly influence variation in results between various research studies. In all seasons, the effects of RWH techniques show higher grain and stover yield from Macia than SV1 variety. This may have been caused by genetic differences between the varieties and their response to environmental conditions in semi-arid areas of Zimbabwe.

Sorghum grain and stover yields increased with different application rates of Leucaena biomass across all three cropping seasons. Grain and stover yield were highest in 2018/19 at all application rates whilst the 2019/20 season had the lowest sorghum grain and stover yield. The 2018/19 cropping season was characterised by evenly distributed rainfall with low intensity storms which was well collected by RWH techniques. Residual effects of Leucaena biomass from 2017/18 season increased nutrient availability in the soil which improved sorghum grain and stover yield in 2018/19 season. Low sorghum grain and stover yield in 2019/20 season was attributed to uneven rainfall distribution associated with long mid-season droughts which negatively affected soil moisture content, decomposition of Leucaena biomass and mineralisation. Higher grain and stover yield due to increased application of Leucaena biomass may have been attributed to high organic carbon, biomass decomposition and mineralisation which increases nutrient availability in the plant root zone (Ramamoorthy et al., 2002; Patil and Sheelavantar, 2004).

Effect of Leucaena biomass and variety was significant on grain and stover yield. Macia variety had higher sorghum grain and stover yield compared with SV1 at 5-10 t ha^{-1}. This could have been attributed to genetic differences between the two varieties, with Macia variety adapting better in semi-arid areas compared with SV1. Macia variety is drought resistant and thrives better than SV1 in soils with low nutrient status. SV1 had higher grain and stover yield at 20-30 t ha^{-1} Leucaena biomass compared with Macia variety. This is because SV1 respond better at high nutrient sources and have the capacity to produce higher yields in clay and other soils than sandy loam soils found at the studied site. This corroborates with findings by Kebede et al. (2012) and Kimaru-Muchai et al. (2021) who reported high sorghum grain yield after applying Leucaena biomass in clay loam soils. Low rainfall and poor soils in semi-arid areas of Zimbabwe have been contributing to low sorghum grain and stover yield. Addition of Leucaena biomass as a nutrient source to these poor soils improves their structure, water and nutrient retention ability and increase sorghum yields.

Higher stover yield from TC and IP over each variety and season may be attributed to ability of these techniques in harvesting runoff water which crops can use during dry period. Tied contours and infiltration pits increased stover yield as a result of increased water retention which improved nutrient uptake and plant growth (Nyagumbo et al., 2015). Decomposition of Leucaena biomass was improved with increased soil moisture content and this increases mineralisation and nutrient availability to sorghum crop. Improved sorghum yield was closely linked to increased nutrients in the plant root zone and improved nutrient uptake (Mafongoya and Dzowela 1999; Ramamoorthy et al., 2002; Mugendi et al., 2003; Mafongoya et al., 2006, 2007). Fast decomposition and mineralisation caused by increased application of Leucaena biomass also contributed to high stover yields.

4.6.4 Rain Water Use Efficiency

Tied contour and IP had comparable RWUE compared with SC. Tied contour and IP improved soil water availability to crops. This increased water use efficiency by sorghum plants. RWUE was above 1.5 kg ha^{-1} mm^{-1} across all seasons and both varieties from TC and IP. Nutrient and water management options improve rainwater use efficiency by 15 to 25 % (Hartfield et al., 2001). RWUE was improved with increase in application rates of Leucaena biomass. This could have been attributed to improved soil moisture content in all plots applied Leucaena biomass. Leucaena biomass act both as soil fertility management option and soil moisture conservation. The increased RWUE among Leucaena biomass levels could be strongly linked to total dry matter than sorghum grain yield.

4.7 CONCLUSION

Tied contours and infiltration pits improved RWUE, grain and stover yield by increasing soil moisture content. This was shown by high soil moisture content harnessed by TC and IP techniques. However, there was a variation in soil moisture content with increasing soil depth. Standard contour had low soil moisture content which negatively affected grain and stover yield resulting in low water use efficiency by sorghum plants. Soil moisture content increased with increase in application rate of Leucaena biomass. This improved grain and stover yield showing yield benefits for every increase in application rate of Leucaena biomass. Grain and stover yield response to Leucaena biomass was improved by TC and IP RWH techniques. A better grain yield response to Leucaena biomass was attained by Macia variety showing better adaptability and yield potential in semi-arid areas of Zimbabwe. This may be due to genetic differences between Macia and SV1 varieties together with their responses to environmental factors in semi-arid areas. Although higher yield was observed at 30 t ha $^{-1}$ Leucaena biomass, farmers are encouraged to adopt Macia variety grown under tied contours at 10 t ha^{-1} Leucaena biomass due to better yield increments per tonne of biomass. Therefore, smallholder farmers are resource poor and there is need to evaluate the economic benefits of using TC and IP in future studies on different soil types since this study was done on sandy loam soils with high water losses.

There is need to combine Leucaena biomass with other organic nutrient sources such as cattle manure and evaluate their compatibility on sorghum yields, net return, agronomic efficiency and rainwater use efficiency.

CHAPTER 5: COMPATIBILITY OF *LEUCAENA LEUCOCEPHALA* BIOMASS AND CATTLE MANURE COMBINATION UNDER RAINWATER HARVESTING ON SORGHUM (*SORGHUM BICOLOR* (L.) MOENCH) PRODUCTIVITY IN SEMI-ARID REGION OF ZIMBABWE

ABSTRACT

Poor soil fertility is one of the constraints contributing to poor sorghum production in semi-arid areas across Africa. To increase sorghum production, there is need to address soil fertility issues. Therefore, the objective was to assess the effects of *Leucaena leucocephala* (Leucaena)/cattle manure combination on grain and stover yields, harvest index and net return of two sorghum varieties (Macia and SV1) under rainwater harvesting techniques. The field experiment was conducted as a randomised complete block design over three cropping seasons in a split-split plot arrangement. Rainwater harvesting was used as a main plot at three levels (tied contour, infiltration pit and standard contours as a control). Split plot factor was a mixture Leucaena/cattle manure combination (cattle manure (0, 2.5, 5, 10 and 15 t ha^{-1})) and Leucaena biomass (0, 2.5, 5, 10 and 15 t ha^{-1}) in quantities to produced combined organic source at a rate of 0, 5, 10, 20 and 30 t ha^{-1}. Sorghum variety was used as a split-split factor at two levels (Macia and SV1). Results showed significant ($p<0.05$) increase in sorghum grain yield with increased applications of Leucaena/cattle manure combinations. Macia variety had statistically greater ($p<0.05$) grain yield than SV1 variety. Tied contour show considerably higher yields for both varieties across all seasons. Stover yield show significant differences ($p<0.05$) as affected by Leucaena/cattle manure and rainwater harvesting techniques. Rainwater harvesting techniques significantly influenced ($p<0.05$) harvest index, with tied contour and infiltration pits having comparably higher harvest index than standard contour. Application of Leucaena/cattle manure combinations show significant increases in harvest index with increased application rates. However, no significant effect was observed at 20 and 30 t ha^{-1} from SV1 variety across all seasons. Leucaena/cattle manure combination significantly influenced ($p<0.05$) sorghum net return across all seasons except at 5 t ha^{-1} where no significant effect was observed. Macia variety had higher net return than SV1. To increase grain yield and net return, farmers can adopt Macia variety, tied contour and 10 t ha^{-1} Leucaena/cattle manure combination due to higher incremental yield per tonne.

Keywords: Rainwater harvesting, Leucaena/cattle manure, sorghum production, Semi-arid, Zimbabwe

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5.1 INTRODUCTION

Soil fertility and water are an important part of agricultural production in semi-arid regions (Javaid et al., 2022). Shortages of nutrients along with irregular and insufficient moisture in the soil significantly affect rainfed agriculture in semi-arid areas (Mupangwa et al., 2016; Tsujimoto et al., 2021). Inadequate mineral fertiliser application by smallholder farmers causes yield reduction and food insecurity in most parts of Zimbabwe (Kubiku et al., 2022a). Yield reduction and food insecurity is worsened by low, erratic and unevenly distributed rainfall received in most parts of semi-arid areas in Sub-Saharan Africa (SSA) (Tsujimoto et al., 2021). There is need for farmers to combine organic nutrient sources which are readily accessible in their environments to improve soil fertility and yields. Furthermore, there is need to come up with strategies which capture and utilise rainwater to recharge groundwater, improve soil moisture in the plant root zone and crop production in rainfed agricultural environments (Javaid et al., 2022). There is need to evaluate the compatibility of organic nutrient sources in combination with rainwater harvesting techniques to determine their effects on soil fertility and crop yields.

Compatibility of organic nutrient sources play a pivotal role in restoring soil fertility and improving crop yields in semi-arid regions. Smallholder farmers in semi-arid regions across the world are resource poor and unable to buy the required quantities of mineral fertilisers. However, combining organic nutrient sources which are readily available in smallholder farming environments can have the potential to improve crop production (Timsina, 2018; Mamuye et al., 2021). Smallholder farmers apply organic nutrient sources but use small amounts in order to cover large areas. Organic nutrient sources play an important role in improving biological, physical and chemical properties of soil which include increased microbial population, soil structure, soil water retention capacity and cation exchange capacity which improves nutrient availability (Yadav and Singh, 2016; Mugwe et al., 2019; Mamuye et al., 2021). Application of organic nutrient sources improve nutrient content, soil moisture and this increases plant growth and yields as a result of increased nutrient availability (Timsina, 2018). Long term addition of organic manure increases soil organic carbon (SOC), total nitrogen, total phosphorous, available phosphorous and available potassium in plant root zone (Li et al., 2020; Zhang et al., 2022). Availability of these macronutrients improves soil fertility and crop yields.

Sorghum grain yields in semi-arid areas of Africa have been mainly affected by poor soil fertility, erratic rainfall and lack of knowledge by smallholder farmers on climate smart agricultural techniques (Nyagumbo et al., 2019). Sorghum has excellent drought tolerance and utilise nutrients more efficiently than maize under drought conditions (Kolozsvári et al., 2022). Soil fertility issues in semi-arid areas can be addressed with the use of organic nutrient amendments such as *Leucaena* leucocephala biomass and cattle manure. These organic sources have the potential to supply large quantities of nitrogen which is the most limiting nutrient in most soils (Timsina, 2018; Kugedera et al., 2022) together with other macronutrients. Combining Leucaena biomass with cattle manure augment phosphorus (Leucaena have 1.7 g kg^{-1} compared with 6 g kg^{-1} for cattle manure) which is low in the former compared with the later (Timsina, 2018).

Leucaena species fixes 300kgN $year^{-1}$ ha^{-1} and this can reduce the need for farmers to add mineral N fertilisers (Timsina, 2018). However, when Leucaena biomass and cattle manure are mixed compatibility studies can be evaluated to find out synergism or antagonism effects on crop yields. Adoption of rainwater harvesting methods such as tied contours, infiltration pits and tied ridges can improve soil water availability and nutrient absorption (Kugedera and Kokerai, 2019; Tapiwa et al., 2020). Several authors reported that rainwater harvesting techniques improve soil moisture content in the plant root zone and nutrient availability to crops (Mandumbu et al., 2021; Kubiku et al., 2022a). Infiltration pits capture rainwater, reduce soil erosion and increase soil moisture content (Nyagumbo et al., 2019). Availability of soil moisture in plant root zone have the potential to reduce the risk of total crop failure due to frequent droughts in semi-arid areas regions (Yadav and Singh, 2016; Muchai et al., 2020). Tied contours are one of the cheapest rainwater techniques for conserving moisture available for smallholder farmers in Zimbabwe (Kubiku et al., 2022b; Kugedera et al., 2022). Rainwater harvesting techniques can make water available in the plant root zone by reducing surface runoff and prolonging the water availability in dry conditions which enhance water use efficiency and crop yields (Javaid et al., 2020; Kolozsvári et al., 2022).

Whilst water harvesting improves water availability to crops, there have been few studies done on determining the effects of mixing Leucaena biomass and cattle manure on crop productivity. The rate of mineralisation differs among organic fertilizers and therefore it is pertinent that information on compatibility be generated and evaluated. Literature is also awash with different rates of organic fertilizers which may be site and environmental conditions specific. Hence the need to generate information that is area or region specific. There are limited studies which evaluated the economic returns of two or more organic fertilizers mixed together and this is another thrust of this study. Therefore, the objective was to evaluate the compatibility of Leucaena/cattle manure combinations on grain and stover yields, harvest index and net return for two sorghum varieties (Macia and SV1) under rainwater harvesting techniques in semi-arid areas of Zimbabwe.

5.2 MATERIALS AND METHODS

5.2.1 Experimental site description

The experiment was carried out in Chivi district communal farming systems of Masvingo Province located in agroecological zone V of Zimbabwe (20º13.42´S and 30º28.565´E, 900 metres above sea level) during the period described in section 4.2.1. The area has characteristics as described in section 4.2.1.

5.2.2 Soil characterisation

Soil samples were collected and analysed using the procedure described in section 4.4.2.

5.2.3 Experimental design and treatments

The experiment was carried out in a completely randomised block design arranged as split-split plot with three treatment factors replicated three times. Rainwater harvesting was used as a main plot factor at three levels, infiltration pits (IP) of 50 cm width and 100 cm deep, tied contours (TC) of 50 cm wide and 50 cm deep and standard contours (SC). Sub-plot factor was a mixture of Leucaena/cattle manure combination (cattle manure (0, 2.5, 5, 10 and 15 t ha^{-1}) and Leucaena biomass (0, 2.5, 5, 10 and 15 t ha^{-1})) in quantities to produce combined organic source at a rate of 0, 5, 10, 20 and 30 t ha^{-1}. Leucaena biomass and cattle manure were analysed to determine nutrient composition before applying (Table 5.1). The two sorghum varieties (SV1 and Macia) were used as sub-sub plot factor. Treatments were allocated randomly to experimental plots measuring 4.5 m long x 3.0 m wide. Land was prepared and ploughed to a depth of 15-20 cm using ox-drawn mouldboard plough. Leucaena/cattle manure combination was encooperated at a rate of 0, 5, 10, 20 and 30 t ha^{-1}. Planting was done on 19 December 2017, 13 December 2018 and 16 December 2019 for 2017/2018, 2018/2019 and 2019/2020 seasons respectively. Two seeds were sown per planting station and thinned to one three weeks after emergence. Total population of 66666 plants ha^{-1} was achieved by using a row spacing of 0.75 m and 0.2 m for intra row. Weeding was carried out twice using hand hoe, at 15 days and 30 days after crop emergence. Thinning was also done simultaneously with second weeding. Fall armyworm was controlled using Demise 60 EC and birds were controlled using scaring method. Top dressing of ammonium nitrate (AN) was done in two splits, after second weeding and at six weeks after emergence using 50 kg ha^{-1} per split to all treatment plots.

Table 5.1: Nutrient composition of Leucaena biomass and cattle manure applied

Treatments	N (g kg^{-1})	P (g kg^{-1})	Mg (g kg^{-1})	Ca (g kg^{-1})	K (g kg^{-1})	C (g kg^{-1})
Leucaena biomass	35	2	4.2	13.5	18	397.8
Cattle manure	11	2	4	9	18	112

5.3 DATA COLLECTION

5.3.1 Grain and stover yield

Grain yield was obtained by cutting panicles using sharp knife at maturity from a net plot measuring 3 m long x 2 m wide. Threshing was done after panicles were sun dried. Sorghum grains were moisture tested and yield correlated to 12.5 % moisture for standardisation. Grain and stover yields were determined using procedure described in section 4.3.2.

5.3.2 Harvest Index (HI)

This is a percentage of grain yields from total yield (biological yield). Biological yield is the sum of grain and stover yield. It was calculated as a percentage using the following formula.

$$\text{HI \%} = \frac{Grain\ yield\ (t\ ha^{-1})}{Total\ above\ ground\ biomass\ (tha^{-1})} \times 100 \text{…………………. equation 6}$$

5.3.3 Economic analysis

To evaluate the economic effects of Leucaena/cattle manure combination, local market price gazetted by Grain Marketing Board (GMB) of RTGS$32000 per tonne was used and this was converted to US$ at an official bank rate of US$1=RTGS$116. Transport and labour costs were included for analysis. Cattle manure and *Leucaena leucocephala* biomass was obtained freely from local farmers and research stations respectively. Costs for land preparation, incorporation of Leucaena/cattle manure combination and construction of rainwater harvesting structures (TC, IP and SC) was constant for all treatments during first season. Reconstruction was done freely for succeeding seasons by local farmers but cost was evaluated (Table 5.2). Net return was calculated as below:

Net returns = Values grain yields harvested – total costs incurred.

Table 5.2: Parameters used to calculate net returns of Leucaena/cattle manure combination and rainwater harvesting technologies.

Parameter	Monetary value (US$)
Transport cost	$\$0.02\ kg^{-1}$
Labour cost	$\$0.15\ h^{-1}$
Labour cost for applying Leucaena/cattle manure	$\$15\ ha^{-1}$
Labour cost for construction of RWH methods	$\$50\ ha^{-1}$
Price of sorghum grain	$\$0.276\ kg^{-1}$
Price of stover	$\$0.015\ kg^{-1}$

5.4 STATISTICAL DATA ANALYSIS

The data show normality and homoscedasticity tests were done using Statistical Package for Social Sciences (SPSS) version 25. The data met normality and homoscedasticity. Data was then subjected to two-way analysis of variance (ANOVA) for split-split plot analysis using GenStat 14th edition to examine interaction effects over seasons on grain and stover yield, harvest index and net return. Significant means were separated using least significance differences (LSD) at $p \leq 0.05$. Regression analysis was done using Microsoft excel to determine correlation coefficient (R^2) of yield, harvest index versus Leucaena/cattle manure combination.

5.5 RESULTS

5.5.1 Soil characterisation

Initial soil characterisation was described in section 4.5.1. Results showed an increase in all parameter in the 2018/19 and 2019/20 seasons (Table 5.3). Application of Leucaena/cattle manure combination increase soil chemical properties. Residual effects of Leucaena/cattle manure combination boost soil chemical parameters such as structure, water retention ability, nitrogen, organic carbon and phosphorous.

Table 5.3: Chemical characteristics of soil from experimental field

Soil parameter	Composition over three seasons		
	2017/18	**2018/19**	**2019/20**
pH ($CaCl_2$)	5.3	5.8	6.0
SOC g kg^{-1}	14.7	15.3	15.5
Total Nitrogen g kg^{-1}	1.5	2	2.3
P_2O_5 g kg^{-1}	0.0426	0.0564	0.0576
K_2O g kg^{-1}	0.029	0.032	0.036
Calcium g kg^{-1}	0.092	0.096	0.101
Magnesium g kg^{-1}	0.035	0.042	0.047

5.5.2 Rainfall

Rainfall received at the experimental site was below the seasonal average for agroecological region V of Zimbabwe. Each cropping season received low rainfall compared with the long-term average of 450 mm. Rainfall received at the beginning of the cropping seasons was low although amount received in 2017/18 season was 40 % and 29 % more than amounts received in 2018/19 and 2019/20 respectively (Figure 5.1). The cropping seasons were associated with several dry spells due to uneven distribution of low rainfall received.

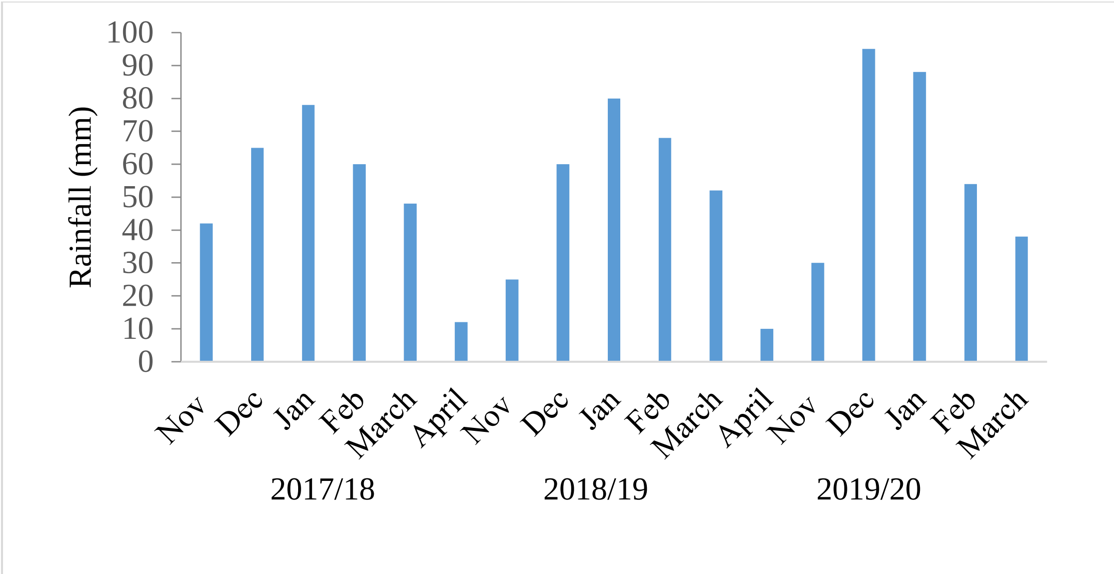

Figure 5.1: Rainfall received over three cropping seasons in the experimental site.

5.5.3 Sorghum grain yield

Results showed that sorghum grain yield was significantly influenced ($p<0.05$) by RWH techniques, Leucaena/cattle manure combination and sorghum variety as shown in Table 5.4. Significant interactions ($p<0.05$) observed between RWH techniques, Leucaena/cattle manure combinations and sorghum variety were used to provide explanations on yield differences. Leucaena/cattle manure combination increased sorghum yield with increase in application rate (ranges from 0.64 to 1.12 t ha^{-1}). The lowest grain yield (0.64 t ha^{-1}) was obtained from 0 t ha^{-1} of Leucaena/cattle manure and highest (1.12 t ha^{-1}) from 30 t ha^{-1} (Table 5.4). Grain yield increased by 17 % when 30 t ha^{-1} Leucaena/cattle manure combination was added. Rainwater harvesting techniques show significant effect ($p<0.05$) on grain yields with TC having higher yield which was 31 % and 5 % more than SC and IP respectively. Macia variety yielded more ($p<0.05$) than SV1 over a period of three seasons (2017/18 to 2019/20) (Table 5.4). Sorghum yield was statistically influenced ($p<0.05$) by cropping seasons with higher yield (0.98 t ha^{-1}) observed in 2018/19 and lowest (0.83 t ha^{-1}) in 2019/20 season.

Table 5.4: Effects of variety, RWH and organic resources combination on grain yield

Treatments	Grain yields (t ha^{-1})
Variety	
Macia	0.95
SV1	0.88
P value	**<0.001**
LSD	0.0054
RWH	
IP	0.89
TC	0.94
SC	0.63
P value	**<0.001**
LSD	0.0066
Leucaena/cattle manure combination (t ha^{-1})	
0	0.64
5	0.81
10	0.96
20	1.05
30	1.12
P value	**<0.001**
LSD	0.0086
Season	
2018	0.89
2019	0.98
2020	0.83
P value	**<0.001**
LSD	0.0066

Interactive effects of Leucaena/cattle manure combination and season significantly influenced ($p<0.05$) sorghum grain yields. The highest grain yield was observed in the 2018/19 season from all application rates of Leucaena/cattle manure combination and the lowest yield was recorded in 2019/20 (Figure 5.2). All plots with no amendments of Leucaena/cattle manure combination had the lowest grain yield compared with all treatments applied the amendment (Figure 5.2). However, increase in Leucaena/cattle manure combination application rates, sorghum grain yield increased in all seasons ($R^2 = 0.974$). Significant increases ($p<0.05$) on grain yield were indicated with the use of more than 5 t ha^{-1} Leucaena/cattle manure combination.

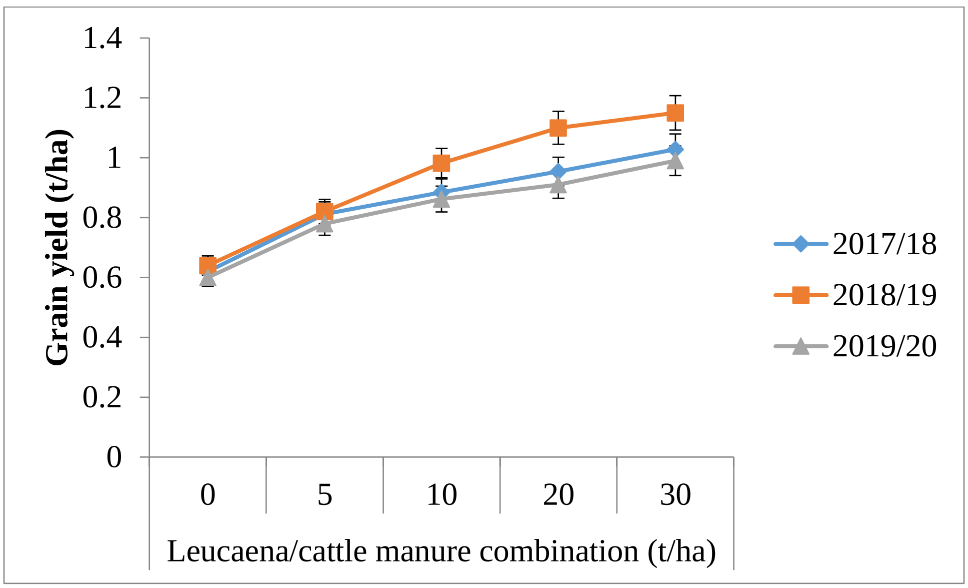

Figure 5.2: The interaction effects of Leucaena/cattle manure application and seasons on grain yield.

Rainwater harvesting techniques and Leucaena/cattle manure combination show significant interactive effects ($p<0.05$) on sorghum grain yields. Sorghum grain yields were significantly lower ($p<0.05$) from standard contour (SC) compared with tied contours (TC) and infiltration pit (IP) at all levels of Leucaena/cattle manure combination (Figure 5.3). No significant variations on grain yields were observed from plots without application of Leucaena/cattle manure. Results showed that grain yields were significantly lower at 0 t ha^{-1} from all RWH techniques compared with all treatments applied Leucaena/cattle manure combination (Figure 5.3). Increase in application rates of Leucaena/cattle manure combination increased sorghum grain yield, with highest yield observed in TCs.

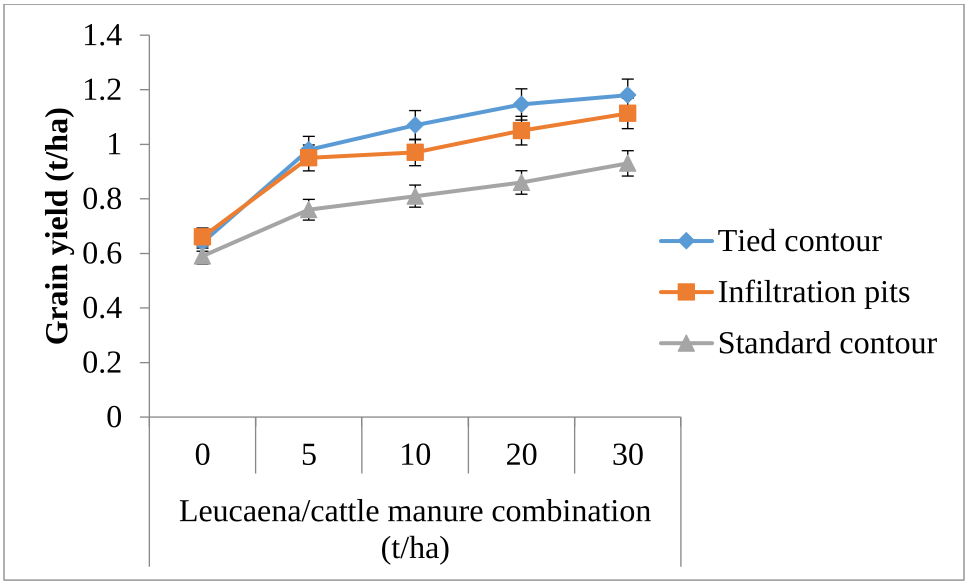

Figure 5.3: The interactions of organic fertiliser resources application and RWH techniques on sorghum grain yield (Three-year average).

Interactive effects of sorghum variety and Leucaena/cattle manure combination significantly ($p<0.05$) affected grain yields. Results showed that Macia variety had significantly higher ($p<0.05$) grain yield compared with SV1, except at 20 t ha^{-1} where yield show no significant differences (Figure 5.4). There were no significant differences in sorghum grain yields between Macia and SV1 variety at control treatments (Figure 5.4). Treatments applied Leucaena/cattle manure combinations showed significant differences ($p<0.05$) in sorghum grain yields compared with the control treatments (no organic resources applied). Macia variety had 13 % higher grain yield compared with SV1 variety at application rate of 30 t ha^{-1} Leucaena/cattle manure combination.

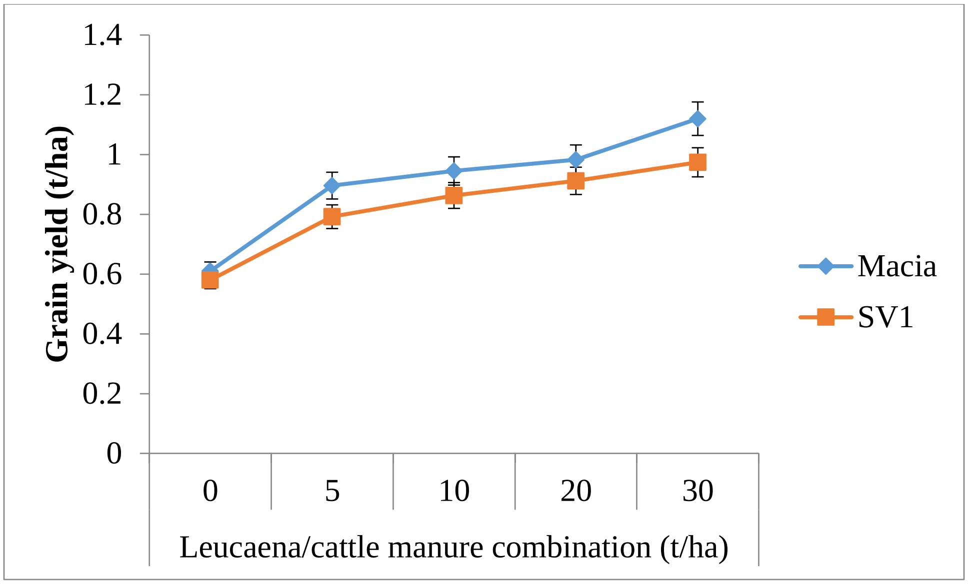

Figure 5.4: The interaction effects of organic fertiliser resources application and sorghum variety on grain yields.

Integrated effects of RWH techniques, sorghum variety and season were significant on sorghum grain yield. Infiltration pit and TC had significant comparable yield among varieties and seasons. Tied contour had significantly higher ($p<0.05$) yields from both varieties and seasons (Figure 5.5). In the 2018/19 season, TC had the highest grain yields under Macia variety and yield decreased in the following order: TC > IP > SC. Under sorghum variety SV1, TC had significantly greater grain yield ($p<0.05$) compared with IP and SC. RWH method of SC show low grain yields which were significantly different ($p<0.05$) from other methods from all seasons and varieties (Figure 5.5). Sorghum grain yield under standard contour show no significant differences ($p>0.05$) among sorghum varieties from 2017/18 to 2019/20.

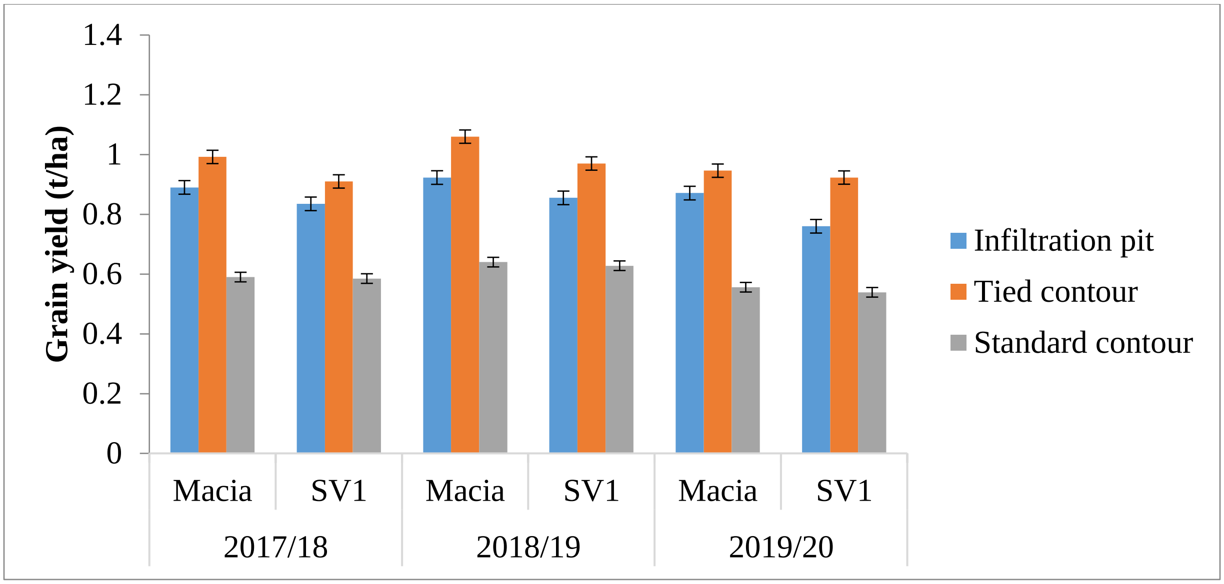

Fig 5.5: Effects of RWH techniques x variety x season interactions on sorghum grain yield.

Interactive effects of sorghum variety, Leucaena/cattle manure combination and season show significant effects ($p<0.05$) on grain yields. Sorghum grain yields show no significant differences ($p> 0.05$) at 5 t ha^{-1} Leucaena/cattle manure combination between both varieties in all seasons (Figure 5.6). Sorghum grain yields were significantly lower ($p<0.05$) for Macia and SV1variety from treatments control treatments compared with treatments applied Leucaena/cattle manure combination. Sorghum grain yield significantly increased with increase in Leucaena/cattle manure application levels as influenced by two varieties and seasons (Figure 5.6). Macia variety had significantly higher grain yields compared with SV1 variety at 10 t ha^{-1} and above in all three seasons (Figure 5.6). Highest yield was observed in 2018/19 season for both varieties from all application rates of Leucaena/cattle manure combination.

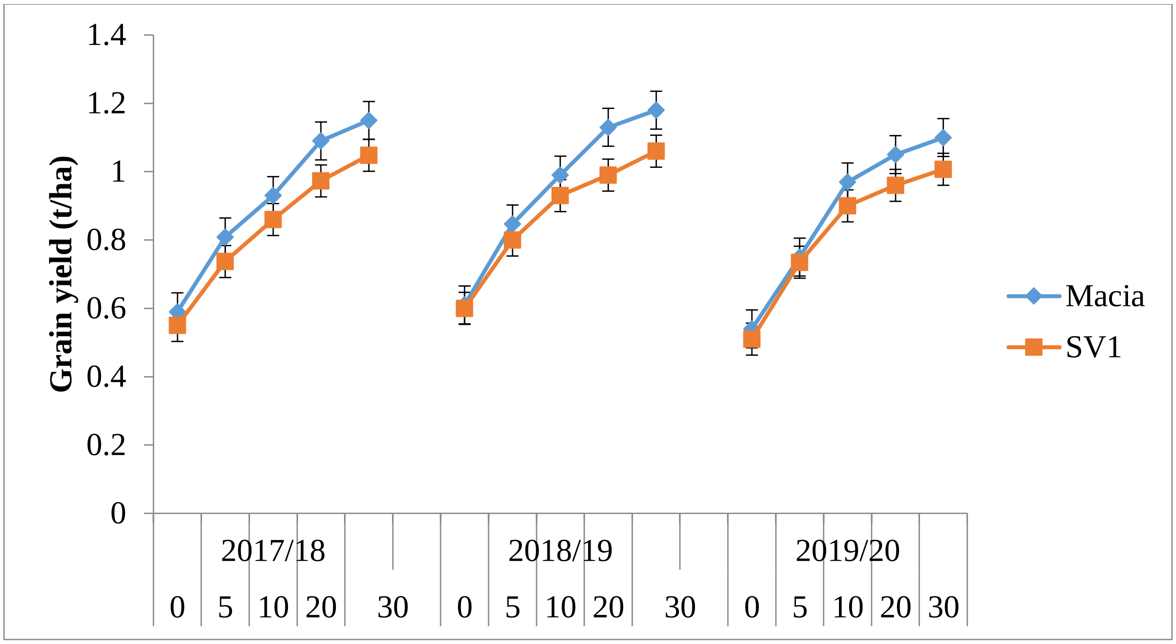

Figure 5.6: Sorghum grain yields as influenced by variety, organic fertiliser resources and season.

5.5.4 Stover yield

Stover yield show significant differences ($p<0.05$) among different quantities of Leucaena/cattle manure combinations. Stover yield improved with increase in application levels of Leucaena/cattle manure combination over three seasons for both sorghum varieties (Table 5.5). It is evident for data in Table 5.5 that increasing application rate of Leucaena/cattle manure combination increased stover yield. The increment followed the trend: 30>20>10>5>0 t ha^{-1} regardless of variety and season. Macia variety had significantly ($p<0.05$) higher stover yield compared with SV1 variety (Table 5.5). All treatments applied with Leucaena/cattle manure combination had higher stover yield compared with those not applied. Treatments applied Leucaena/cattle manure combination increased stover yield by 6-21% for Macia and 4-19% for SV1 over the control treatments in all seasons.

Table 5.5: Effects of Leucaena/cattle manure x sorghum variety and season on sorghum stover yield.

Factor	**Mean Macia stover yields (t ha^{-1})**			**Mean SV1 stover yields (t ha^{-1})**		
Leucaena/cattle manure rate (t ha^{-1})	**2017/18**	**2018/19**	**2019/20**	**2017/18**	**2018/19**	**2019/20**
0	2.282^{e}	2.211^{e}	2.22^{e}	2.259^{e}	2.216^{e}	2.218^{e}
5	2.374^{d}	2.302^{d}	2.394^{d}	2.344^{d}	2.305^{d}	2.318^{d}
10	2.495^{c}	2.564^{c}	2.526^{c}	2.431^{c}	2.508^{c}	2.443^{c}
20	2.642^{b}	2.662^{b}	2.662^{b}	2.553^{b}	2.634^{b}	2.566^{b}
30	2.835^{a}	2.758^{a}	2.763^{a}	2.773^{a}	2.737^{a}	2.723^{a}
P-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
LSD (0.05)	0.034	0.0239	*0.0158*	0.034	0.0239	*0.0158*
CV (%)	*3.8*	*2.8*	*1.8*	*3.8*	*2.8*	*1.8*

Stover yield was significantly influenced ($p<0.05$) by rainwater harvesting techniques for both varieties over three cropping seasons (Table 5.6). Rainwater harvesting techniques of TC and IP had higher stover yields compared with SC, for both sorghum varieties across all seasons. RWH technique of SC gave considerably lower ($p<0.05$) stover yield (Table 5.6). Stover yields followed the trend TC>IP>SC as influenced by sorghum variety and season. Results showed that TC significantly increased ($p<0.05$) sorghum stover yield. Stover yields under TC and IP were comparable although IP gave lower stover yield with smaller margin. That smaller margin indicated that TC and IP can be used to improve sorghum stover yield.

Table 5.6: Effects of RWH techniques, varieties and seasons on sorghum stover yield.

Treatments	**Mean Macia stover yield t ha^{-1})**			**Mean SV1 stover yield (t ha^{-1})**		
RWH techniques	**2017/18**	**2018/19**	**2019/20**	**2017/18**	**2018/19**	**2019/20**
Infiltration pit	2.522^{b}	2.511^{b}	2.487^{b}	2.461^{b}	2.494^{b}	2.433^{b}
Tied contour	2.603^{a}	2.584^{a}	2.61^{a}	2.525^{a}	2.566^{a}	2.564^{a}
Standard contour	2.451^{c}	2.403^{c}	2.443^{c}	2.429^{c}	2.381^{c}	2.365^{c}
P-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
LSD (0.05)	*0.00862*	*0.0138*	*0.0115*	*0.013*	*0.0071*	*0.0092*

5.5.5 Harvesting Index (HI)

Leucaena/cattle manure combination significantly influenced ($p<0.05$) percent harvest index. Results showed that HI increased with increase in application rates of Leucaena/cattle manure combination regardless of sorghum variety and season (Figure 5.7). Higher HI was observed from Macia variety during 2018/19 season at 30 t ha^{-1} of Leucaena/cattle manure combination. Macia variety show high positive correlation (R^2=0.86) in 2017/18 season with low positive correlation (R^2=0.57 and 0.59) in 2018/19 and 2019/20 seasons respectively (Figure 5.7). Sorghum variety, SV1 show high correlation (R^2=0.86, 0.87 and 0.79) with increase in application rates of Leucaena/cattle manure combination across all seasons (Figure 5.7).

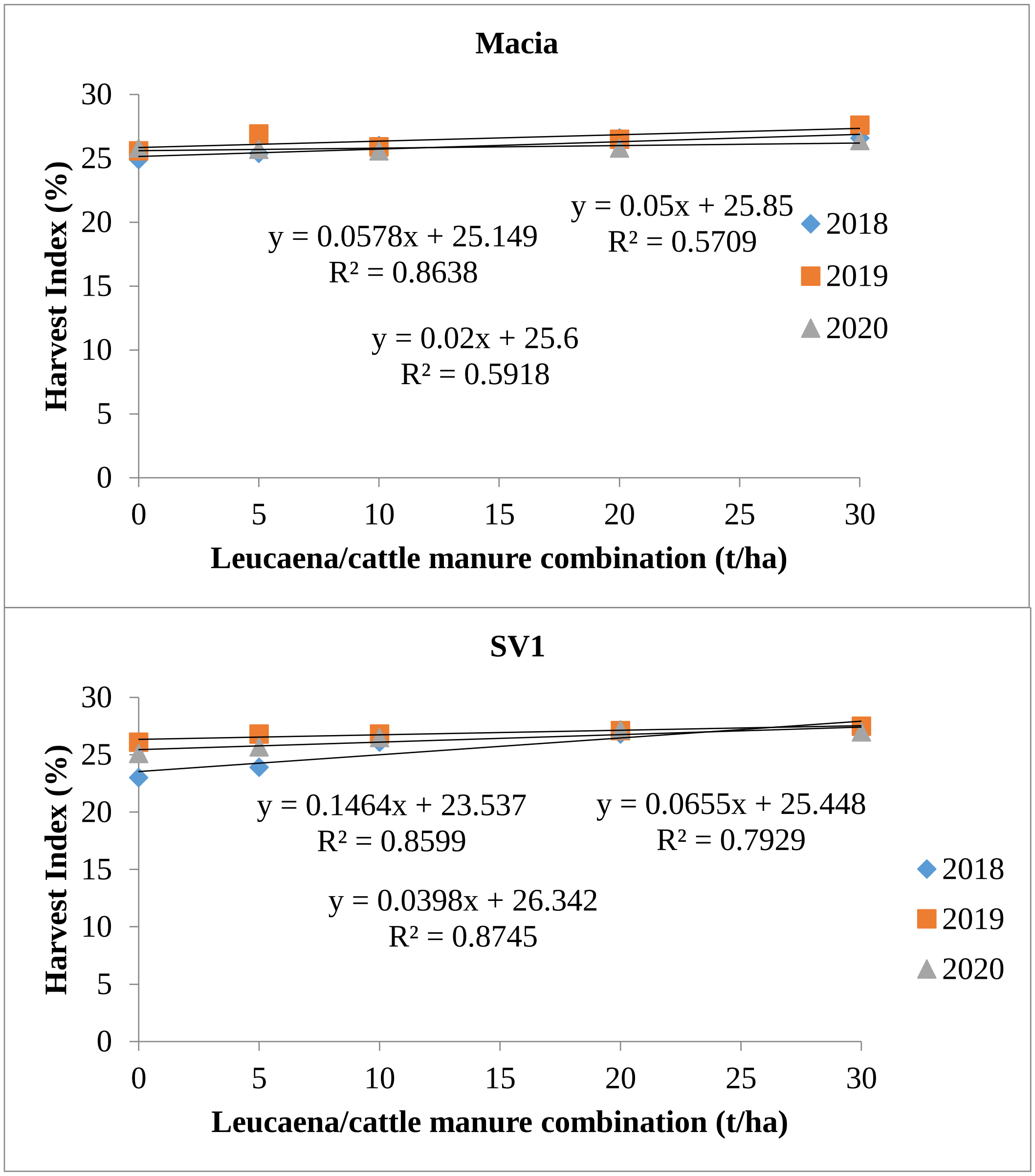

Figure 5.7: Relationships of Leucaena/cattle manure combination on sorghum percent harvest index

Rainwater harvesting techniques had significant effects ($p<0.05$) on HI. Harvest index was highly comparable for TC and IP compared with SC although the differences were relatively small. The TC had statistically higher ($p<0.05$) HI than IP and SC for both varieties across all seasons except in 2018/19 where the effects were not significant (p>0.05; Table 5.7). Interactive effects of Leucaena/cattle manure combination and RWH techniques was not significant.

Table 5.7: Interactive effects of RWH, Variety and season on sorghum HI

Treatment	Mean Macia HI (%)				Mean SV1 HI (%)			
RWH	**2017/18**	**2018/19**	**2019/20**	**Mean**	**2017/18**	**2018/19**	**2019/20**	**Mean**
Infiltration pit	26^{b}	26.7^{a}	25.9^{b}	26.2	25.5^{b}	27^{a}	26.3^{b}	26.3
Tied contour	26.8^{a}	27^{a}	26.2^{a}	26.7	26.1^{a}	27^{a}	26.7^{a}	26.6
Standard contour	24.9^{c}	25.9^{b}	25.4^{c}	25.4	24.7^{c}	26.7^{b}	26^{c}	25.8
P value	*<0.001*	*<0.001*	*<0.001*		*<0.001*	*<0.001*	*<0.001*	
LSD (0.05)	0.668	0.326	0.099		0.512	0.29	0.242	

5.5.6 Sorghum net return

Significant interactive effects (p<0.05) of RWH techniques, Leucaena/cattle manure combination, sorghum variety and season influenced sorghum net return. The highest sorghum net return was observed in 2018/19 season across all Leucaena/cattle manure quantities. The lowest net return was observed during 2019/20 from all treatments applied Leucaena/cattle manure combinations (Figure 8). Treatments with 0 t ha^{-1} Leucaena/cattle manure combination had the lowest sorghum net return across all seasons compared with treatments applied Leucaena/cattle manure (Figure 5.8). Furthermore, increase in application rates of Leucaena/cattle manure combination significantly increased sorghum net return. However, application of 5 t ha^{-1} Leucaena/cattle manure combination had no significant effect (p>0.05) on sorghum net return for all treatments (Figure 5.8). Considerable significant increase (p<0.05) on sorghum net return was shown when Leucaena/cattle manure combination level was above 5 t ha^{-1} (Figure 5.8).

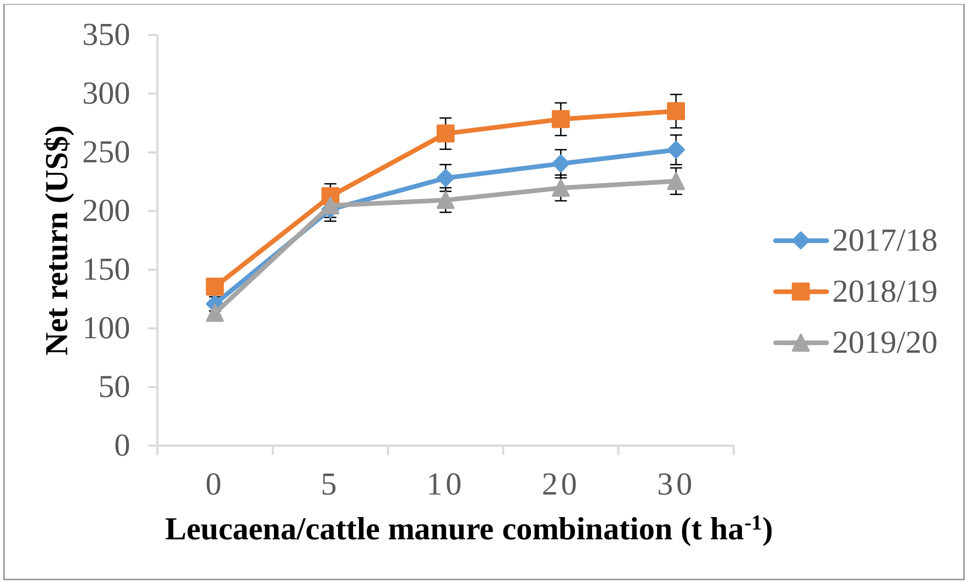

Figure 5.8: Interactive effects of Leucaena/cattle manure and season on sorghum net return.

Interactive effects of varieties and different rates of Leucaena/cattle manure combination show significant effects p<0.05) on net return. Macia variety had considerably greater sorghum net return compared with SV1 except at 5 t ha^{-1} which shows no significant influence on net return (Figure 5.9). There were no significant differences on sorghum net return amongst varieties at 0 t ha^{-1} of Leucaena/cattle manure combination (Figure 5.9). Treatments applied Leucaena/cattle manure combination had significantly higher (p<0.05) sorghum net return than treatments not the amendments. However, application level of 10 t ha^{-1} Leucaena/cattle manure combination show 13 % increment in sorghum net return. This was considerably higher than increments from all other application rates used for both sorghum varieties.

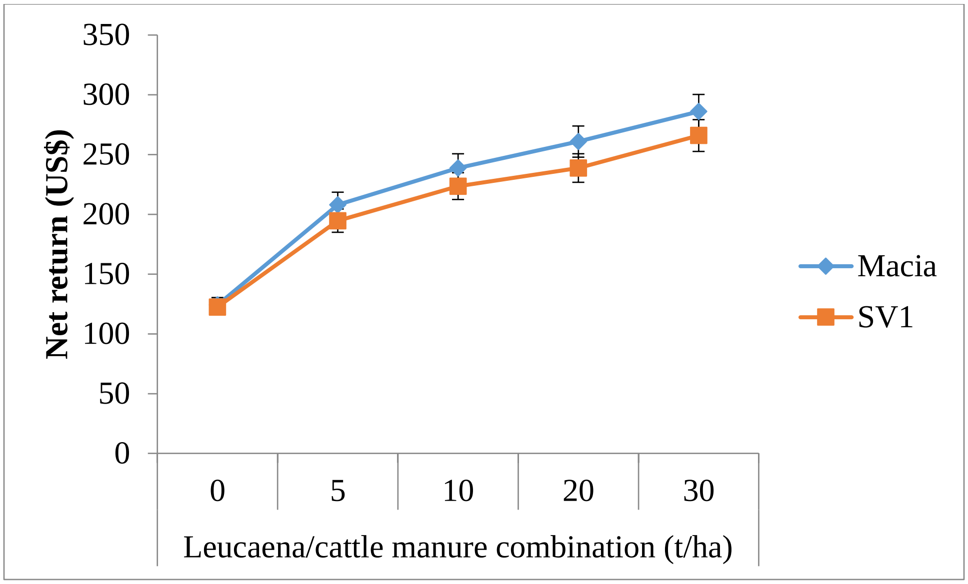

Figure 5.9: Interactive effects of Leucaena/cattle manure and variety on sorghum net return

Net returns were statistically influenced ($p < 0.05$) by interactive effects of sorghum variety, Leucaena/cattle manure combination and season (Figure 5.10). Sorghum net return varied significantly among varieties, application rates and season, with highest net return observed at 30 t ha^{-1} Leucaena/cattle manure combination for both varieties (Figure 5.10). Net return was highest in 2018/19 as influenced by sorghum variety and Leucaena/cattle manure combination. Sorghum net return was lowest in 2019/20 season for both varieties and Leucaena/cattle manure combination levels. Results showed no significant effects on sorghum net return at 5 t ha^{-1} Leucaena/cattle manure combination for both sorghum varieties across all seasons (Figure 5.10).

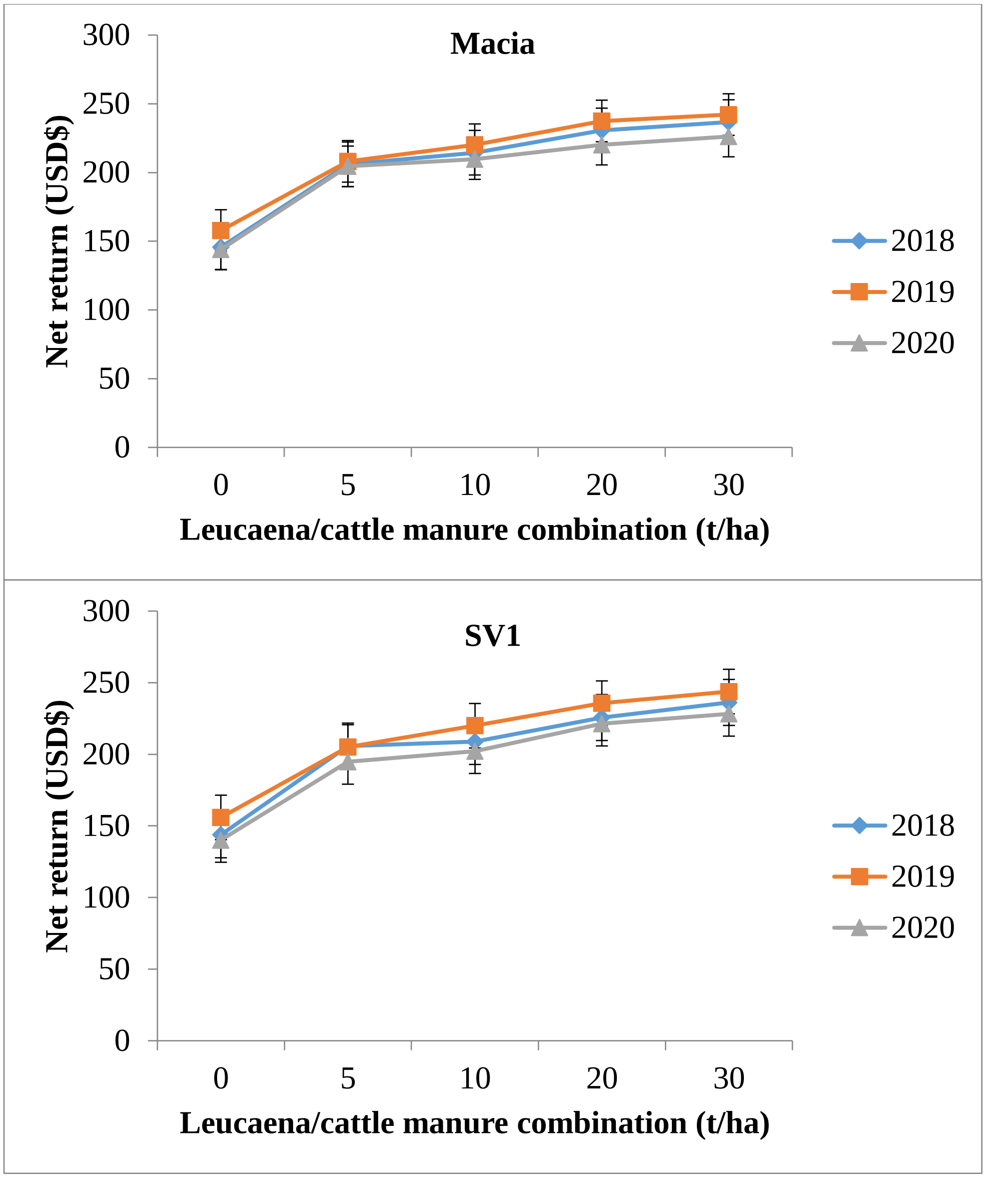

Figure 5.10: Interaction of sorghum varieties, Leucaena/cattle manure and season on sorghum net return.

Net return was considerably influenced ($p<0.05$) by interactive effects of Leucaena/cattle manure combination, rainwater harvesting techniques and variety in 2017/18 and 2019/20, with no statistical differences ($p>0.05$) shown in 2018/19 season (Table 5.8). Net benefits increased across all treatments over three cropping seasons as a result of increased in application levels of Leucaena/cattle manure. Net benefits ranged from US$187.93 to US$263.16 for Macia and US$184.45 to US$257.65 for SV1 variety (Table 5.8).

Table 5.8: Interaction of Leucaena/cattle manure combination RWH and sorghum variety on net return (US$)

		Macia Mean net return (US$)			SV1 Mean net return (US$)		
Leucaena/cattle manure combination (t ha^{-1})	**RWH techniques**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
0		140.6^{ef}	142.87	139.45^{g}	140.25^{fg}	141.7	136.9^{h}
5	Infiltration pit	214.48^{c}	210	197.13^{e}	210.92^{c}	205.4	198.97^{h}
10		232.18^{b}	211.72	214.72^{c}	208.28^{c}	203.85	222.07^{d}
20		227.18^{b}	221.66	220.75^{b}	232.7^{a}	225.34	226.28^{c}
30		230.86^{b}	240.17	224.54^{b}	251.21^{a}	237.41	230.97^{b}
0	Tied contour	145.89^{e}	147.21	140.75^{g}	143.9^{f}	144.65	138.21^{h}
5		221.97^{b}	214.59	228.28^{ab}	184.25^{d}	208.16	211.84^{f}
10		217.47^{b}	219.31	227.59^{b}	193.56^{cd}	225.75	221.15^{d}
20		233.62^{b}	227.18	229.94^{a}	230.86^{b}	229.03	238.22^{a}
30		255.8^{a}	263.16	231.9^{a}	257.65^{a}	248.45	236.49^{a}
0	Standard contour	126.59^{f}	135.79	124.8^{h}	122.12^{g}	129.76	121.58^{i}
5		187.93^{d}	188.85	192.53^{f}	188.85^{d}	201.72	206.32^{g}
10		199.08^{c}	198.16	200.92^{e}	204.59^{cd}	197.24	216.55^{e}
20		203.28^{c}	205.11	208.79^{d}	213.39^{bc}	209.72	221.66^{d}
30		216.01^{b}	215.34	211.66^{cd}	213.51^{bc}	222.7	217.18^{e}
P value		*0.028*	*ns*	*0.001*	*0.028*	*ns*	*0.001*
LSD (0.05)		18.29	11.29	4.15	18.29	11.29	4.15
CV (%)		*5.3*	*3.2*	*2.4*	*5.3*	*3.2*	*2.4*

5.6 DISCUSSION

5.6.1 Soil characterisation

At the beginning of field experiment, pH was acidic but increased after using Leucaena/cattle manure combination over three cropping seasons. This is because organic nutrient sources increase basic cations which have liming effect which reduces exchangeable hydrogen ions (H^+) (Mahmood et al., 2017; Sayği et al., 2021; Sher et al., 2022). Organic manure contains basic cations which acts as buffer and raise soil pH (Si et al., 2016). Application of organic nutrient sources also increased include SOC, nitrogen, exchangeable basic cations (calcium, magnesium) as well as available phosphorous. The use of organic nutrient sources such as Leucaena biomass and cattle manure which improve soil structure and nutrient retention ability hence reduce nutrient loss by leaching (Mamuye et al., 2021). This reduces leaching of basic cations (Si et al., 2016; Timsina, 2018). This seems to increase microbial activities in the soil and reduces leaching of cations in the soil. Application of organic manure increase major nutrients (N, P and K) due to their high content in organic nutrient sources (Si et al., 2016; Mamuye et al., 2021; Mugwe and Otieno, 2021). Organic nutrient sources such as cattle manure produce humic acids which complexes with Aluminium and improve availability of nutrients in the soil (Kubiku et al., 2022a).

5.6.2 Rainfall

High rainfall variability affected the study area together with agroecological region V in Zimbabwe. Rainfall was insufficient, erratic and unreliable in agroecological region V affecting crop production. The growing seasons were affected by mid-season dry spells and low rainfall totals. The site received low rainfall below the long-term average of 450 mm per annum (Nyagumbo et al., 2019; Kugedera et al., 2022). The situation was worsened by recent climate change which triggered an increase in temperatures which decrease rainfall in agroecological region V of Zimbabwe (Tapiwa et al., 2020), especially in the southern and eastern parts of

Zimbabwe where sorghum production is a major crop. Most smallholder farmers rely on rainfed agriculture which is mainly influenced by climatic change (Nyagumbo et al., 2019). Hence, the need to come up with strategies which conserve the little rainfall received in these areas. The techniques which can be adopted include the use of RWH methods in supplementing rainfed agriculture in smallholder farming systems in agroecological region V of Zimbabwe. Climate change shifted start of cropping season from October to mid-November, making it shorter.

5.6.3 Sorghum grain yield

The use of TC and IP represents innovative and sustainable climate smart agriculture options which can be adopted by farmers in dry regions to improve sorghum production. Standard contours were widely used by farmers in most communal arable lands in semi-arid areas. These structures have been neglected because they remove runoff water from fields which can be used to supplement soil moisture content (Nyagumbo et al., 2019; Kubiku et al., 2022a) This contributed to moisture stress to plants, reducing photosynthesis and grain filling processes causing low sorghum grain yields across all seasons. Tied contours and infiltration pits harvest runoff and retain a lot of water which can sustain crops in dry spell periods and droughts (Nyagumbo et al., 2019; Kubiku et al., 2022b; Kugara et al., 2022). Higher sorghum grain yields from TC and IP have been attributed to high soil moisture content during grain filling. Plants take up more water during this stage which contribute to increased enzyme action and photosynthesis, positively influencing allocation of photosynthetic materials to the grain (Mahinda et al., 2018; Zhang et al., 2020). Tied contours and IPs hold water for longer periods, allowing it time to infiltrate and recharge the root zone making it available for plant uptake promoting plant growth and improved crop yields (Nyagumbo et al., 2019; Mandumbu et al., 2021; Kubiku et al., 2022b). Tied contours and IP allow water to penetrate deep in soil and reduces evaporation loss (Kolozsvári et al., 2022). This increases photosynthesis, promote grain filling and seed development leading to higher yields.

These techniques make water available during critical growth stages, making pollination, fertilisation and grain filling successful (Deng et al., 2019; Zhang et al., 2022).

Sorghum grain yield improved with increases in application rates of Leucaena/cattle manure combination. Sorghum grain yield was higher form all treatments applied Leucaena/cattle manure than those not applied. This is attributed to increased soil nutrients availability in the plant rooting zones (Li et al., 2020; Mamuye et al., 2021; Zhang et al., 2022). Control treatments showed stunting which affected growth and yield. Organic fertilisers regulate soil pH eliminating the organic matter deficiency in the soil and ensuring that nitrogen is absorbed more efficiently by the crop (Sayği, 2022). By regulating soil pH, fixation of phosphorous by iron and aluminium hydrous oxides (or sesquioxides) is reduced making it available for absorption by crops (Soma et al., 2018; Sher et al., 2022). This contributed positively towards plant growth and grain development leading to higher yields. Organic nutrient sources improve nitrogen use efficiency (NUE), recovery of macro and micronutrients, resulting in improvements in growth and biomass production traits (Mahmood et al., 2017; Owusu-Sekyere, 2021; Sher et al., 2022). Organic nutrient sources such as Leucaena biomass and cattle manure improve availability of nutrients, soil organic matter (SOM), soil structure and N uptake which resulted in significant increase in protein content hence higher yields (Adekiya et al., 2020).

Organic nutrient sources have high total exchangeable cations and pH which favour decomposition and mineralisation process releasing more cations required by crops. Organic nutrient sources such as cattle manure and legume tree biomass increase soil health (Vanlauwe and Dobermann, 2020). This boosts plant growth, increasing photosynthetic surface area and contributing to improved sorghum grain yields. Results from this study are similar to findings by Kimaru-Muchai et al. (2021) who observed increase in sorghum grain yield after using legume tree biomass. Organic fertiliser (Leucaena/cattle manure combination) boosted plant development by increasing nutrient availability and reducing nutrient loss (Sher et al., 2022). Application of organic fertilisers improves soil health, crop tolerance to stressful conditions and improves grain yields (Aina et al., 2019; Kusvuran et al., 2021). Application of legume tree biomass such as Leucaena biomass, cattle manure or compost improves soil structure, lower soil bulk densities and increase total soil porosity. This increases soil water retention, reduce leaching and improve nutrient absorption by plants causing increased grain yield.

Grain yield was considerably affected by interactive effects of Leucaena/cattle manure combination and season, with higher yields observed in 2018/19 for all rates. This could be attributed to residual effect of organic resources (Leucaena/cattle manure combinations) from previous seasons which decomposed during the first rains releasing nutrients. Long term application of organic manure increased availability of nitrogen (N), phosphorous (P) and potassium (K) elements in the soil which improve photosynthesis, root growth and tolerance to various stresses (Guo et al., 2018; Ye et al., 2019; Kusvuran et al., 2021). Availability of K and N in the soil alleviates drought stress to crops (Saudi et al., 2017; Haider et al., 2021) especially in drought prone areas where sorghum is grown. Even distribution of rainfall in 2018/19 season improved soil moisture content, improved nutrient absorption by sorghum crops promoting biochemical processes such as photosynthesis and protein synthesis which improved yield. Leucaena/cattle manure combination increased soil total porosity, soil moisture content, growth and P uptake by crops causing higher yields (Zahida et al., 2017). However, low yield observed in 2019/20 season from all application rates of Leucaena/cattle manure combination may be attributed to poor rainfall distribution and drought stress which reduced photosynthetic area and grain filling. This concurs with Nyagumbo et al. (2019) and Kubiku et al. (2022a) who reported low grain yields from seasons associated with low rainfall and high variability which negatively affected pollination, fertilisation and grain filling.

Grain yield show significant difference with interaction of Leucaena/cattle manure and RWH technologies compared with SC. Similar studies by Mahinda et al. (2018) and Kubiku et al. (2022b) reported improvements in grain yields from interactive effects of nutrient sources and RWH techniques. Organic nutrient sources increase available macro and micronutrients whereas RWH techniques make water available for plants. This engineer crop tolerance against several abiotic stresses (Fahad et al., 2021; Owusu-Sekyere, 2021) increase crop growth and development which increase crop yields. Rainwater harvesting technologies of TC and IP had considerably higher yield in combination with Leucaena/cattle manure compared with SC. This is because organic nutrient sources increase soil total porosity, water retention and nutrient availability. Combining organic fertilisers with RWH techniques enhance nutrient absorption during grain filling which is needed for protein synthesis causing heavier grains to be produced. However, besides increasing soil fertility, Leucaena/cattle manure combination improves soil microbial population which play an important role in improving decomposition and mineralisation making nutrients available to sorghum crops and increase grain yield especially when integrated with RWH techniques (Mugwe et al., 2019; Gram et al., 2020; Tapiwa et al., 2020). The uses of organic fertiliser and rainwater harvesting techniques can increase nutrient content, mitigating climate change and sorghum production in Sub-Saharan African countries (Mugwe and Otieno, 2021).

Sorghum variety Macia had higher yield than SV1 variety under all application rates of Leucaena/cattle manure combination. This might have been caused by differences in genetic makeup of the varieties and response to environmental factors in agroecological region V. Macia variety is dominantly grown by several farmers in agroecological region V because of its drought tolerance (Kubiku et al., 2022a) compared with SV1. SV1 variety was mainly affected by low rainfall during its grain filling stage and this contributes to low yield. Furthermore, Macia variety produced significantly higher yield than SV1 in all seasons with interaction of RWH technologies. This is because Macia variety is highly tolerant to environmental stress and thrives better than SV1 in semi-arid areas (Kugedera et al., 2022). Tied contour and IP collect and store water which improves soil moisture content, making it available throughout the growing season (Nyagumbo et al., 2019; Kubiku et al., 2022a).

5.6.4 Sorghum stover yield

Higher stover yield observed after use of Leucaena/cattle manure combination were related to improvements in N, P and K availability which increased plant growth and development. Availability of P promote root growth and development while K alleviate drought stress by allowing crops take up more water and reduce transpiration rate (Haider et al., 2021). Leucaena/cattle manure combinations improve exchangeable cations and soil organic carbon which increased microbial population. These microbes play an important role in decomposition of organic materials making nutrients available for absorption (Han et al., 2016). Absorbed nutrients stimulate action of plant growth regulators such as gibberellins which promote plant growth and development. Organic manures increase water retention and soil moisture content which facilitate decomposition and mobilisation of nutrients to promote plant growth and development hence higher stover yields (Han et al., 2016). Related researches by several authors reported improved sorghum yields through application of organic nutrient sources at different rates (Shuaibu et al., 2018; Kisinyo et al., 2019). Basing on results from this study, the use of 10 t ha^{-1} Leucaena/cattle manure indicated higher yield increment which was slightly lower than yield from application rates of 20-30 t ha^{-1}. Yield increment was poor with an additional of 10 t ha^{-1} making application rates of 20 and 30 t ha^{-1} less compatible. Sorghum stover was significantly higher from TC than IP and

SC. This could be attributed to improved water retention from the use of TC which increased nutrient absorption promoting plant growth producing higher stover yield. Macia variety had higher stover yield compared with SV1. This might have been attributed to differences in genetic makeup and Macia variety is drought tolerant compared with SV1. Furthermore, further studies can be done to analyse N, P and K uptake by plants and analyse stover to determine these nutrients.

5.6.5 Harvest Index (HI)

Harvest index was significantly improved with increase in application of Leucaena/cattle manure combination. This can be linked to improvements in physiological mechanisms such as stress tolerance, photosynthesis and grain filling caused by nutrient availability in the soil. Improvements in these processes enhance plant growth and higher yields which translated to high sorghum HI (Hakeem et al., 2018). Differences in HI between Macia and SV1 varieties were due to their genetic differences. Improvements in HI can be achieved through breeding making the varieties more tolerant to abiotic stress to increase growth and yield. Tied contours and IP have the potential to mitigate crucial moisture deficit, allowing more water to be retained in the rhizosphere promoting growth, nutrient absorption and nutrient accumulation in the grains (Mupangwa et al., 2016; Mahinda et al., 2018). This contributed to higher grain and stover yield which transform to higher HI compared with that from SC. Standard contour collect runoff water and dispose it off the field, causing water deficit which reduces nutrient absorption, cause wilting and reduces plant growth. This has the potential to reduce HI.

5.6.6 Sorghum net return

Relatively low net return was caused by low application rates of Leucaena/cattle manure combination which reduced sorghum production. There is need for adding more quantities of organic nutrient sources to improve nutrient content especially in sandy soils which widely cover most smallholder farming areas in Zimbabwe. Increasing application rates of Leucaena/cattle manure combination improve nutrient availability in the soil, reduce the need for costly mineral fertiliser and reduce cost of production. Since organic manure decompose slowly and release nutrients throughout the growing season making constant supply of nutrients which promote plant growth and higher yields (Kimaru-Muchai et al., 2021). Although transport and labour costs increase with quantity of Leucaena/cattle manure combination, yield increment caused by these quantities produce huge profits to farmers. RWH treatments without amendments show that the use of RWH techniques alone does not have lucrative net returns but farmers can realise significant net benefits when they combine them with nutrient sources to boost yields and profits (Moswetsi et al., 2017; Kimaru-Muchai et al., 2021). Higher net return from Macia variety at low application rates compared with SV1 was because Macia is a drought tolerant variety which thrives better in semi-arid areas. Interaction of RWH techniques, Leucaena/cattle manure, sorghum variety and season had better net returns compared with other treatments. This may be attributed to the fact that the combination of organic fertiliser resources and RWH techniques has the potential to mitigate moisture stress, improve nutrient availability in the soil, plant growth and produce higher yields. Higher yields contributed towards high net return which may be lucrative to smallholder farmers. Sorghum net return was low in 2019/20 season compared with all other seasons. This may be caused by long mid-season droughts and dry spell periods experienced in 2019/20 season which contributed immensely towards low sorghum yield and net return.

5.7 CONCLUSION

The use of Leucaena/cattle manure combination has a capacity to restore soil fertility, improve sorghum production, and economic benefits to farmers in semi-arid areas. Rainwater harvesting techniques of TC and IP improved soil moisture content in the plant root zone, sorghum grain yield and reduce the effects of moisture stress in semi-arid areas. Leucaena/cattle manure combination increased the photosynthetic capacity, plant growth and development by making nutrients available in the plant root zone. Tied contours and infiltration pits also accelerated these processes by capturing rainwater and allow its utilisation by plants. Crop productivity in semi-arid areas of Zimbabwe largely depends on rainfall which is low and poorly distributed. High cost of mineral fertiliser also reduced net benefits for farmers. However, the use of organic nutrient sources, Macia variety, tied contours and infiltration pits have greater advantages compared with use of standard contours and SV1 variety. Organic nutrient sources regulate soil pH; improve soil structure, microbial population and total porosity which reduce chances of leaching of basic actions. Macia variety is drought tolerant and can survive abiotic stresses in semi-arid areas compared with SV1, producing better yields. Tied contours and infiltration pits have the capacity to capture small amounts of rainfall received, store it and allow its utilisation by crops during dry periods to mitigate moisture stress, improve photosynthetic capacity and grain yield. Integrating organic fertiliser, Macia variety, tied contour or infiltration pits have the capacity to boost sorghum production and increase net benefits to smallholder farmers. The genetic make-up of Macia variety makes it a suitable sorghum variety to be grown by farmers in semi-arid areas. Application rate of 10 t ha^{-1} Leucaena/cattle manure show higher yields increment per tonne and this can be combined with Macia variety and TC to improve food security. The cost of constructing tied contours and infiltration pits is higher than that of standard contour but this cost can be compensated with higher net benefits from using tied contours and infiltration pits in combination with organic manure. However, there is need to evaluate these strategies on large scale in semi-arid areas to evaluate their economic feasibility. However, future studies can evaluate the effects of various levels of organic nutrient sources on soil physiochemical parameters including bulk density and soil moisture content. Further studies can also evaluate the effects on organic nutrient sources on NUE, agronomic efficiencies and grain nutrient content under different application rates of organic amendments.

To come up with clear recommendations to smallholder farmers about the use of Leucaena, there is need to augment Leucaena biomass with NPK fertiliser (7%N:14%P_2O_5:7K_2O) which farmers has been using but at reduced levels to determine their effects on sorghum yields, agronomic efficiency and rainwater use efficiency.

CHAPTER 6: INTEGRATING MINERAL WITH ORGANIC FERTILISER RESOURCES AND RAINWATER HARVESTING FOR INCREASED SORGHUM YIELD, RAINWATER USE EFFICIENCY AND AGRONOMIC EFFICIENCY IN SEMI-ARID ZIMBABWE

ABSTRACT

Food security in semi-arid regions is threatened by declining soil fertility, soil moisture stress and long frequent droughts as a result of erratic rainfall. Therefore, the objective was to assess the effects of augmenting *Leucaena leucocephala* (Leucaena)biomass (organic manure) with mineral fertiliser on rainwater use efficiency, agronomic efficiency, grain and stover yields for two sorghum varieties (Macia and SV1) under rainwater harvesting techniques. The experiment was laid out in a split-split plot arrangement with rainwater harvesting techniques at three levels (tied contour, infiltration pit and standard contour as a control) as main plot factor, with Leucaena biomass + NPK fertiliser at five levels (NPK (0, 25, 50, 100 and 150 kg ha^{-1}) and Leucaena biomass (0, 2.5, 5, 10 and 15 t ha^{-1}) as subplot factor and two levels of sorghum variety (Macia and SV1) as sub-sub plot factor over three cropping seasons. Data collected include rainwater use efficiency, agronomic efficiency, grain and stover yields. Results showed that tied contours have significantly ($p \leq 0.05$) higher grain and stover yields from all varieties and seasons. Regardless of sorghum variety, tied contours had significant ($p \leq 0.05$) sorghum grain and stover yield followed by infiltration pits and lastly standard contours. Grain and stover yields improved with increasing levels of Leucaena biomass + NPK fertiliser combination. Highest grain yields observed were 1.146 t ha^{-1} (Macia) and 1.1 t ha^{-1} (SV1) from tied contour + 15 t ha^{-1} biomass + 150 kg ha^{-1} NPK fertiliser (10.5 N+ 21P_2O_5 + 10.5 K_2O kg ha^{-1}) treatments. Rainwater use efficiency was significantly ($p \leq 0.05$) higher from tied contours compared with infiltration pits and standard contour. Rainwater use efficiency was statistically ($p \leq 0.05$) influenced by increasing application levels of Leucaena biomass + NPK fertiliser in all seasons. Agronomic efficiencies were considerably ($p \leq 0.05$) affected by rainwater harvesting, Leucaena biomass +NPK fertiliser and interaction of all factors. It was concluded that Leucaena biomass +NPK fertiliser, tied contours and infiltration pits improve sorghum yields. Augmenting 2.5 t ha^{-1} biomass with 25 kg ha^{-1} NPK fertiliser (1.75N + 3.5 P_2O_5 + 1.75 K_2O kg ha^{-1}) under tied contours and Macia have better agronomic efficiencies.

Keywords: Rainwater harvesting; *L. leucocephala*; NPK fertiliser; sorghum; semi-arid regions; sandy soils.

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6.1 INTRODUCTION

Nutrient management is a key factor under rain-fed agriculture to improve food security in Sub-Saharan Africa (SSA) because agricultural production is failing to meet food demands (Gram et al., 2020). Small holdings in semi-arid regions are mainly affected by excessive nutrient loss through surface runoff which causes poor soil fertility. This causes soils in semi-arid regions to suffer on low nutrient status and efficiencies especially nitrogen (N) which is the most limiting nutrient (Cobo et al., 2010; Tully et al., 2015; Zingore et al., 2015; Gram et al., 2020). To increase efficiency of rainfed agriculture in meeting food requirements, there is need to increase nutrient concentration in agricultural systems. Sustainable nutrient intensification is a key aspect in reducing food insecurity and soil degradation. Many farmers in SSA have been applying inadequate organic and inorganic fertilisers, failing to meet required levels needed in improving soil nutrient status and increasing crop yields (Mucheru-Muna et al., 2014; Murimi et al., 2020).

Continuous conventional cultivation and monoculture have resulted in soil degradation causing loss of soil organic matter, increased soil erosion and reduced crop yields. Application of organic nutrient sources such as *Leucaena* biomass has the capacity to increase soil organic matter, microbial population and improve soil structure (Mafongoya and Dzowela, 1999). Organic nutrient sources can be augmented with mineral fertiliser at reduced rates to reduce soil acidity and increase nutrient availability. The use of organic nutrient sources release nutrient slowly in the plant root zone hence increase nutrient availability to crops (Muchai et al., 2020). By contrast, inorganic nutrient sources have the capacity to quickly release nutrients and maintain positive nutrient balances in the soil thereby increasing crop growth and yields (Hakeem et al., 2018). The use of organic and inorganic nutrient sources has been reported to increase sorghum grain and stover yields (Mahinda et al., 2018).

Climate change is another factor which negatively affect crop production in SSA (Nyagumbo et al., 2019). Rainfall variability is increasing rapidly in many semi-arid areas of Africa, especially marginalised areas of SSA where sorghum is a staple food. Sorghum is grown under rainfed conditions in areas characterised with low and erratic rainfall (Kilasara et al., 2015; Hakeem et al., 2018; Masaka et al., 2019). Performance of sorghum is mainly affected by soil moisture stress and declining soil fertility resulting in low grain yields (Masaka et al., 2019). Sorghum grain yields have been declining in most marginalised areas due to low soil fertility amendments for example in Zimbabwe grain yield averages at 532kg ha^{-1} (Chiduza et al., 1995; Twomlow et al., 2008). There is need to adopt soil fertility management options to improve nutrient availability in the plant root zone and increase crop yields (Njeru et al., 2013; Vanlauwe et al., 2014) particularly sorghum in semi-arid regions. However, soil moisture in semi-arid areas also contribute to low sorghum yields hence the need to adopt rainwater harvesting techniques to improve soil moisture (Zougmoré et al., 2004, Ayanlade et al., 2018; Muchai et al., 2020). Integration of organic and inorganic nutrient sources with RWH techniques can improve soil nutrients status, water retention and grain yields (Zougmoré et al., 2003; Rockstrom et al., 2010; Zougmoré et al., 2014). Several authors (Nyakudya et al., 2014; Kilasara et al., 2015; Nyamadzawo et al., 2015; Nyagumbo et al., 2019; Chilagane et al., 2020; Mandumbu et al., 2021) reported that rainwater harvesting techniques reduced surface runoff, harvest a lot of rainfall, store it and sustain plant during dry spell. This combination brings in climate smart agriculture which has the potential to improve sorghum production in semi-arid regions. Therefore, the objective was to assess the effects of augmenting *Leucaena leucocephala* biomass with mineral fertiliser on rainwater use efficiency, agronomic efficiency, grain and stover yields for two sorghum varieties (Macia and SV1) under rainwater harvesting techniques.

6.2 MATERIALS AND METHODS

6.2.1 Study site

The study was carried out as on-farm experiment in ward 11 (20º13.441′ S and 30º28.656′ E, 775 m above sea level) of Chivi District, which is located at 78 km west of Masvingo in south-eastern part of Zimbabwe. The area has characteristics as described in section 4.2.1.

6.2.2 Soil sampling and analysis

Soil samples were collected and analysed using the procedure described in section 4.4.2.

6.2.3 Experimental design and treatments

A completely randomised block design was used with treatments arranged in a split-split plot. Rainwater harvesting methods were used as main treatment factor at three levels (infiltration pits, tied contour and standard contour) with Leucaena biomass +NPK fertiliser used as sub-plot factor at five application rates ($L_0(NPK)_0$ (control), $L_{2.5}(NPK)_{25}$, $L_5(NPK)_{50}$, $L_{10}(NPK)_{100}$ and $L_{15}(NPK)_{150}$) where $L_{2.5}(NPK)_{25}$ contain 2.5 t ha^{-1} Leucaena biomass + 25 kg NPK ha^{-1} (1.75N + 3.5 P_2O_5 + 1.75 K_2O kg ha^{-1}), $L_5(NPK)_{50}$ (50 t ha^{-1} Leucaena biomass + 50 kg NPK ha^{-1} (3.5N + 7 P_2O_5 + 3.5 K_2O kg ha^{-1}), $L_{10}(NPK)_{100}$ (10 t ha^{-1} Leucaena biomass + 100 kg NPK ha^{-1} (7N + 14 P_2O_5 + 7 K_2O kg ha^{-1}) and $L_{15}(NPK)_{150}$ (15 t ha^{-1} Leucaena biomass + 150 kg NPK ha^{-1} (10.5N + 21 P_2O_5 + 10.5K_2O kg ha^{-1}) and two sorghum varieties (Macia and SV1) were tested as sub-sub plot. Treatments were replicated three times. The experiment ran over three consecutive cropping seasons: from 2017/18 through to 2019/20. Tied contours used were constructed using cross ties after every 5 m producing structures with the following dimensions: 5 m in length x 0.5 m breath x 1 m deep. Cross tie was constructed by leaving soil between each contour. Infiltration pits (IP) were constructed along the contour and measured 3 m in length x 0.5 m breath x 1 m deep with spacing of 0.5 m in each contour. Standard contour of 35 m long was a control treatment.

Rainwater harvesting techniques were spaced 1.5 m apart. Each sub plot measured 20 m long and 5 m wide, replicated three times. Two rows at edge of every plot were used as buffer lines. Sub-sub plots measured 2 m long x 4.5 m wide and replicated three times. The site had an average slope of 3 %.

Land preparation was done using animal drawn mouldboard plough to a depth between15 cm and20cm. Ploughing was done between the block and did not interfere with rainwater harvesting methods. Leucaena biomass was incorporated at rates of 0, 2.5, 5, 10 and 15 t ha^{-1} and NPK fertiliser at a rate of 0, 25, 50, 100 and 150 kg ha^{-1} mixed together. Leucaena biomass used was obtained from 5-year-old trees which contained 3.5 % nitrogen, 0.2 % P_2O_5, 0.42% magnesium, 1.35 % calcium and 1.8 % K_2O. NPK fertiliser used contains 7 % N, 14 % P_2O_5 and 7% K_2O. The recommended application rate of NPK fertiliser is 350 kg ha^{-1} (24.5N +49P_2O_5 + 24.5 K_2O kg ha^{-1}). Planting was done on 20 December 2017, 12 December 2018 and 30 December 2019 for 2017/2018, 2018/2019 and 2019/2020 seasons respectively. Sorghum seeds were sown using spacing of 0.75 m between rows and 0.2 m within rows achieving plant population of 66666plants ha^{-1}. Weeding was done twice using hand hoe. Top dressing of sorghum plants was done using ammonium nitrate fertiliser (34.5 % N) at a rate of 150 kg ha^{-1} (51.75 N kg ha^{-1}). Split application was done at a rate of 26 N kg ha^{-1} (75 kg AN ha^{-1}) per split, 3 and 7 weeks after emergence. Fall armyworm was controlled using Demise 65EC during vegetative and prior flowering stage.

6.2.4 Sorghum varieties

The experiment used two sorghum varieties (Macia and SV1) as test crop. Macia is an open pollinated variety which is widely grown in Chivi due to its drought tolerance and it thrives well under harsh conditions. Macia variety attains its physiological maturity with an average of 115-

120 days. The variety has a yield potential of 3-6 t ha^{-1} under favourable conditions (Gasura et al., 2015). SV1 is an open pollinated semi-dwarf variety with an average of 115-125 days to maturity. The variety was developed in Zimbabwe in 1985 (Chikobvu, 2008). Yield potential of SV1 ranges between 3-6 t ha^{-1} under optimum condition. The variety has not been widely grown in Chivi and was used to compare its performance with Macia.

6.3 DATA COLLECTION

6.3.1 Rainfall

Rainfall was measured using a standard rain gauge installed at the experimental site throughout the growing seasons. Rainfall data were collected every morning at 8 am and recorded in the book. Monthly rainfall was calculated by summing up all daily values. Days dry per month were determined.

6.3.2 Grain and stover yield

Grain and stover yields were harvested from 9 m^2 per treatment plot. Grain and stover yields were determined using procedure described in section 4.2.2.

6.3.3 Rain Water Use Efficiency (RWUE)

Rain water use efficacy was determined using procedure described in section 4.3.3.

6.3.4 Agronomic Efficiency (AE)

The agronomic efficiency was calculated as crop yield increase from control treatment divided by amount of amendment applied as given below (Gram et al., 2020, equation 7):

$$\text{Agronomic efficiency (AE)} = \frac{\text{Grain yield of fertilised plot (kg)} - \text{grain yield in control plot(kg)}}{Amount\ of\ ammendment\ applied\ (kg)} \quad \text{...equation 7}$$

6.4 STATISTICAL DATA ANALYSIS

Data were subjected to two-way analysis of variance (ANOVA) for split-plot analysis using GenStat 14th edition. The least significance differences (LSD) were used to separate significant means at 5 % level. Regression analysis was done using Microsoft Excel to estimate correlation coefficient (r^2).

6.5 RESULTS

6.5.1 Rainfall

Rainfall totals received over three experimental seasons were 295 mm (2017/18 and 2019/20) and 305 mm received during 2017/18 and 2019/20 seasons (Table 6.1). The least rainfall was received in 2018/19 cropping season. The experimental area experienced the longest long dry spell (24 days) in the 2018/19 cropping season from mid-March to early April 2019. The seasonal rainfall totals received in each of the season (305, 295 and 305 mm respectively) were below a 30-year average of 335 mm received in Chivi during the growing season (Table 6.1). Table 6.1 shows that climate change affected the experimental site as there was a shift in growing season start and cessation.

Table 6.1: Seasonal monthly rainfall distribution during experiment (2018-2020).

	Month						
Season	**October**	**November**	**December**	**January**	**February**	**March**	**April**
2017/18	0	42	65	78	60	48	12
2018/19	0	25	60	80	68	52	10
2019/20	0	30	95	88	54	38	0
Dry days (Average)	30	23	19	18	20	17	25
Rainfall (30-year mean)	10	28	69	80	70	51	27
Dry days (30 years mean)	25	22	16	14	15	13	17

Dry days: days not received rainfall per month

6.5.2 Soil characterisation

Soil texture was classified as sandy loam soil with 76 % sand, 21% silt and 3 % clay. The soil was slightly acidic (pH=5.8) with 0.02% total nitrogen and 0.27% SOC. Exchangeable cations were 0.11 $cmol_c\ kg^{-1}$ sodium, 0.15 $cmol_c\ kg^{-1}$ potassium, 0.68 $cmol_c\ kg^{-1}$ magnesium and 1.25 $cmol_c\ kg^{-1}$ calcium during the 2017/18 cropping season before planting (Table 6.2). An increase in all other soil parameters was observed except for sodium which decreased with application of Leucaena biomass + NPK fertiliser (Table 6.2). The residual effect of Leucaena biomass has contributed towards increase in total nitrogen, pH and exchangeable cations.

Table 6.2: Physiochemical characteristics of soil from experimental field

Soil parameter	Composition over three seasons		
	2017/18	**2018/19**	**2019/20**
pH ($CaCl_2$)	5.8	6.1	6.1
SOC (%)	0.27	0.72	0.84
Total Nitrogen (%)	0.02	0.02	0.023
P_2O_5 mg kg^{-1}	3.46	4.87	4.92
Exchangeable K g $cmol_c$ kg^{-1}	0.15	0.19	0.2
Calcium $cmol_c$ kg^{-1}	1.25	1.32	1.35
Magnesium $cmol_c$ kg^{-1}	0.68	0.69	0.71
Sodium $cmol_c$ kg^{-1}	0.11	0.082	0.056
CEC $cmol_c$ kg^{-1}	2.19	2.28	2.32

6.5.3 Effects of RWH techniques on sorghum grain and stover yields

Rainwater harvesting techniques significantly ($p \leq 0.05$) affected sorghum grain yields for both varieties, with the trend tied contours having the greatest yield ($p \leq 0.05$) followed by infiltration pits and lastly the standard contour (Table 6.3). The same trend was observed on stover yields from both varieties across all the three seasons. The highest mean grain yield of 0.876 t ha^{-1} under tied contour + Macia and a lowest (0.743 t ha^{-1}) from standard contour + SV1 treatments were observed over a period of three years. Stover yields ranged from 2.482 t ha^{-1} and the lowest was 2.305 t ha^{-1} observed from the standard contour. Mean stover yield was highest (2.447 t ha^{-1}) and a lowest (2.326 t ha^{-1}) from tied contours and standard contours over three years respectively (Table 6.3).

Table 6.3: Effects of RWH on sorghum grain and stover yields

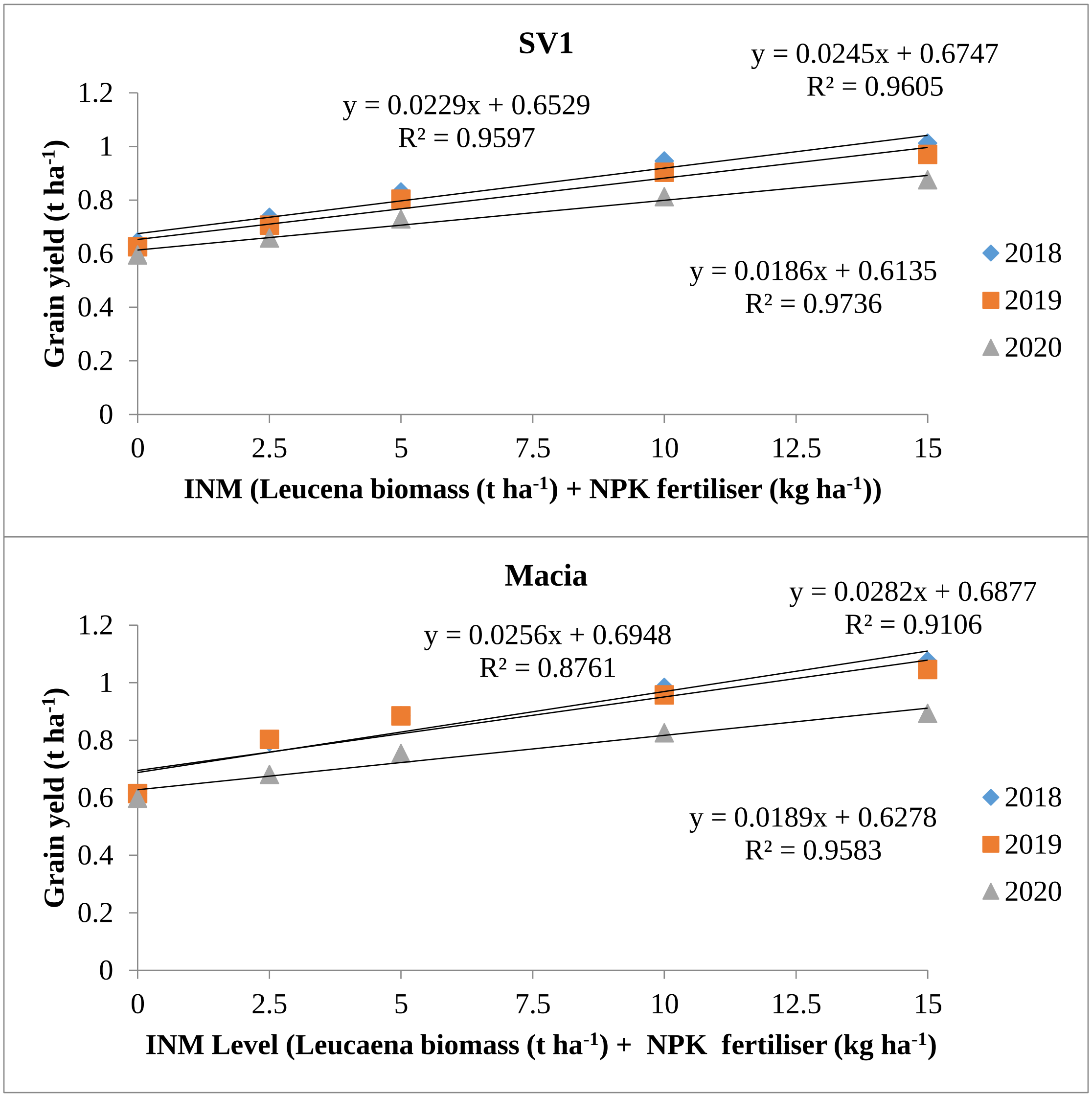
RWH techniques	Mean Macia grain yield (t ha^{-1})				Mean SV1 grain yield (t ha^{-1})			
	2018	**2019**	**2020**	**Mean**	**2018**	**2019**	**2020**	**Mean**
Standard contour	0.806^{b}	0.811^{b}	0.719^{b}	0.779	0.766^{b}	0.757^{c}	0.705^{b}	0.743
Infiltration pits	0.877^{ab}	0.86^{ab}	0.748^{ab}	0.823	0.844^{ab}	0.787^{b}	0.737^{ab}	0.789
Tied contour	0.93^{a}	0.911^{a}	0.786^{a}	0.876	0.891^{a}	0.862^{a}	0.761^{a}	0.838
P-value	*<0.05*	*<0.05*	*<0.05*		*<0.05*	*<0.05*	*<0.05*	
$LSD_{0.05}$	0.0849	*0.0521*	0.0439		0.0849	*0.0521*	0.0439	
	Mean Macia stover yield (t ha^{-1})				**Mean SV1 stover yield (t ha^{-1})**			
Standard contour	2.32^{c}	2.316^{a}	2.343^{c}	2.326	2.317^{c}	2.305^{b}	2.394^{a}	2.339
Infiltration pits	2.413^{b}	2.404^{ab}	2.377^{b}	2.398	2.402^{b}	2.387^{ab}	2.328^{b}	2.372
Tied contour	2.482^{a}	2.461^{a}	2.398^{a}	2.447	2.481^{a}	2.451^{a}	2.383^{a}	2.438
P-value	*0.023*	*NS*	*<0.05*		*0.023*	*NS*	*<0.05*	
$LSD_{0.05}$	0.0548	0.1048	0.0497		0.0548	0.1048	0.0497	

Same superscripts in same column denotes no significant different between treatments at $p \leq 0.05$

6.5.4 Effects of Leucaena biomass + NPK fertiliser on sorghum grain and stover yields

Leucaena biomass + NPK fertiliser show significant effects ($p \leq 0.05$) on grain yields of both Macia and SV1 sorghum varieties. Increasing application rate of Leucaena biomass + NPK fertiliser show increased grain yield for both varieties although Macia outperformed SV1 variety. Increasing Leucaena biomass + NPK fertiliser levels show increase in three-year mean yield of 0.61-1.01 t ha^{-1} (Macia) and 0.62-0.95 t ha^{-1} (SV1). Highest grain yield (1.08 t ha^{-1}) was obtained from Leucaena biomass + NPK fertiliser treatment with 15 t ha^{-1} Leucaena biomass + 150kg ha^{-1} NPK fertiliser in 2017/18 season under Macia variety. The relationship between grain yield and

Leucaena biomass + NPK fertiliser were significantly ($p \leq 0.05$) linear with r^2 ranging from 0.88-0.96 for Macia and 0.96-0.97 for SV2 (Figure 1). SV1 variety had perfect positive correlation with Leucaena biomass + NPK fertiliser at different levels throughout the three seasons compared with Macia variety. SV1 had a higher ($r^2 = 0.97$) correlation in 2019/20 season compared with all other seasons and Macia variety (Figure 6.1).

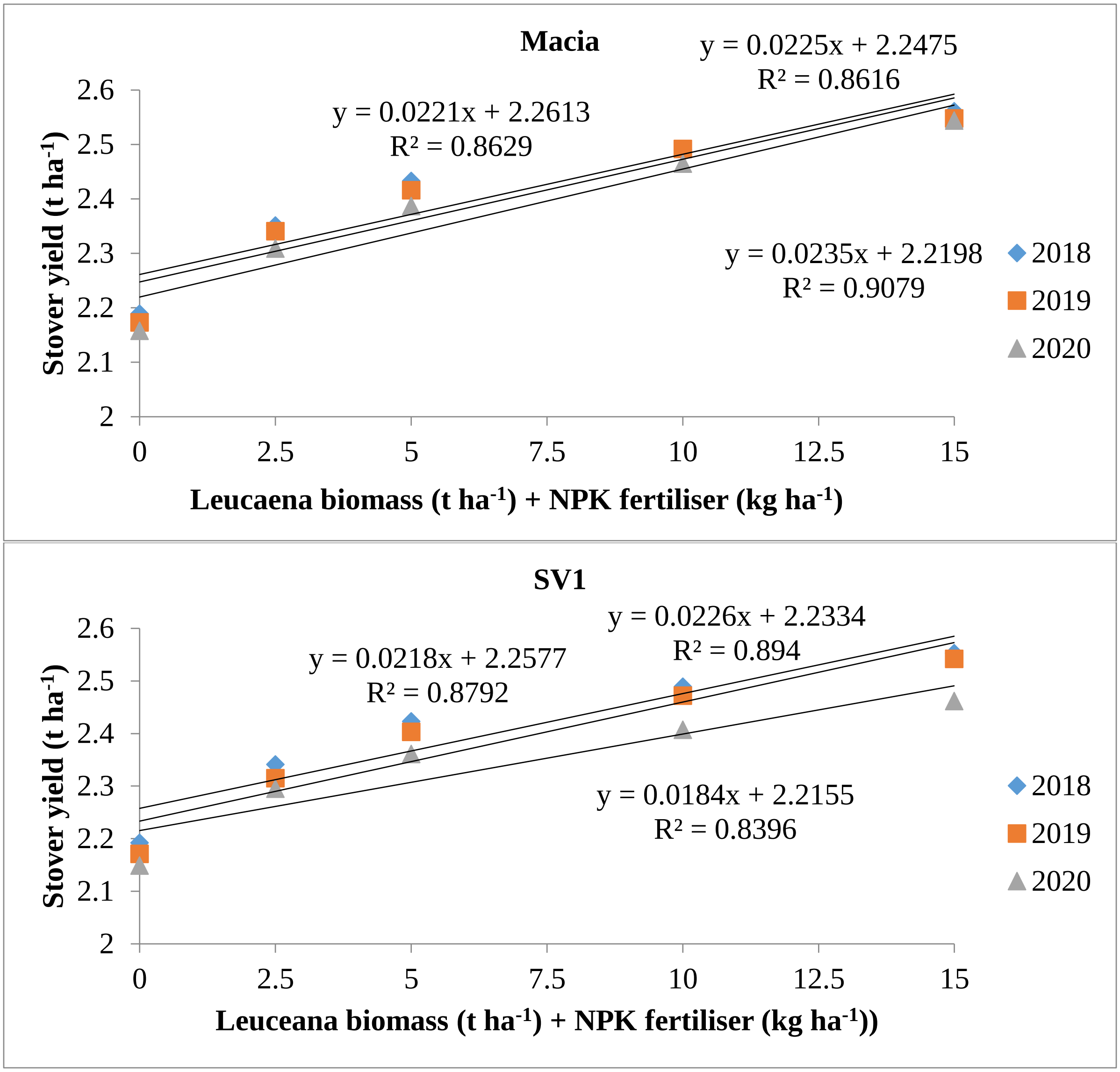


Where: 0=No amendment; 2.5= 2.5tha^{-1} Leucaena biomass+25 kg ha^{-1}NPK fertiliser; 5=5 t ha^{-1} Leucaena biomass +50 kg ha^{-1}NPK fertiliser; 10= 10t ha^{-1} Leucaena biomass +100 kg ha^{-1}NPK fertiliser and 15= 15 t ha^{-1} Leucaena biomass +150 kg ha^{-1}NPK fertiliser.

Figure 6.1: Relationship between Integrated nutrient management and sorghum grain yields over the three seasons.

Stover yields were affected ($p \leq 0.05$) by different Leucaena biomass + NPK fertiliser levels except in 2018/19 season where no significant effect ($p > 0.05$) was observed. Increasing Leucaena biomass + NPK fertiliser levels show significant effect on stover yields with the highest yield of

2.56 t ha^{-1} observed in 2017/18 season from 15 t ha^{-1} Leucaena biomass + 150 kg ha^{-1} NPK fertiliser ((10.5N + 21 P_2O_5 + 10.5K_2O kg ha^{-1}) for Macia variety. Regardless of Leucaena biomass + NPK fertiliser and season, Macia showed higher stover yields than SV1. The results also show significant correlation ($p \leq 0.05$; $r^2 = 0.84$-0.91) between different levels of Leucaena biomass + NPK fertiliser and stover yield (Figure 6.2). Macia stover yields were positively correlated (R^2 = 0.86-0.91) to Leucaena biomass + NPK fertiliser levels. The highest correlation ($r^2 = 0.91$) was observed in 2019/20 season (Figure 2). Furthermore, results showed positive correlation (r^2 = 0.83-0.89) between SV1 stover yields and Leucaena biomass + NPK fertiliser levels. The highest correlation ($R^2 = 0.89$) was observed in 2018/19 season (Figure 6.2).



Where: 0=No amendment; 2.5= 2.5tha^{-1} Leucaena biomass+25 kg ha^{-1}NPK fertiliser; 5=5 t ha^{-1} Leucaena biomass +50 kg ha^{-1}NPK fertiliser; 10= 10t ha^{-1} Leucaena biomass +100 kg ha^{-1}NPK fertiliser and 15= 15 t ha^{-1} Leucaena biomass +150 kg ha^{-1}NPK fertiliser.

Figure 6.2: The relationship between stover yields and Leucaena biomass + NPK fertiliser quantity.

6.5.5 Interaction effects of RWH, Leucaena biomass + NPK fertiliser and variety on sorghum grain yields

Rainwater harvesting practices x Leucaena biomass + NPK fertiliser x variety show significant interaction effects ($p \leq 0.05$) on sorghum grain yields across all treatments (Table 6.4). Effects of

RWH x Leucaena biomass + NPK fertiliser x Macia variety had yield advantage compared with SV1 variety. The highest grain yield (1.146 t ha^{-1}) was obtained from tied contour + 15 t ha^{-1} Leucaena biomass + 150 kg ha^{-1}NPK fertiliser (10.5N + 21 P_2O_5 + 10.5K_2O kg ha^{-1}) + Macia variety during 2017/18 cropping season. Tied contour x Leucaena biomass + NPK fertiliser x Macia variety had the highest grain yields (0.612-1.146 t ha^{-1}) followed by infiltration pits (0.604-1.104 t ha^{-1}) throughout the three cropping seasons. Sorghum variety SV1 had yields ranging from 0.609-1.1 t ha^{-1} (tied contour x Leucaena biomass + NPK fertiliser) and 0.595-1.021 t ha^{-1} (infiltration pits x Leucaena biomass + NPK fertiliser). However, standard contour x Leucaena biomass + NPK fertiliser had the lowest grain yields ranging from 0.571-0.989 t ha^{-1} (Macia) and 0.581-917 t ha^{-1} (SV1) compared with other RWH practices x Leucaena biomass + NPK fertiliser levels (Table 6.4).

Table 6.4: Interaction of RWH, Leucaena biomass + NPK fertiliser and variety on sorghum grain yields

Treatments		Macia Mean grain yield (kg ha^{-1})			SV1 Mean grain yield (kg ha^{-1})		
RWH techniques	**Leucaena biomass t ha^{-1} + NPK fertiliser kg ha^{-1}**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
Infiltration pits	$L_0(NPK)_0$	0.636^{h}	0.636^{g}	0.604^{i}	0.631^{j}	0.606^{g}	0.595^{g}
	$L_{2.5}(NPK)_{25}$	0.807^{f}	0.817^{e}	0.664^{h}	0.752^{h}	0.675^{f}	0.653^{ef}
	$L_5(NPK)_{50}$	0.89^{e}	0.882^{d}	0.758^{f}	0.836^{g}	0.787^{e}	0.752^{d}
	$L_{10}(NPK)_{100}$	0.947^{d}	0.959^{c}	0.822^{d}	0.978^{c}	0.883^{cd}	0.812^{c}
	$L_{15}(NPK)_{150}$	1.104^{b}	1.011^{b}	0.89^{b}	1.021^{b}	0.982^{b}	0.872^{b}
Tied contour	$L_0(NPK)_0$	0.634^{h}	0.636^{g}	0.612^{a}	0.699^{i}	0.671^{f}	0.609^{e}
	$L_{2.5}(NPK)_{25}$	0.823^{f}	0.813^{e}	0.732^{f}	0.776^{h}	0.772^{f}	0.684^{e}
	$L_5(NPK)_{50}$	0.952^{d}	0.959^{c}	0.794^{g}	0.884^{e}	0.867^{d}	0.749^{d}
	$L_{10}(NPK)_{100}$	1.095^{c}	1.011^{b}	0.861^{c}	0.998^{c}	0.97^{b}	0.856^{bc}
	$L_{15}(NPK)_{150}$	1.146^{a}	1.137^{a}	0.929^{a}	1.1^{a}	1.03^{a}	0.905^{a}
Standard contour	$L_0(NPK)_0$	0.574^{i}	0.571^{h}	0.58^{ij}	0.602^{jk}	0.6^{g}	0.581^{g}
	$L_{2.5}(NPK)_{25}$	0.754^{g}	0.779^{f}	0.648^{hi}	0.678^{i}	0.672^{f}	0.636.7^{f}
	$L_5(NPK)_{50}$	0.813^{f}	0.813^{e}	0.709^{g}	0.771^{h}	0.754^{e}	0.688^{e}
	$L_{10}(NPK)_{100}$	0.911^{e}	0.904^{d}	0.796^{e}	0.861^{f}	0.86^{d}	0.77^{d}
	$L_{15}(NPK)_{150}$	0.977^{d}	0.989^{b}	0.863^{c}	0.917^{d}	0.899^{c}	0.849^{bc}
P-value		*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
$LSD_{0.05}$		*0.019*	0.0117	0.00981	*0.019*	0.0117	0.00981
CV (%)		*1.4*	*0.9*	0.8	*1.4*	*0.9*	*0.8*

Same superscripts in same column denotes no significant different between treatments at $p \leq 0.05$.

6.5.6 Interaction effects of RWH, Leucaena biomass + NPK fertiliser and variety on sorghum stover yields

Rainwater harvesting techniques x Leucaena biomass + NPK fertiliser x sorghum variety had significant interaction effect ($p \leq 0.05$) on stover yield throughout three cropping seasons. Regardless of RWH and season, stover yields from Macia were greater than those obtained from SV1 at each application rate of Leucaena biomass + NPK fertiliser (Table 6.5). Stover yields from Macia variety at each RWH technique and different levels of Leucaena biomass + NPK fertiliser ranged of 2.09 – 2.667 t ha^{-1}compared to 2.1–2.666 t ha^{-1} from SV1variety across all treatment combinations. Tied contour and infiltration pits integrated with different Leucaena biomass + NPK fertiliser levels show higher yields compared with standard contour which had lowest stover yields throughout the three seasons (Table 6.5).

Table 6.5: Interaction of RWH, Leucaena biomass + NPK fertiliser and sorghum variety on stover yields

		Macia Mean stover yield (tha^{-1})			SV1Mean stover yield (tha^{-1})		
RWH techniques	**Leucaena biomass ($t\ ha^{-1}$) + NPK fertiliser ($kg\ ha^{-1}$)**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
Infiltration pits	$L_0(NPK)_0$	2.193^h	2.184^i	2.183^g	2.192^g	2.172^h	2.167^g
	$L_{2.5}(NPK)_{25}$	2.377^f	2.382^e	2.296^f	2.353^e	2.33^{ef}	2.269^f
	$L_5(NPK)_{50}$	2.464^{cd}	2.436^d	2.41^d	2.438^{cd}	2.402^d	2.354^d
	$L_{10}(NPK)_{100}$	2.478^c	2.503^c	2.456^c	2.479^c	2.488^c	2.398^c
	$L_{15}(NPK)_{150}$	2.552^b	2.515^j	2.538^j	2.547^b	2.543^b	2.452^{ab}
Tied contour	$L_0(NPK)_0$	2.284^c	2.219^h	2.188^g	2.286^f	2.225^g	2.181^g
	$L_{2.5}(NPK)_{25}$	2.398^{ef}	2.366^e	2.356^{ef}	2.394^d	2.37^e	2.369^d
	$L_5(NPK)_{50}$	2.484^c	2.494^c	2.419^d	2.482^c	2.477^c	2.411^{bc}
	$L_{10}(NPK)_{100}$	2.578^b	2.567^b	2.477^b	2.579^b	2.558^b	2.46^{ab}
	$L_{15}(NPK)_{150}$	2.667^a	2.658^a	2.551^a	2.666^a	2.624^a	2.494^a
Standard contour	$L_0(NPK)_0$	2.09^i	2.115^j	2.102^h	2.1^h	2.116^i	2.1^h
	$L_{2.5}(NPK)_{25}$	2.278^g	2.274^g	2.275^f	2.277^f	2.246^g	2.247^f
	$L_5(NPK)_{50}$	2.35^f	2.317^f	2.332^{ef}	2.35^e	2.331^{ef}	2.319^{de}
	$L_{10}(NPK)_{100}$	2.415^e	2.406^{de}	2.462^c	2.411^d	2.37^e	2.365^d
	$L_{15}(NPK)_{150}$	2.465^{cd}	2.472^{cd}	2.543^a	2.447^{cd}	2.459^c	2.439^b
P-value		*0.03*	*<0.001*	*<0.001*	*0.03*	*<0.001*	*<0.001*
$LSD_{0.05}$		0.0123	0.0234	0.0111	0.0123	0.0234	0.0111
CV (%)		*0.3*	*0.6*	*0.3*	*0.3*	*0.6*	*0.3*

6.5.7 Rain Water Use Efficiency (RWUE)

Rainwater harvesting techniques significantly ($p \leq 0.05$) affected RWUE in all three cropping seasons. Effects of RWH techniques were significant on RWUE for both varieties except in 2017/18 season where no significant effect was observed ($p > 0.05$). Macia variety had higher

RWUE which ranged from 2.58 to 2.91 kg ha^{-1} mm^{-1} compared with SV1 (2.48-2.78 kg ha^{-1} mm^{-1}) over three years (Figure 6.3). Tied contour recorded highest RWUE (3.09 kg ha^{-1} mm^{-1}) from Macia variety in 2018/19 season and a lowest of 2.31 kg ha^{-1} mm^{-1} from standard contour + SV1 in 2019/20 season. Results also show significant differences ($p \leq 0.05$) among varieties. Standard contour treatments had the lowest RWUE regardless of variety and season, with RWUE ranging from 2.31-2.75 kg ha^{-1} mm^{-1} (Figure 6.3).

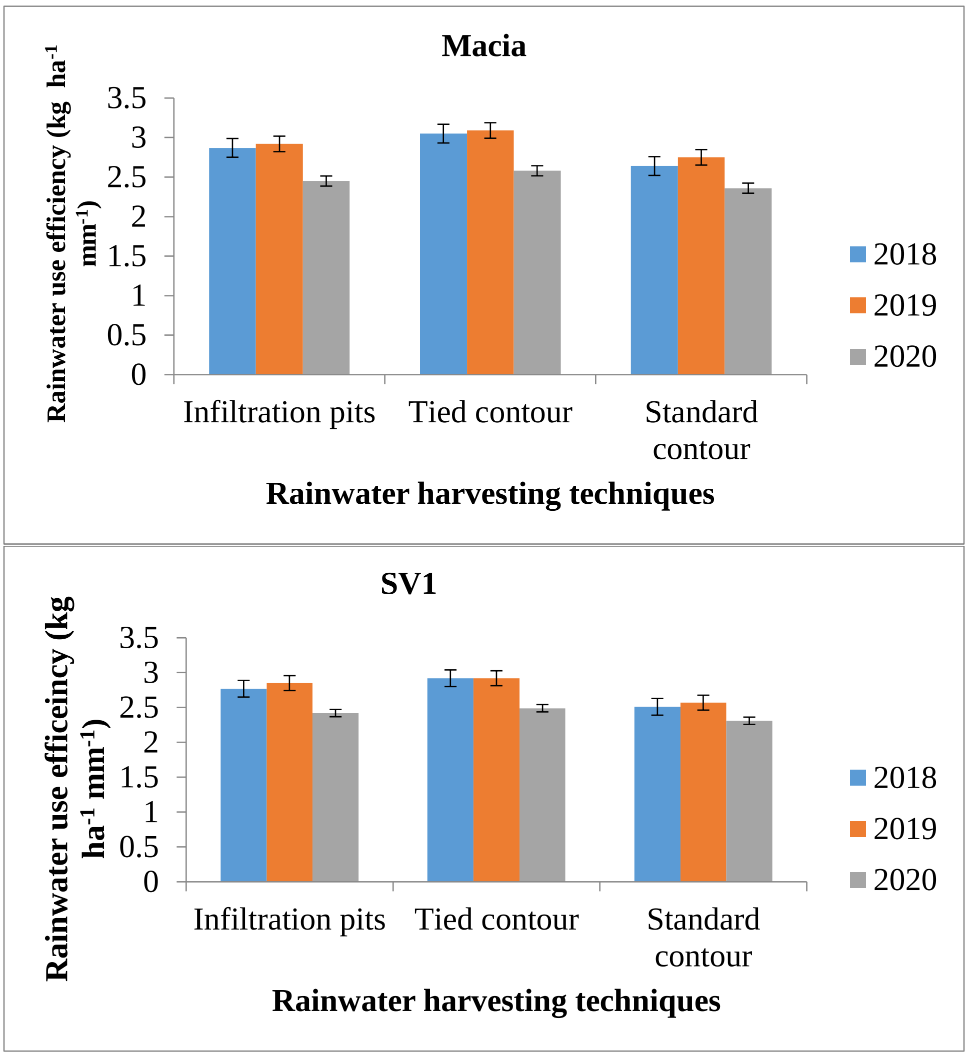
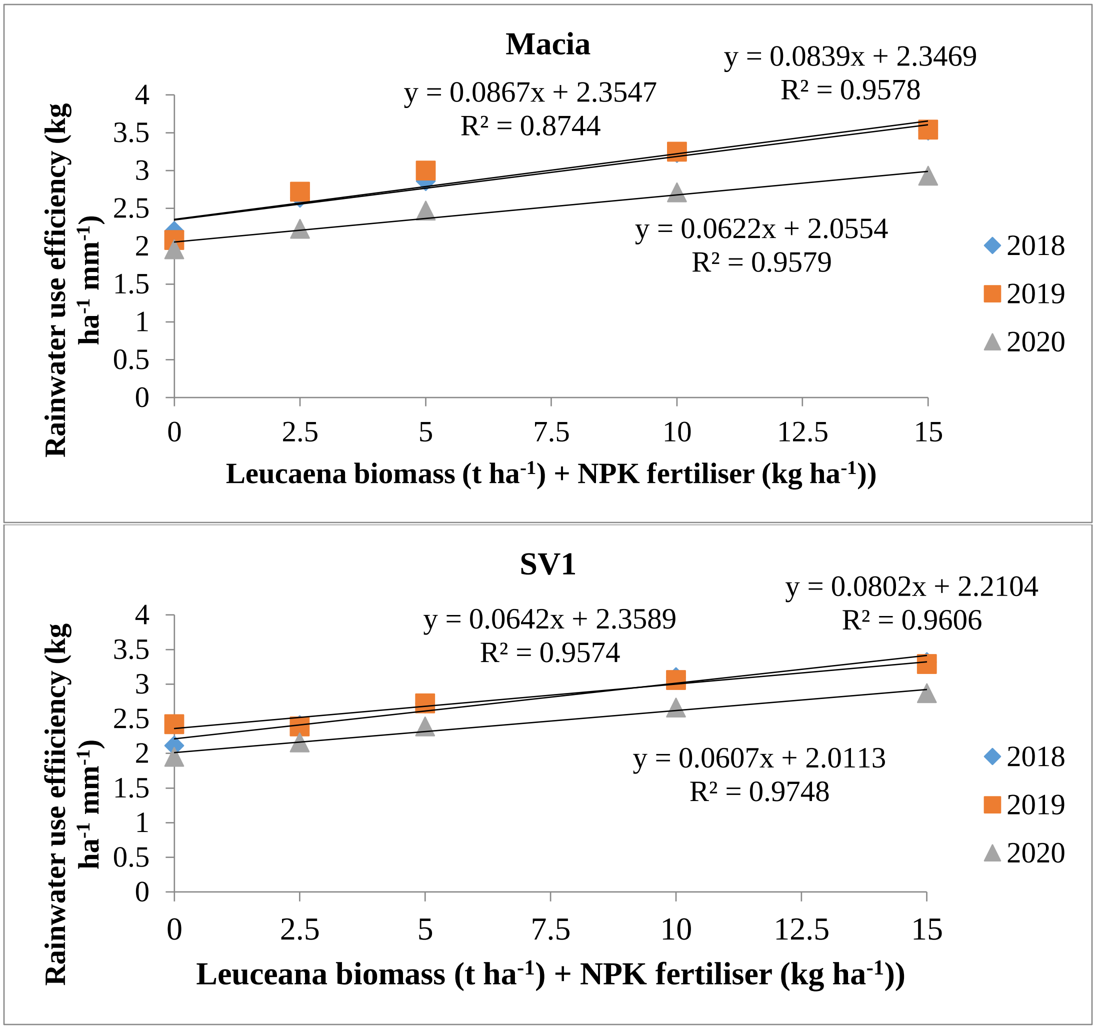


Figure 6.3: Effect of water harvesting methods on rainwater use efficiency of Macia and SV1 over the three seasons.

Rainwater use efficiency was significantly affected ($p \leq 0.05$) by Leucaena biomass + NPK fertiliser levels regardless of sorghum variety and season. Increasing Leucaena biomass + NPK fertiliser levels over control show significant increase in RWUE with highest (3.53 kg ha^{-1} mm^{-1}) and lowest of 2.02 kg ha^{-1} mm^{-1} observed from Macia variety. Macia variety responds well from different application rates of Leucaena biomass + NPK fertiliser, with three-year mean ranging from 2.02-3.33 kg ha^{-1} mm^{-1} compared with 2.16-3.16 kg ha^{-1} mm^{-1} from SV1 variety. Rainwater use efficiency from Macia was positively correlated to Leucaena/NPK fertiliser levels but less than that of SV1 (Figure 6.4). SV1 variety was highly correlated (r^2 = 0.96-0.97) to Leucaena biomass + NPK fertiliser application rates. The highest correlation (r^2 = 0.97) was observed in 2019/20 cropping season from SV1 variety (Figure 6.4). Macia variety had the lowest correlation with increase in Leucaena biomass + NPK fertiliser levels in 2017/18 cropping season.



Where: 0=No amendment; 2.5= 2.5tha^{-1} Leucaena biomass+25 kg ha^{-1}NPK fertiliser; 5=5 t ha^{-1} Leucaena biomass +50 kg ha^{-1}NPK fertiliser; 10= 10t ha^{-1} Leucaena biomass +100 kg ha^{-1}NPK fertiliser and 15= 15 t ha^{-1} Leucaena biomass +150 kg ha^{-1}NPK fertiliser.

Figure 6.4: The relationship between rainwater use efficiency and Leucaena biomass + NPK fertiliser levels.

Rainwater use efficiency was significantly affected ($p \leq 0.05$) by interaction of RWH, Leucaena biomass + NPK fertiliser and sorghum variety (Table 6.6). Highest RWUE (3.85 kg ha^{-1} mm^{-1}) was observed in 2018/19 from tied contour + 15 t ha^{-1} Leucaena biomass + 150 kg ha^{-1} NPK fertiliser (10.5N + 21 P_2O_5 + 10.5K_2O kg ha^{-1}) treatment + Macia variety. Furthermore, lowest RWUE (1.88 kg $ha^{-1}mm^{-1}$) was observed from SC with no amendment under Macia variety (Table 6.6). Tied contours and infiltration pits show better RWUE compared with standard contours which had lowest RWUE throughout three cropping seasons.

Table 6.6: Interaction of RWH, Leucaena biomass + NPK fertiliser and variety on RWUE

Treatments		Mean Macia RWUE (kg ha^{-1} mm^{-1})			Mean SV1 RWUE (kg ha^{-1} mm^{-1})		
RWH techniques	**Leucaena biomass t ha^{-1} + NPK fertiliser kg ha^{-1}**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
Infiltration pits	$L_0(NPK)_0$	2.08^{f}	2.15^{f}	1.98^{i}	2.07^{h}	2.95^{c}	1.95^{gh}
	$L_{2.5}(NPK)_{25}$	2.63^{d}	2.77^{e}	2.18^{h}	2.47^{f}	2.29^{e}	2.14^{f}
	$L_5(NPK)_{50}$	2.92^{c}	2.99^{d}	2.48^{f}	2.74^{e}	2.67^{d}	2.46^{de}
	$L_{10}(NPK)_{100}$	3.1^{bc}	3.25^{c}	2.7^{d}	3.21^{c}	2.99^{c}	2.66^{cd}
	$L_{15}(NPK)_{150}$	3.62^{a}	3.43^{b}	2.92^{b}	3.35^{b}	3.33^{b}	2.86^{b}
Tied contour	$L_0(NPK)_0$	2.08^{f}	2.16^{f}	2.01^{i}	2.29^{g}	2.27^{e}	2^{g}
	$L_{2.5}(NPK)_{25}$	2.7^{d}	2.75^{e}	2.4^{f}	2.54^{f}	2.62^{d}	2.24^{f}
	$L_5(NPK)_{50}$	3.12^{bc}	3.25^{c}	2.6^{e}	2.9^{d}	2.94^{c}	2.46^{de}
	$L_{10}(NPK)_{100}$	3.59^{ab}	3.43^{b}	2.82^{c}	3.27^{b}	3.29^{b}	2.81^{b}
	$L_{15}(NPK)_{150}$	3.76^{a}	3.85^{a}	3.05^{a}	3.61^{a}	3.49^{a}	2.99^{a}
Standard contour	$L_0(NPK)_0$	1.88^{g}	1.94^{g}	1.9^{i}	1.97^{h}	2.03^{f}	1.9^{gh}
	$L_{2.5}(NPK)_{25}$	2.57^{de}	2.64^{d}	2.12^{h}	2.22^{g}	2.28^{e}	2.09^{g}
	$L_5(NPK)_{50}$	2.55^{de}	2.75^{e}	2.33^{g}	2.53^{f}	2.56^{d}	2.26^{f}
	$L_{10}(NPK)_{100}$	2.99^{c}	3.06^{d}	2.61^{e}	2.82^{e}	2.92^{c}	2.53^{d}
	$L_{15}(NPK)_{150}$	3.2^{bc}	3.35^{bc}	2.83^{c}	3.01^{d}	3.05^{c}	2.78^{bc}
P-value		*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
$LSD_{0.05}$		0.0623	0.0393	0.0323	0.0623	0.0393	0.0323
CV (%)		*1.4*	*0.8*	0.8	*1.4*	*0.8*	*0.8*

Same superscripts in same column denotes no significant different between treatments at $p \leq 0.05$.

6.5.8 Agronomic efficiency of sorghum under RWH techniques and Leucaena biomass + NPK fertiliser

Higher sorghum agronomic efficiency (AE) of 0.054 kg kg^{-1} was obtained in 2017/18 season from Macia grown under tied contours. Sorghum agronomic efficiency was significantly affected ($p \leq 0.05$) by rainwater harvesting techniques (Table 6.7). On average, sorghum AE was better from Macia under tied contours compared with same treatment under SV1 variety during all three seasons.

Table 6.7: Effects of RWH on Agronomic efficiency of sorghum

RWH techniques	Mean Macia AE (kg kg^{-1})			Mean SV1 AE (kg kg^{-1})		
	2018	**2019**	**2020**	**2018**	**2019**	**2020**
Standard contour	0.044^b	0.023^b	0.047^b	0.027^c	0.02^c	0.026^c
Infiltration pits	0.045^b	0.023^b	0.044^c	0.037^a	0.023^b	0.029^b
Tied contour	0.054^a	0.032^a	0.051^a	0.031^b	0.025^a	0.033^a
P-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
$LSD_{0.05}$	0.0046	0.0016	0.0026	0.0046	0.0016	0.0026

Sorghum agronomic efficiency was significantly influenced ($p \leq 0.05$) by different application rates of Leucaena biomass + NPK fertiliser. Higher AE of 0.074 kg kg^{-1} was observed from Macia variety + 2.5 t ha^{-1} Leucaena biomass + 25 kg ha^{-1} NPK fertiliser (1.75N + 3.5 P_2O_5 + 1.75 K_2O kg ha^{-1}) in 2019/20 cropping season (Figure 6.5). Agronomic efficiency decreased with increasing levels of nutrient sources. Macia variety had better AE compared with SV1 variety at all application rates. Agronomic efficiency of SV1 variety were in the same range as influenced by Leucaena biomass +NPK fertiliser x season (Figure 6.5).

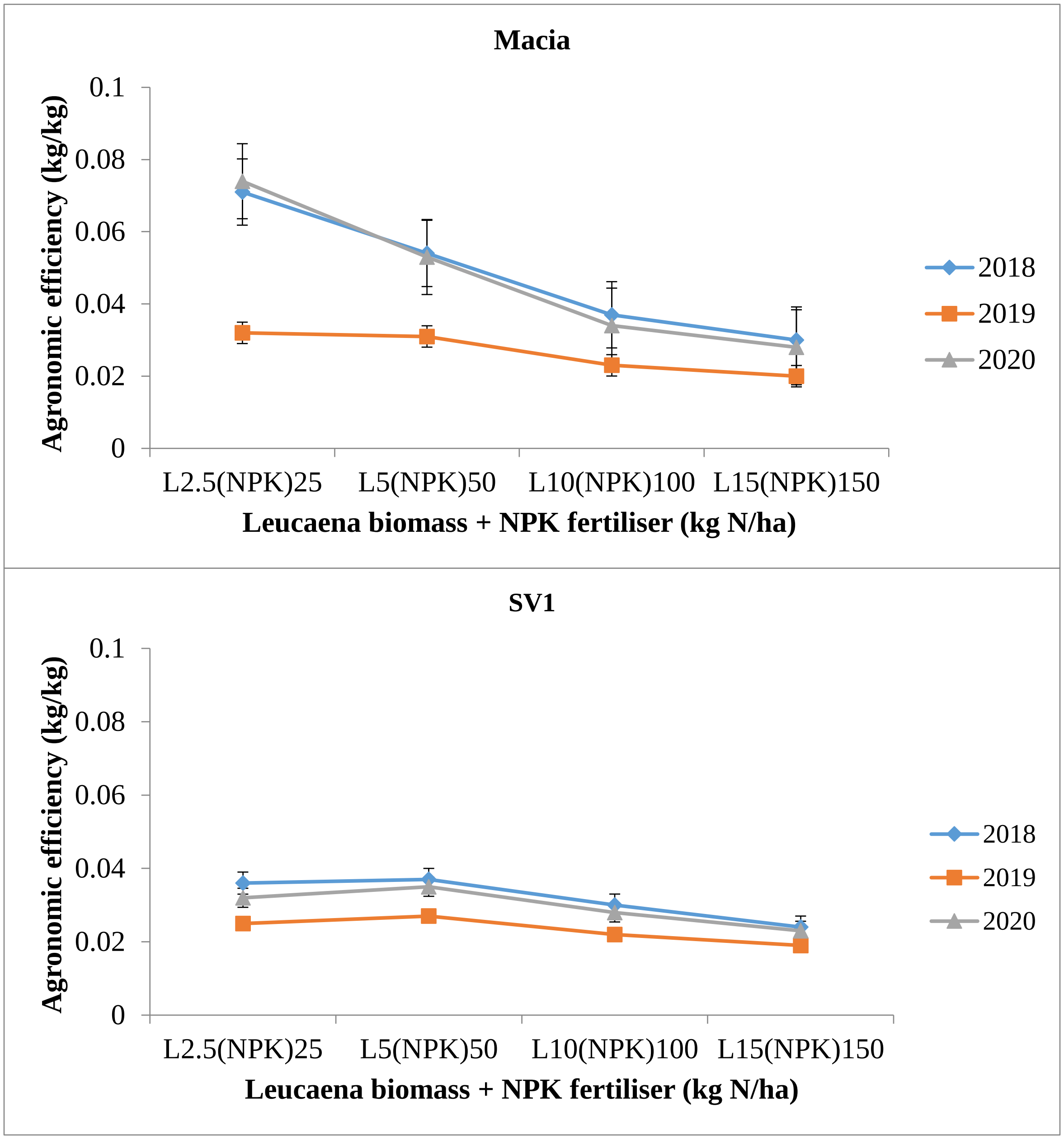


Figure 6.5: Effects of Leucaena biomass + NPK fertiliser on agronomic efficiency (AE) of Macia and SV1

Sorghum agronomic efficiency was significantly influenced ($p \leq 0.05$) by interaction of RWH and Leucaena biomass + NPK fertiliser except in 2017/18 season where no significant effect ($p>0.05$) on AE was observed (Table 6.8). Highest sorghum agronomic efficiency of 0.082 kg kg^{-1} was observed from standard contour + 2.5 t ha^{-1} Leucaena biomass + 25 kg ha^{-1} NPK fertiliser (1.75N

+ 3.5 P_2O_5 + 1.75 K_2O kg ha^{-1}). Macia variety show better AE compared with SV1 in all three cropping seasons (Table 6.8).

Table 6.8: Interaction of RWH and Leucaena biomass + NPK fertiliser on Macia and SV1 agronomic efficiency

Treatments		**Mean Macia AE (kg kg^{-1})**			**Mean SV1 AE (kg kg^{-1})**		
Rainwater harvesting techniques	**Leucaena biomass (t ha^{-1}) + NPK fertiliser (kg ha^{-1})**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
Infiltration pits	$L_{2.5}(NPK)_{25}$	0.068	0.022^{e}	0.072^{b}	0.048	0.023^{bc}	0.027^{c}
	$L_5(NPK)_{50}$	0.05	0.03^{c}	0.049^{c}	0.041	0.031^{a}	0.036^{ab}
	$L_{10}(NPK)_{100}$	0.031	0.022^{e}	0.032^{d}	0.034	0.021^{bc}	0.027^{bc}
	$L_{15}(NPK)_{150}$	0.031	0.019^{f}	0.025^{e}	0.026	0.018^{i}	0.025^{bc}
Tied contour	$L_{2.5}(NPK)_{25}$	0.075	0.047^{a}	0.07^{b}	0.031	0.03^{a}	0.04^{a}
	$L_5(NPK)_{50}$	0.063	0.036^{b}	0.064^{b}	0.037	0.028^{a}	0.039^{a}
	$L_{10}(NPK)_{100}$	0.046	0.025^{h}	0.037^{d}	0.03	0.024^{b}	0.032^{b}
	$L_{15}(NPK)_{150}$	0.034	0.021^{j}	0.033^{d}	0.027	0.02^{bc}	0.024^{bc}
Standard contour	$L_{2.5}(NPK)_{25}$	0.07	0.027^{c}	0.082^{a}	0.03	0.022^{bc}	0.029^{b}
	$L_5(NPK)_{50}$	0.047	0.026^{d}	0.047^{c}	0.033	0.021^{bc}	0.031^{b}
	$L_{10}(NPK)_{100}$	0.033	0.022^{e}	0.033^{d}	0.026	0.019^{bc}	0.026^{bc}
	$L_{15}(NPK)_{150}$	0.027	0.019^{f}	0.028^{de}	0.021	0.018^{cd}	0.02^{c}
P-value		*ns*	*<0.001*	*<0.001*	*ns*	*<0.001*	*<0.001*
$LSD_{0.05}$		0.0093	0.0031	0.0052	0.0093	0.0031	0.0052
CV (%)		*14.2*	*7.7*	*8.2*	*14.2*	*7.7*	*8.2*

Same superscripts in same column denotes no significant different between treatments at $p \leq 0.05$.

6.6 DISCUSSION

6.6.1 Rainfall

Rainfall received at the experimental site in all seasons was less than the 30-year average of 335 mm and ranged from 295 to 305 mm per growing season. Sorghum can be grown in areas which receive 300 to 900 mm well distributed throughout the growing season and require an average of 350 mm up to harvesting stage. Rainfall received was influenced by frequent dry spells and could not sustain crops to harvesting stage. These results were confirming assertion by Mugandani et al. (2012), Mugandani and Mafongoya (2019) and Nyagumbo et al. (2019) who reported that climate change affected rainfall in semi-arid regions. Climate changes greatly affected Chivi district with rainfall received ranging from 295 to 305 mm per growing season compared with a 30-year average of 335 mm. Dry days were more per month compared with 30-year average due to climate change. This may call for adoption of climate smart agriculture to increase crop yields (Mugandani et al., 2012; Thornton et al., 2014; Winter-Nelson et al., 2016).

6.6.2 Soil characterisation

Soil chemical properties were increased with application of Leucaena biomass + NPK fertiliser. This could have been contributed by decomposition of Leucaena biomass producing nitrogen, exchangeable cations and liming of soil pH. The residual effect of Leucaena biomass has contributed towards increase in total nitrogen, pH and exchangeable cations. Potassium and phosphorous supplied by NPK fertiliser also contributed to improvement in these soil chemical properties. Applications of Leucaena biomass have been reported to increase SOC, potassium, phosphorous and pH (Mafongoya et al., 2007; Mugwe, 2007; Timsina, 2018). Soil organic carbon from this study was in the same range of 0.06-2.3 % as reported from Chivi by Mapanda and Mavengahama (2011). Organic nutrient sources amended with inorganic fertilisers play a pivotal role in improving soil fertility as a result of decomposition and mineralisation (Gram et al., 2020;

Kimaru-Muchai et al., 2021; Mamuye et al., 2021). Augmenting Leucaena biomass with NPK fertiliser has shown the potential in improving soil fertility. This may have been a result of high organic carbon and fast decomposition of organic sources (Kisinyo et al., 2019; Mugwe and Otieno, 2021). During decomposition of organic manure, humic acids are produced which bind to Aluminium and increase availability of basic cation essential for growth to crops.

6.6.3 Grain and stover yield

Rainwater harvesting techniques of tied contours and IP improved sorghum grain yields compared with standard contours (SC) during the experimental period. Tied contours and IP recorded higher yields compared with SC which had the lowest grain yields at all seasons and varieties. This may have been associated with increased soil moisture content impounded by tied contour and infiltration pits which increased water availability leading to higher grain yield. This was in agreement with results from related studies by several authors (e.g., Mupangwa et al., 2006; Nyakudya et al., 2014; Kilasara et al., 2015; Nyamadzawo et al., 2015; Mahinda et al., 2018; Nyagumbo et al., 2019; Chilagane et al., 2020; Mandumbu et al., 2021) who reported improved water retention which results in increasing grain yields. Rainwater harvesting techniques retain water in the plant root zone, improving soil moisture content and grain yields (Mandumbu et al., 2021; Kubiku et al., 2022b). Availability of water in the plant root zone influence nutrient availability to plants, improve response of crops to nutrients and increase nutrient use efficiency (Mupangwa et al., 2012; Kilasara et al., 2015; Mahinda et al., 2018; Kugedera and Kokerai, 2019; Chilagane et al., 2020; Mandumbu et al., 2021). This is in agreement with results by Mahinda et al. (2018) and Chilagane et al. (2020) who observed higher sorghum and pearl millet yields after using rainwater harvesting methods respectively. Low water retention by standard contours contributed immensely to low sorghum yields throughout three cropping seasons irrespective of sorghum variety. This concurs with findings by several authors (e.g., Mupangwa et al., 2012;

Nyamadzawo et al., 2015; Nyagumbo et al., 2019; Kubiku et al., 2022a) who reported low yields from standard contours which impound very little water during the growing season.

Augmenting Leucaena biomass with NPK fertiliser increased sorghum grain yields and can be a better option as integrated soil fertility management. Grain yields were significantly increased with increase in application rates of nutrient sources. Organic nutrient sources such as Leucaena biomass have the capacity to increase SOC, microbial population and soil total porosity (Mafongoya and Dzowela, 1999) which when augmented with mineral fertiliser can significantly increase sorghum grain yields. This was in agreement with Kilasara et al. (2015) and Kubiku et al. (2022a) who reported increased sorghum yields after combining organic manure and mineral fertiliser. Increasing application rates of Leucaena biomass + NPK fertiliser improved soil structure, nutrient status and sorghum yields.

Sorghum grain yields were significantly improved by integration of RWH techniques and Leucaena biomass + NPK fertiliser at different application rates. Grain yields were high from all treatments of tied contours combined with Leucaena biomass + NPK fertiliser. This may be attributed to better water capture by tied contours compared with infiltration pits and standard contours. This corroborates with results by Kubiku et al. (2022b) who reported higher yields from tied contours combined with cattle manure + N fertiliser. Related research work in Africa show that integration of rainwater harvesting with INM increased sorghum grain yields especially in arid and semi-arid areas (Zougmoré et al., 2003; Kilasara et al., 2015; Kimaru, 2017). Water management and INM research in sorghum by Zougmoré et al. (2003), show grain yield ranging from 0.365 to 2.627 t ha^{-1} which were in the same range (0.59-1.146 t ha^{-1}) with results from this study. Results from this study were in agreement with results by Kilasara et al. (2015) who reported increase in sorghum grain yields (0.313-2.787 t ha^{-1}) after using infiltration pits (IP) and cattle manure + NPK fertiliser in Tanzania. This was linked to reduced soil erosion, surface runoff and increased soil moisture in the plant root zone (Mupangwa et al., 2012; Kilasara et al., 2015; Nyamadzawo et al., 2015; Nyagumbo et al., 2019; Muchai et al., 2020; Mandumbu et al., 2021) and improved nutrient levels in the top soil due to INM (Sebnie et al., 2020).

Sorghum stover yields were significantly affected by RWH techniques. This could have been caused by synergistic effects of available soil moisture from tied contours and improved nutrient availability (Nyamadzawo et al., 2015; Nyagumbo et al., 2019; Kimaru-Muchai et al., 2021). Stover yields were improved with increasing integrated nutrient management (INM) levels. This was in agreement with Mesfin et al. (2009), Hakeem et al. (2018) and Sebnie et al. (2020) who reported improved sorghum stover yield with increased application rates of nutrient sources. Stover yield was highly correlated to Leucaena biomass + NPK fertiliser application rates. Integration of RWH and Leucaena biomass + NPK fertilisers how improvements in sorghum stover yields for both varieties. Highest stover yield observed from tied contours integrated with INM may have been caused by improved soil moisture and nutrients availability in plant rooting zone. This may also have been attributed to better soil-water and nutrient management which improved nutrient use efficiency by crops (Mugwe et al., 2019).

6.6.4 Rain Water Use Efficiency (RWUE)

Rainwater use efficiency was improved by tied contours and infiltration pits than standard contours. Higher RWUE values were observed from tied contours and infiltration pits than standard contours over three cropping seasons. These results were in agreement to findings by Fatondji et al. (2006) and Coulibaly (2015) who reported ranges from 2.2 to 3.45 kg ha^{-1} mm^{-1}

after using *in situ* rainwater harvesting method of Zai pits. Results from this study were also corroborated to findings by Itabari (1999) and Chiroma et al. (2008) who reported RWUE values ranging from 2.2 to 3.75 kg ha^{-1} mm^{-1} from sorghum under tied ridges and 2.83-3.38 kg ha^{-1} mm^{-1} from sorghum grown under Zai pits. Increasing application rates of nutrient sources improved RWUE (Hakeem et al., 2018). However, results from integration of RWH techniques and Leucaena biomass + NPK fertiliser from this study were higher than findings by Fatondji et al. (2006) which ranges from 1.8-2.1 kg ha^{-1} mm^{-1} after using Zai pits + manure + straw in pearl millet. Results from this experiment were in the same range with results by Gonda (2015) who observed RWUE values ranging from 0.97-2.84 kg ha^{-1} mm^{-1} after using combination of water management techniques + compost manure + NPK fertiliser applied in pearl millet. The use of soil fertility and water management practices has the potential to improve RWUE with 15 - 25% (Hartfield et al., 2001).

6.6.5 Agronomic Efficiency

Tied contours had better sorghum AE compared with infiltration pits and standard contour. Higher AE was observed from Macia variety than SV1. Highest AE from tied contours was in agreement with findings by Fatondji (2002) who reported better AE under insitu rainwater harvesting of *Zai* pits. Agronomic efficiency of sorghum was high at low application levels of nutrient sources (2.5 t ha^{-1} Leucaena biomass + 25 kg ha^{-1}NPK fertiliser). Findings obtained corroborates with results by Gonda (2015) and Coulibaly (2015) who reported low AE with high application levels of nutrient sources. Furthermore, Vanlauwe et al. (2011) and Gram et al. (2020) reported high AE at low rates of inorganic and organic nutrient sources. Sorghum agronomic efficiency declined with increasing application levels of Leucaena biomass + NPK fertiliser. This was in agreement with results by Fatondji et al. (2006) who reported low AE with manure application rates more than 1000 kg ha^{-1}. This was also affirmed by Gram et al. (2020) who reported decline in AE with application of more than 1000 kg ha^{-1} of organic manure. Macia variety proved to have better agronomic efficiency than SV1 and it is a promising variety to improve food security in semi-arid regions especially in SSA. Integration of RWH and Leucaena biomass + NPK fertiliser show significant effect on AE. These results were contrary to findings by Coulibaly (2015) who reported no significant effect on AE after combining rainwater harvesting methods, organic and inorganic fertilisers in Mali.

6.7 CONCLUSION

Results from this study clearly demonstrated that augmenting Leucaena biomass with NPK fertiliser has the potential to improve nutrient availability to crops and increase sorghum yields. Tied contours and infiltration pits had higher sorghum yields compared with standard contour in all cropping seasons. Tied contours and Macia variety had better agronomic efficiency when combined with 2.5 t ha^{-1} Leucaena biomass + 25 kg ha^{-1} NPK fertiliser (1.75N + $3.5P_2O_5$ + $1.75K_2O$ kg ha^{-1}). Augmenting Leucaena biomass with NPK fertiliser under tied contours and Macia variety proved to increase sorghum yields, rainwater water use efficiency and have better agronomic efficiencies in semi-arid regions. Although 15 tha^{-1} Leucaena biomass +150 kg ha^{-1} NPK fertiliser (10.5N + $21P_2O_5$ + $10.5K_2O$ kg ha^{-1}). gave higher yields, they have low agronomic efficiency compared with 2.5 t ha^{-1} Leucaena biomass + 25 kg ha^{-1} NPK fertiliser (1.75N + $3.5P_2O_5$ + $1.75K_2O$ kg ha^{-1}). I can recommend that tied contours combined with 5 t ha^{-1}Leucaena biomass + 50 kg ha^{-1} NPK + Macia can be adopted by farmers to reduce food insecurity in semi-arid regions due to higher yield increment compared with other treatments. Therefore, smaller quantities of Leucaena biomass can be used and the rest turned in to fodder for livestock.

CHAPTER 7: SYNTHESIS

7.1 SORGHUM PRODUCTION IN SEMI-ARID REGIONS

Sorghum production has been greatly reduced by moisture stress and poor soil fertility in most semi-arid areas of Africa. The result has been low yields leading to variability in increased food insecurity especially in communities living in marginalised areas. The impacts have been worsened by the use of poor farming methods such as conventional tillage in the smallholder farming areas. In addition, most farmers do not apply, or if they do, they apply inadequate quantities of mineral fertilisers. All this has seen the smallholder farmer ushering deep into poverty, and living on food handouts on an annual basis.

In most of Sub-Saharan Africa, Zimbabwe included, sorghum grain yields range from 0.45 to 2.0 t ha^{-1} (Akram et al., 2007; Twomlow et al., 2008; Mwadalu and Mwangi, 2013; Kimaru, 2017; Hakeem et al., 2018; Masaka et al., 2019; Marumbi et al., 2020; Kubiku et al., 2022a). In Zimbabwe average sorghum yields range between 0.45 and 0.6 t ha^{-1} in agroecological region V (Chiduza et al., 1995; Nyakatawa et al., 1996; Marumbi et al., 2020) and a range of 0.7-2.0 t/ha in agroecological regions III and IV (Twomlow et al., 2020; Masaka ret al., 2019; Marumbi et al., 2020). In other countries like Tanzania, Kenya, Burkina Faso, Mozambique and Nigeria sorghum yields ranges from 0.312 to 4.37 t ha^{-1}, but vary depending on farming practice, soil type and rainfall received in the area (Mwangi and Mwadalu, 2013; Kilasara et al., 2015; Tsusaka et al., 2015; Quattara, 2015; Hakeem et al., 2018). All these yields are well below the yield potential of the sorghum varieties, and efforts should be done to close the yield gap if we are to improve food security in the smallholder communities whose staple food is sorghum.

7.2 EFFECTS OF RAINWATER HARVESTING AND LEUCAENA BIOMASS ON SOIL MOISTURE CONTENT, GRAIN AND STOVER YIELD, AND RAINWATER USE EFFICIENCY ON SORGHUM

7.2.1 Effects of rainwater harvesting and Leucaena biomass on soil moisture content

The use of rainwater harvesting techniques has been reported to improve soil moisture content. Tied contours and infiltration pits have the capacity to harvest runoff water, store and allow it to infiltrate deeper into the soil recharging plant root zone. Soil moisture content increases in the top soil (0-40 cm). The same concept was reported by several authors (e.g., Mupangwa et al., 2006; Mupangwa et al., 2012a; Nyamadzawo et al., 2015; Wuta et al., 2018; Nyagumbo et al., 2020; Mandumbu et al., 2021; Kubiku et al., 2022a) who observed increase in soil moisture content with the use of several rainwater harvesting techniques such as infiltration pits compared with standard contours. Tied contours retained a lot of water followed by infiltration pits because they act as soil moisture conservation structures. This was in agreement with the use of contour ridges with cross ties (Mugabe et al., 2004; Gumbo et al., 2012) and *Fanya juus* (Nyagumbo et al., 2019). Moisture stored can be used by plants during dry spell period to improve growth and development.

Addition of Leucaena biomass increases SOC, improve soil structure, water retention and hydraulic conductivity of the soil (Nyamadzawo et al., 2008). Organic nutrient sources such as Leucaena biomass provide food for microbes and increase microbial population leading to increased decomposition rate, improving soil structure and infiltration of water (Patil and Sheelavantar, 2004; Mugwe, 2007; Zhang et al., 2022). Similar effects were reported through the use of Leucaena (Kebede et al., 2012), Sesbania (Mugendi et al., 1999), Tithonia (Kimaru-Muchai et al., 2021) and Gliricidia (Opala et al., 2020) in various crops. Combining tied contours and infiltration pits with Leucaena biomass significantly increased soil moisture content. This was because tied contours and infiltration pits reduce surface runoff and harvest water while Leucaena biomass increases soil's capacity to hold more water by creating sponges from the added biomass. Leucaena biomass also act as mulch to reduce evaporation water loss from the soil. Collected water infiltrates deeper into the soils, recharging water in the plant root zone leading to higher soil moisture content in 21-40 cm depth.

7.2.2 Effects of rainwater harvesting and Leucaena biomass on rainwater used efficiency, grain and stover yields.

Tied contours and infiltration pits make more water available to plants, increasing photosynthetic area and promote grain filling. This increases movement of proteins, lipids and carbohydrates to the grain translating to higher yields. Tied contours and infiltration pits harvest little rainwater received in semi-arid areas and make it available to crops during critical growth stages and reduces moisture stress facilitating flowering, pollination and grain filling (Mahinda et al., 2018; Deng et al., 2019). Low yields from standard contour may have been attributed to moisture stress especially during grain filling which affected grain development since this structure dispose-off rainwater from the field. This corroborates to results from similar researches by Nyakudya et al. (2015), Nyagumbo et al. (2019) and Kubiku et al. (2022a) who reported low maize and sorghum grain yields through use of standard contours respectively. Infiltration pits and tied contours are able to mitigate effects of moisture stress in low rainfall areas and contribute to yield increment (Mupangwa et al., 2012a; Kilasara et al., 2015; Mahinda et al., 2018; Nyagumbo et al., 2019; Kubiku et al., 2022a, b). Reports of moisture stress reduction strategies were also reported in semi-arid areas across the world (Nyamadzawo et al., 2015; Deng et al., 2020; Kubiku et al., 2022a) and improve crop yields.

Leucaena biomass applied to the soil increase available nitrogen in the soil which boosts growth and improves yields (Mugendi et al., 1999; Mafongoya et al., 2006; Mugwe, 2007). The N is released slowly as the biomass decomposes and this is buffered against leaching losses when compared with mineral fertilisers. This boost plant survival under drought conditions, allowing the plants to flower, pollinate, fertilise and fill grains. Minerals such as P and K added in large quantities through addition of organic nutrient sources play an important role in nutrient stress tolerance, promote water uptake and induce growth. Nitrogen increases surface area for photosynthesis and alleviate drought stress hence higher yields achieved (Guo et al., 2018; Ye et al., 2019). However, even though water harvested naturally partially addresses the challenges of low water availability and erratic rainfall in semi-arid regions, the use of rainwater harvesting methods alone may not increase yields. Thus, there is need to combine RWH and the use of external organic amendments to increase rainwater use efficiency by plants. Addition of Leucaena biomass of up to 30 t ha^{-1} increased available nutrients for plants and their uptake can only be increased by the availability of soil moisture which is improved by RWH. This is supported by Kimaru-Muchai et al. (2021) who reported improved sorghum yields after integrated Zai pits and Tithonia biomass in Kenya. Rainwater use efficiency was improved by increasing application rates of Leucaena biomass. Increases in nutrient supply allow crops to demand more water as a result of improved plant growth and development (Hakeem et al., 2018; Mahinda et al, 2018). Sorghum yields and rainwater use efficiency were higher from Macia compared with SV1 variety. This can be linked to genetic differences between the two varieties, with Macia thrive better than SV1 in semi-arid areas. Macia variety is drought tolerant and when nutrients and moisture are improved, its adaptation to semi-arid areas improves.

7.3 EFFECTS OF LEUCAENA/CATTLE MANURE COMBINATION ON YIELDS, RAINWATER USE EFFICIENCY AND ECONOMIC BENEFITS UNDER RAINWATER HARVESTING TECHNIQUES

7.3.1 Effects of Leucaena/cattle manure combination on sorghum yields and harvest index under rainwater harvesting techniques

Combining the two organic nutrient sources improves soil physical and chemical properties. This supply both macro and microelements essential for plant growth and development. Organic nutrient sources such as cattle manure increase microbial population which are responsible for decomposition and mineralisation, improving nutrient availability in the top soil (Yadav and Singh, 2016; Mugwe et al., 2019; Mamuye et al., 2021). In addition, Leucaena/cattle manure combination buffer soil pH creating suitable conditions for plant growth hence increase nutrient availability and crop yields (Timsina, 2018). Long term addition of organic fertilisers increases soil organic carbon (SOC), total nitrogen, total phosphorous, available phosphorous and available potassium which all contribute towards yield increment (Li et al., 2020; Zhang et al., 2022). This also causes improvements in harvest index and water use efficiency by sorghum plants. Rainwater use efficiency improved with increase in application levels. This may have been attributed to high plant growth and increased water demand by plants. Cattle manure contains a lot of stover which need to be decomposed by decomposers. An average C/N ratio of cattle manure is 19:1 and influence microbial reduction. These decomposers use N for decomposition and this reduce available N in the soil (Nyamadzawo et al., 2008). This also contributed to reduced growth and yields at high levels of cattle manure. Farmers can add legume stover or any other material which can be easily decomposed to release N instead of utilising N making it unavailable to plants.

Both sorghum varieties responded by improving yield with increase in application levels of Leucaena/cattle manure combination although SV1 responded better than Macia at rates ≥ 10 t ha^{-1}. Macia variety does well in semi-arid areas where soil fertility and moisture stress are major limiting factors. Since the variety performs positively at low application levels less than 10 t ha^{-1}, it has been noted to have better genetic attributes to survive in semi-arid areas. This was in agreement with Kubiku et al. (2022b) who reported higher yields from Macia variety compared with hybrid variety SC Sila.

Combining Leucaena/cattle manure combination with rainwater harvesting techniques improved sorghum yields, harvest index and rainwater use efficiency. Both organic manure and rainwater harvesting techniques play an important role in improving soil moisture content and decomposition. This increases soil moisture and nutrients in the top soil allowing its utilisation by plants especially during reproductive stage and reduce physiological stresses in plants (Fahad et al., 2021; Owusu-Sekyere, 2021; Srinivasarao et al., 2021) boosting crop yields. Although yield increased as a result of this integration, low increment was observed in standard contours. This may have been attributed to water stress which affected grain filling. Grain yields obtained from combination of Leucaena biomass and cattle manure were slightly higher compared with those reported with the use of Leucaena biomass only. The integration of organic nutrient sources increases nutrient quantities and their availability (Timsina et al., 2018). Grain yield at 30 t ha^{-1} Leucaena biomass only was 1.083 t ha^{-1} which was 0.097 t ha^{-1} less than yields obtained from 30 t ha^{-1} of Leucaena/cattle manure combination. This may have been attributed to improved soil chemical parameters by application of Leucaena/cattle manure combination. Stover yields were higher from experiments done using Leucaena biomass only compared with stover from Leucaena/cattle manure combinations. Stover yield ranged from 2.172 to 4.023 t ha^{-1} (Macia) and 2.188 to 3.94 t ha^{-1} (SV1) from treatments with Leucaena biomass only and lower yields were obtained from Leucaena/cattle manure combination with Macia having 2.211 to 2.835 t ha^{-1} and SV1 (2.216 to 2.773 t ha^{-1}). This may have been linked to low nutrient lease caused by low decomposition of cattle manure. Rainwater use efficiency was in the same range for the experiment done using Leucaena biomass only compared with Leucaena/cattle manure combinations.

7.3.2 Effects of Leucaena/cattle manure combination and rainwater harvesting on return on investment

Net returns were higher in 2018/19 cropping season. The seasons received evenly distributed rainfall although it was low but this promotes biochemical and physiological processes in sorghum plants. Nutrient availability engineer drought and stress tolerance allowing maximum utilisation of nutrients promoting photosynthesis, protein synthesis and nutrient accumulation in grains. This was in agreement to research by Nyamangara et al. (2005) who reported increased net benefits with high application rates of cattle manure. Mucheru-Muna et al. (2007) reported high net benefits with then use of Leucaena biomass and concur with results from this study. This indicates that yields obtained from the experiment have the capacity to pay off costs incurred by farmers.

In three seasons under the experiment, higher net benefits were realised in treatments with tied contours and Leucaena/cattle manure combination due to high water and nutrient availability compared with infiltration pits and standard contour under same treatments. This implies that net returns are high when rainwater harvesting is integrated with nutrient management which improved grain and stover yields. Higher net returns motivate farmers to adopt these techniques. Low net returns from standard contours integrated with Leucaena/cattle manure indicated that nutrient management alone without managing rain water use does not significantly increase economic benefits. This was in agreement with findings by Kimaru-Muchai et al. (2021) who reported higher net benefits when Zai pits were amended with organic nutrient sources.

7.4 EFFECTS OF AUGMENTING LEUCAENA BIOMASS WITH NPK FERTILISER ON SORGHUM YIELD, RAINWATER USE AND AGRONOMIC EFFICIENCY

7.4.1 Effects of Leucaena biomass + NPK fertiliser on sorghum grain and stover yields

Sorghum grain and stover yields were significantly increased with increase in application rates of Leucaena biomass+ NPK fertiliser. Mineral fertiliser applied contributed immensely towards N provision to crops since decomposition rate of organic sources maybe slow and affect N mineralisation (Mwadalu et al., 2022). Mineral fertiliser applied at planting provided sorghum crops with readily available nitrogen which boost crop growth, photosynthesis and protein synthesis. Besides providing nutrients, Leucaena biomass acted as a soil moisture conservation option, improve microbial population and other soil physio-chemical properties (Mafongoya and Dzowela, 1999; Mugwe, 2007).

Leucaena biomass has the capacity to release more nitrogen (Mafongoya et al., 2006b; Murovhi and Materechera, 2006; Katanga et al., 2007b) which has high possibility of increasing sorghum yields when augmented with mineral fertiliser. Macia variety responded better at low application rates of 2.5 and 5 t ha^{-1} of Leucaena biomass augmented with 25 kg and 50 kg ha^{-1} NPK fertiliser (3.5N + $7P_2O_5$ + $3.5K_2O$ kg ha^{-1}) compared with SV1 variety and this can be linked to genetic disparities of the two sorghum varieties. Integrating mineral and organic fertiliser resources create the potential to improve nutrient availability and sorghum yields (Mwadalu et al., 2022; Sher et al., 2022). Nutrient status in the soil directly affects growth and crop biomass. Combining mineral fertiliser and organic manure improve mineralisation of nutrients from organic manure and increase crop yields. Grain and stover yields observed from use of Leucaena biomass + NPK fertiliser were higher than those reported from use of Leucaena biomass only but less compared with Leucaena/cattle manure combination. Use of NPK fertiliser made quick availability of nutrients but does not sustainable throughout the season as compared to nutrients released from cattle manure. Leucaena biomass +NPK fertiliser had better yields compared with Leucaena biomass only due to improved agronomic efficiencies associated with low application rates (Mwadalu et al., 2022).

7.4.2 Effects of Leucaena biomass + NPK fertiliser combination on Rainwater use and agronomic efficiency

The application of Leucaena biomass reduced leaching of nutrients by improving soil structure and promotes efficiency nutrient utilisation. This causes higher agronomic efficiency of using organic manure in combination with mineral fertiliser. Integration of organic and inorganic fertiliser builds up soil quality, increasing NUE and promotes higher yields (Sher et al., 2022). Since organic manure improves soil water holding capacity promoting efficient water utilisation by plants. This is in agreement with Hakeem et al. (2018) who reported higher water use efficiency with application of N fertiliser. Results from this study concur with Hartfield et al. (2001) and Gonda (2015) who reported that combining organic and mineral fertiliser improves soil and water conservation leading to improved RWUE of crops.

Higher agronomic efficiency was observed from Macia variety applied 2.5 t ha^{-1} of Leucaena biomass augmented with 25 kg ha^{-1} NPK fertiliser. This indicates that Macia performs better in semi-arid areas. Application of low levels of organic and inorganic fertiliser improves AE because of high utilisation of nutrients. Application of higher levels nutrient sources indicated low agronomic efficiency. This can be attributed to nutrient toxicity which may cause rank growth. Rainwater use efficiency reported from Leucaena biomass +NPK fertiliser was in the same range with results from use of Leucaena biomass only and Leucaena/cattle manure combination.

7.5 CONCLUSIONS

In semi-arid region of Zimbabwe where rainfall is low, erratic and soils are poor, the use of RWH and biomass transfer has a potential to increase sorghum yields and improve household food security. This is because RWH techniques harvest surface runoff water, store it and improve soil moisture content making it available to plants. This moisture will be used by plants for growth, photosynthesis and grain filling which increases crop yields. Rainwater harvesting practices reduces surface runoff and soil erosion which cause nutrient loss. Leucaena biomass improves soil nutrient content especially nitrogen which is the most limiting nutrient in many soils. Addition of Leucaena biomass also improves SOC and water retention making more water available to plants for growth and development. This increases photosynthetic area, protein synthesis and movement of carbohydrates from leaves to grains producing higher yield. The combination of RWH and Leucaena biomass improves soil moisture content and nutrients in the plant root zone. This promotes biochemical and physiological process such as protein synthesis and photosynthesis which play an important role in achieving higher yields. Integrating tied contours and Leucaena biomass at 10 t ha^{-1} had the highest incremental effect on soil moisture content, RWUE, grain and stover yields compared with any other application rates. RWH and biomass transfer of Leucaena has the capacity to improve food security for smallholder farmers at 10 t ha^{-1} biomass combined with tied contours or infiltration pits.

Availability of large quantities of Leucaena biomass in smallholder farming areas can be a problem hence the need to combine it with organic manure in equal quantities to boost nutrient levels. Cattle manure available in smallholder farming systems is of poor quality especially in N content and this can be improved by combining with Leucaena biomass. Leucaena/cattle manure combination increases mineral N, phosphorous and trace elements such as boron, zinc and manganese which play important role in photosynthesis, pollination and fertilisation. The combination increases SOC, improve soil structure and water holding capacity. This generally improves crop production. Leucaena/cattle manure combination improves utilisation of nutrients by crops, increase photosynthetic area and stress tolerance especially during critical stages such as grain filling. Application rate of 10 t ha^{-1} of Leucaena/cattle manure combinations can be adopted by farmers as this has better yield benefits, return on investment and yields per increase in application rate (1 t ha^{-1}) compared with other rates. Leucaena/cattle manure combination can be integrated with RWH practices to boost soil moisture content in the long run and reduce soil moisture stress caused by long dry spells and frequent droughts in semi-arid areas. Integrating these technologies has been reported to increase grain yields by more than 30 % and this sustain food availability to smallholder farmers who require 0.8 t of grains per year.

Cattle manure is one of the major organic nutrients sources which smallholder farmers can use but other farmers have no capacity to have large quantities of cattle manure hence the need to augment Leucaena biomass with mineral (NPK) fertiliser. Augmenting Leucaena biomass with NPK fertiliser significantly increase rainwater use efficiency, agronomic efficiency, sorghum grain and stover yields. Augmenting Leucaena biomass at 10 t ha^{-1} with 100 kg ha^{-1}NPK fertiliser produce grain yields above 0.8 t ha^{-1} needed by many households per year. This shows that there is a potential for this technology to improve food supply and even surpass this level. Since moisture stress is one of the major constraints in semi-arid areas, farmers can integrate this technology with RWH to improve water availability in plant root zone and reduces effects of moisture stress especially during grain filling. Integrating 5 t ha^{-1}Leucaena biomass + 50 kg ha^{-1}NPF fertiliser + tied contours meet food demand by smallholder farmers and even surpass the level allowing farmers to enjoy the surplus. This also creates high agronomic efficiencies for smallholder farmers.

Leucaena biomass is not readily available to smallholder farmers but the tree is easy to establish and it grows quickly. Farmers can be provided with a maximum of 50 Leucaena seedlings and grow it. This boost adoption of the technology by farmers and government may implement policies of using biofertilisers to achieve climate smart agriculture and produce organic products. Farmers can also adopt the use of compost prepared using legume residues if Leucaena is not available. This has the potential to boost mineral N and yields. On overall, Macia variety gave the highest sorghum yields, RWUE, agronomic efficiencies and return on investment compared with SV1 variety. Framers may adopt Macia variety since it is drought tolerant and survive under stress conditions in semi-arid areas, improving household food security and provide income to farmers.

7.6 RECOMMENDATIONS

Basing on the results from this study, the following recommendations were made:

- Farmers can adopt the use of Leucaena biomass to improve soil fertility, conserve soil moisture and increase sorghum yields under dryland farming.
- Farmers can combine Leucaena leucocephala biomass with either tied contours or infiltrations pits to improve soil moisture, rainwater use efficiency and sorghum yields.
- Since most dryland farmers in rural communities have cattle, they can combine cattle manure and Leucaena biomass in equal proportions to improve yields, increase economic benefits and reduce cost of production.
- Government through the Ministry of Agriculture, Resettlement, Lands, Water and Fisheries is recommended to provide Leucaena seedling to smallholder farmers by establishing sites where farmers are taught how to grow the tree and harvest biomass.
- Smallholder farmers are resource poor hence they are encouraged to augment Leucaena biomass or compost prepared using legume residues with NPK fertiliser to promote mineralisation and enhance sorghum production under dryland farming.
- It is not economically feasible for farmers to use tied contours and infiltration pits without any soil fertility amendments. Farmers are encouraged to construct tied contours and

infiltration pits just after harvesting since this is non-peak labour requirement hence maximising farm profitability.

- Smallholder farmers under rainfed agriculture are recommended to adopt the use of 10 t ha^{-1} Leucaena biomass, 10 t ha^{-1} Leucaena/cattle combinations and 10 t ha^{-1} Leucaena biomass + 100kg ha^{-1} NPK fertiliser (7N + $14P_2O_5$ + $7K_2O$ kg ha^{-1}) to meet food demand per year and enjoy better return on investment. These levels have the potential to scale up yields by integrating them with tied contours or infiltration pits and Macia variety.
- Policy makers in Agricultural production are recommended to make policies which make it a mandatory for smallholder farmers in semi-arid areas to use tied contours or infiltration pits and organic nutrient sources to improve food security and return on investment.

7.7 FURTHER RESEARCH

- Further research on long term effects of tied contours and infiltration pits on soil moisture, yield and economic benefits on various distances from tied contours and infiltration pits need to be evaluated.
- There is need to study the effects of Leucaena/cattle manure combinations on bulk density, nitrogen use efficiency and plant nutrient content.
- Further economic evaluations should be done not only on sorghum grain and stover yields but on short to long term effects of these technologies such as soil conservation and soil physio-chemical properties.

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