Bindura University of Science Education

ENHANCING CLIMATE CHANGE RESILIENCE IN *SORGHUM BICOLOR L.* (SORGHUM) PRODUCTION THROUGH SUSTAINABLE CROP INTENSIFICATION

BY

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ABSTRACT

Low and poorly distributed rainfall coupled with insufficient nitrogen (N) fertilizer use in rain-fed smallholder farming systems affect *Sorghum bicolor L.* (sorghum) yields. Contour-based rainwater harvesting (RWH) practices can provide viable adaptative climate change resilient crop intensification practices to overcome rainfall variability due to climate change in semi-arid regions of Zimbabwe. The research aimed to quantify sorghum grain yield response to *in-situ* water retention techniques (basins, ripper, and tied ridges), and RWH (Tied Contour (TC) and Infiltration Pits (IP)) under different nutrient management practices. A meta-analysis was conducted to determine sorghum grain yield response to *in-situ* rainwater retention techniques. Using the weighted mean yield difference approach, the *in-situ* rainwater retention practices were assessed under different rainfall amounts, soil texture, mulch, and nitrogen fertility. The results of the meta-analysis showed that basins, ripper, and tied ridges had no sorghum grain yield advantage over the conventional practice in all agronomic environments. To determine the grain yield performance of sorghum varieties (Macia and Sc Sila) in RWH practices at varying nutrient management practices (inorganic nitrogen fertilizer, inorganic nitrogen fertilizer + organic fertilizer, and organic fertilizer), a field experiment was set up. Experiment 1 was made up of the two sorghum varieties under RWH practices and inorganic nutrient management practice. Experiment 2 was made up of the two sorghum varieties under inorganic nitrogen + organic fertilizer. Experiment 3 consisted Macia and Sc Sila sorghum varieties under RWH practices and organic nitrogen management. In all the three experiments a randomised completed block design experiment in a split-split plot configuration was conducted in 2016/17 to 2018/19 seasons at Mt Zonwe smallholder farming area in Mutare district, Zimbabwe. Nitrogen and rainwater use efficiencies were also evaluated under RWH practices and inorganic nitrogen fertilizer experiments. Soil moisture and grain yield data were subjected to analysis of variance and least significant difference at $p<0.05$ was used to separate significantly different means. The results revealed that TC and IP increased gravimetric soil water content (gwc). Tied Contour and IP yielded more sorghum grain than modified standard contour (SC) in all the seasons, nitrogen application rates, and distance from RWH. In the contour based RWH and inorganic nitrogen + cattle manure experiment, results showed that the grain yields of Macia and Sc Sila were considerably higher under TC and IP than SC in all the seasons. Macia had a higher grain yield at each incremental level of nitrogen addition to cattle manure than Sc Sila. The findings from the contour based RWH practice and cattle manure experiment showed that sorghum grain yield increased with an increase in cattle manure application up to 20 t/ha and varied in the order TC > IP > SC. Macia showed a higher yield than Sc Sila at all cattle manure application rates. The assessment of agronomic efficiency (AE) and rainwater use efficiency (RUE) under the contour based RWH practices and inorganic nitrogen fertilizer showed that TC and IP increased AE compared with SC across all nitrogen application rates, distances from RWH practice, and seasons. Macia had higher AE than Sc Sila at nitrogen application of 50 and 70 kg/ha while nitrogen application >100 kg/ha had no difference in both varieties. Rainwater use efficiency was 21% greater in Macia than Sc Sila while nitrogen fertilizer application increased RUE up to 100 kg N/ ha beyond which there was no difference. The findings suggest that planting basins, ripper planting, and tied ridges have no yield advantage over conventional farming practices, while TC and IP, inorganic and organic nutrient management practices proved to be resilient crop intensification practices in sorghum production. This was evidenced by improved soil moisture, sorghum grain yield, nitrogen use efficiency, and rainwater productivity in rainfed smallholder farming systems.

Keywords; Tied contour, Infiltration pits, basins, tied ridges, ripper planting, nutrient management

DECLARATION: PLAGIARISM

I, Friday Nguvayasvika Mudondo Kubiku declare that:

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

1 Kubiku, F. N. M., Mandumbu, R., & Nyamadzawo, G. (2023). Enhancing nitrogen and rainwater use efficiency through rainwater harvesting in semi-arid smallholder sorghum (*Sorghum bicolor*) farming systems. *Cogent Food & Agriculture, 9*(1), 2235762. https://doi.org/10.1080/23311932.2023.2235762

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3 Kubiku, F. N. M., Nyamadzawo, G., Nyamangara, J., & Mandumbu, R. (2022). Effect of contour rainwater-harvesting and integrated nutrient management on sorghum grain yield in semi-arid farming environments of Zimbabwe, *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, 72(1), 364-374. http://dx.doi.org/10.1080/09064710.2021.

4 Kubiku, F. N. M., Mandumbu, R., Nyamangara, J., & Nyamadzawo, G. (2022). Sorghum (*Sorghum bicolor L.*) yield response to rainwater harvesting practices in the semi-arid farming environments of Zimbabwe: A meta-analysis. *Heliyon, 8*(1), e09164. https://doi.org/10.1016/j.heliyon.2022.e09164

APPROVAL FORM

We the undersigned certify that we have supervised and recommend to Bindura University of Science Education (BUSE) for acceptance of a thesis entitled "Enhancing climate change resilience in *Sorghum bicolor L.* (Sorghum) production through sustainable crop intensification" for submission of the Doctor of Philosophy Degree in Agronomy.

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DEDICATION

To my wife, Rumbidzai Norah, and my children Valour M., Vannyah K., and Vien.

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LIST OF ABBREVIATIONS

AE	-	Agronomic Efficiency
ANOVA	-	Analysis of Variance
$CaCl_2$	-	Calcium Chloride
CV	-	Coefficient of Variation
E	-	East
gwc	-	Gravimetric Water Content
ha	-	Hectare
IFS	-	International Foundation for Science
IP	-	Infiltration pits
K	-	Potassium
Kg	-	Kilogram
LSD	-	Least Significant Difference
m	-	Meter
M	-	Moles
mg	-	Milligram
mm	-	Millimetres
m^2	-	Square metre
MN	-	Mineral Nitrogen
N	-	Sample size

N	-	Nitrogen
P	-	Phosphorus
pH	-	Potential of Hydrogen
RF	-	Rainfall
RWH	-	Rainwater Harvesting
S	-	South
SC	-	Standard Contour
SD	-	Standard Deviation
SE	-	Standard Error
t	-	Tonne
TC	-	Tied Contour
WMD	-	Weighted Mean Difference

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Agriculture is currently grappling with the challenge of increasing food production by 70–100% to meet the food needs of a rising global population expected to reach over 9 billion people by 2050 (King et al., 2017; Whitfield et al., 2018). In most African farming areas, crop yields are poor and continue to decline, which may be a leading cause of the declining per capita food production presenting a serious challenge to food security. Agriculture is the most important economic sector in Africa where more than 70% of its population is directly engaged in agriculture (Nchuchuwe & Adejuwon, 2012). Rapid population growth in sub Saharan Africa continued to force farmers to increase the production of staple food and cash crops, which are heavily reliant on water and external inorganic inputs (Moyo, 2016). The future global food security is not dependant only on high production and access to food but also on the need to address the destructive effects of current agricultural production systems on ecosystem services and increase the resilience of production systems to the effects of climate change (Owenya et al., 2012).

Resilience is defined as the propensity of a system to retain its organizational structure and productivity following a perturbation (Common, 2017). Thus, a resilient agroecosystem will continue to provide a vital service such as food production if challenged by abiotic and biotic stresses such as severe drought or by a large reduction in rainfall, fertility depletion, and pests and diseases (Mustafa et al., 2019). Thus, to meet global food-security requirements agricultural sectors around the world will need to pursue appropriate resilient strategies for agricultural production (Abraham et al., 2014) through sustainable crop intensification. In Zimbabwe, agriculture is one of the mainstays of the economy yet, it is the most volatile sector mainly due to its dependence on rain-fed systems and the seasonal shocks that are frequently observed (Sime & Aune, 2019). Smallholder farmers lack holistic adaptive resilient strategies to mitigate these seasonal shocks as a result of climate change in rainfed farming systems. Small grain crop production especially sorghum (*Sorghum biclor L.)* in semi-arid areas has the to meet food security. However, the average yield of sorghum in smallholder farming system stagnated at 0.5 t/ha, which is below the crop yield potential due to climate change and variability.

1.2 SORGHUM PRODUCTION IN THE SEMI-ARID FARMING SYSTEM

Sorghum is one of the crop species which has the potential to improve people's livelihoods, as well as food security and sovereignty, but not being fully realized because of its limited competitiveness with commodity crops in mainstream agriculture (Ulian et al., 2020). It is a cereal crop, widely grown by resource-poor farmers in Africa (Hambloch et al., 2021). Its production system is generally characterized by extensive (rather than intensive) production practices and limited adoption of improved varieties (Hambloch et al., 2021). Sorghum yields in the semi-arid smallholder farming systems have stagnated because production is being pushed into areas with low rainfall and poor soils (Hadebe et al., 2017a). In Zimbabwe, it is a staple food and the most extensively grown field crop by smallholder farmers in semi-arid regions where it accounts for about 20% of total cereal production (Hadebe et al., 2020). Sorghum is mainly grown in natural regions IV and V characterized by poor soils and limited precipitation of less than 450 mm per annum. The water requirements of sorghum ranges between 450-650 mm per production season (Hadebe et al., 2017a). Many smallholder farmers in semi-arid areas obtain meagre sorghum yields of about 0.5 t/ha which are below the yield potential of the crop (3 to 5 t/ha) (Rurinda et al., 2014). It implies that the yielding ability of sorghum is not only a function of total amount of rainfall received during the production season, but also its even distribution. According to Nyakatawa et al. (1996) and Nyamudeza, 1999), drought and uneven rainfall distribution, and nutrient stress are among the main agro-ecological factors limiting the sorghum grain yield in smallholder farming systems. However, the crop possesses water stress responses which can be physiological, morphological or phenological in nature and degree of responsiveness differs with sorghum genotype. Drought-tolerant sorghum varieties typically have deeper root systems, which allow them to access water deeper in the soil profile (Baum et al., 2019). They also tend to have thicker stems, which help to conserve water and prevent wilting (Jones and Rawson, 2006). In addition, drought-tolerant sorghum varieties often have shorter growing seasons, which reduce the period of time during which they are exposed to drought conditions. Furthermore, drought-tolerant sorghum varieties often have thicker leaves, which help to reduce water loss through transpiration (Hadebe et al., 2020). Finally, some varieties have reduced panicle size, which decreases the amount of water required for photosynthesis and grain filling (Abreha et al., 2022). So, the combination of all these traits can make sorghum more drought tolerant. Hadebe et al. (2020) reported that the degree the high coefient of rainfall variability in semi-arid farming systems tend to set a stronger limit on the extent to which sorghum respond to water stress. Therefore, to close the yield gap between the actual yield and maximum yield water and nutrient productivity of smallholder rain-fed sorghum farming systems need to be improved.

1.3 CLIMATE CHANGE AND VARIABILITY IN SORGHUM PRODUCTION

Climate change is disrupting rainfall patterns causing a drastic drop in precipitation, erratic rainfall, and uneven distribution making farming a risky business and threatening food security among smallholder farmers in semi-arid farming communities. In drylands, water is one of the key challenges to sorghum yield potential due to the extreme variability of rainfall, long dry seasons, and recurrent droughts and dry spells. In addition to the unpredictability and unreliability of annual and seasonal rainfalls, the loss of rainwater through non-productive pathways also contributes significantly to water scarcity in rain-fed agriculture. The little rain that is received in the semi-arid regions more than 50 % is lost as runoff, and very little water is harvested for plant growth or future use (Nyagumbo et al., 2019). In some cases, the area receives heavy short-duration storms with an intensity that far exceeds the infiltration rates of the soils resulting in runoff losses from the field (Nyakudya & Stroosnijder, 2011). Hence, lowering these risks through investments in appropriate rainwater harvesting and management techniques can improve sorghum yield (Kemeze, 2020). To mitigate the effects of climate change and variability, several technologies need to be developed and implemented in semi-arid areas. Integrating rainwater harvesting and nutrient management crop intensification practices may be an alternative strategy to improve sorghum yield if food security is to be realized in drought-prone farming areas.

1.4 CROP INTENSIFICATION

Crop intensification has been technically defined as an increase in crop production per unit of inputs (which may be labour, land, time, fertilizer, seed, feed, or cash) (Hadebe et al., 2020). Intensification occurs when there is an increase in the total volume of agricultural production that results from higher productivity of inputs, or agricultural production is maintained while certain inputs are decreased. Intensification that takes the form of increased production is most critical when there is a need to expand food supply in the face of exploding population, climate change, and a decline in soil fertility. Crop intensification farming options such as rainwater harvesting and nutrient management techniques have been put forward as resilient agro-ecological crop intensification practices to improve productivity, but knowledge on how best these can be integrated into heterogeneous farming systems is inadequate (Hambloch et al., 2021). The full benefits of crop intensification need a holistic approach. Most research studies had not focused on integrating the practices to harness the synergies and interaction effects associated with combing more than one adaptive crop intensification practice in semi-arid farming regions (Nyagumbo et al., 2019). In rain-fed areas, the additional amount of water needed to support agriculture directly depends on gains in water productivity - “more crop per drop" - through efficient water management integrated techniques (Ncube et al., 2018). Improving water use efficiency in Zimbabwe's semi-arid areas can be achieved either by increasing the amount of water available for transpiration and/or by increasing the efficiency with which transpired water produces more biomass (Hadebe et al., 2017a). There are two broad strategies for increasing yields in rain-fed agriculture when water availability in the root zone constrains crop growth: (1) capturing more water and allowing it to infiltrate into the root zone; and (2) using the available water more efficiently (increasing water productivity) by increasing the plant water uptake capacity and/or reducing non-productive soil evaporation (Moswetsi et al., 2017). Rainwater harvesting is a growing technique to significantly increase water productivity, thus mitigating agricultural water scarcity and allowing increases in crop production levels.

1.5 SOIL FERTILITY CHALLENGE IN SORGHUM PRODUCTION

Declining soil fertility has been identified as another major production constraint for smallholder farmers (Rusinamhodzi et al., 2016). In Sub-Saharan Africa, there is evidence that inorganic inputs are either not used at all or applied in suboptimal quantities due to unreliable rainfall, unavailability, and high cost (MacCarthy et al., 2018). As a result, most of the income from subsistence-oriented farms is derived from nutrient mining putting in danger the long-term sustainability of the agricultural production system (Namoi et al., 2014). Drought due to climate change reduces the responsiveness of crops to inorganic and organic fertilizer applications (Jiri et al., 2018). Indeed, plant nutrient use efficiency particularly nitrogen in cereal-based farming systems is very low because of limited soil moisture conditions.

Traditionally horizontal expansion of cultivatable area has been one way of achieving increased fertility, as, farmers cleared land, grow a few crops, and then moved on to clear more land, leaving the land fallow to regain its fertility (Cairns, 2015). However, this is no longer possible due to the ever-exploding population, climate change, and labour shortage in the smallholder farming sector (Ulian et al., 2020). Many smallholder farmers occupy marginal lands which are inherently infertile and receive sub-optimal rainfall which threatens productivity and call for adaptive practical crop intensification measures. High rates of nutrient transfers through crop harvests and insufficient recycling of nutrients through the use of compost and manure is common in semi-arid smallholder farming regions (Kemeze, 2020). Smallholder farmers in semi-arid regions are characterized by poor resource endowments and limited capacity to use inputs such as labour and fertilizer. Their organic source of nutrients had shrinked as evidenced by a smaller number of cattle which average +/-4 per household (Kemeze, 2020). The organic fraction in the form of crop residues is also limited due to competing uses like livestock and firewood (Nyakatawa et al., 1996; Nyamudeza, 1999). In addition, the resources i.e., labour, inorganic and organic fertilizer among other inputs are generally used over the cropland, which they cannot support resulting in meagre yields which are far below subsistence (Rusinamhodzi et al., 2016). This scenario makes it difficult for the farmers to practice intensification because of poor resource endowments. Limited research has been carried out to address resilient and adaptive agricultural intensification practices, and the results are fragmented and have not been collated or made easily accessible (Rusinamhodzi et al., 2016). The increase in food production must therefore come from crop intensification practices such as integrating rainwater harvesting and nutrient management in the form of improved inorganic and/or organic fertilizer, adaptive seed varieties, and optimum cropping intensities.

Generally, sorghum requires nitrogen, phosphorus, and potassium (NPK) for optimal growth and yield. The specific nutrient requirements can vary depending on the variety, climate, and other environmental factors. For example, varieties with high yield potential may require higher amounts of NPK than lower-yielding varieties. In general, sorghum requires approximately 60 kg/ha to 120 kg/ha of nitrogen, 30 kg/ha to 50 kg/ha of phosphorus, and 30 kg/ha to 50 kg/ha of potassium. The actual nutrient requirements may vary depending on the specific situation. One critical issue for the expansion of fertilizer use into the semi-arid regions is insufficient water. Various studies were conducted on the use of organic matter, mulching, and various types of fertilizers for improving soil fertility in Zimbabwe. From a study conducted in Zimbabwe, Nyakatawa (1996) reported sorghum yield increases from 118 to 388 kg/ha when 1.5-m tied-ridges were used and increases to 1071 kg/ha when 50 kg N/ ha was applied to the tied-ridges in years of limited rainfall. Ismaeil et al. (2012) and Kugedera et al. (2022) found that the use of manure, compost, and fertilizer can all improve the yield of sorghum and a combination of manure and mineral fertilizer increased the biomass of sorghum plants by up to 40%. Masvaya et al. (2017) found that mulching and minimum tillage can significantly increase sorghum yields. In addition, a study by Nyamangara et al. (2014) showed that using crop rotation and cover crops can also improve soil fertility for sorghum production in Zimbabwe. The findings of these studies suggest that various soil fertility management practices can be effective in increasing crop yields in Zimbabwe.

1.6 RAINWATER HARVESTING AND NUTRIENT MANAGEMENT

Rainwater harvesting has been promoted in sub-Saharan Africa as a means of inducing, collecting, and storing local surface runoff (Nyamadzawo et al., 2013). The runoff is intercepted and concentrated for subsequent storage either in soil for direct use by plants or in reservoirs for later application when needed to mitigate dry spells (Mzirai, 2010). Rainwater harvesting is based on the utilization of runoff and requires a runoff producing area and a runoff receiving area. In crop production, the runoff producing area is called the catchment area, and the runoff utilization area is called a cropped basin (Rockström et al., 2010). They vary from macro to micro *in-situ* systems based on the size of the catchments and runoff transfer distances. The movement of water in soils under rainwater harvesting is affected by several soil physics concepts. First is the concept of infiltration, which refers to the movement of water into the soil. The rate of infiltration is affected by factors such as soil texture, soil structure, and the presence of roots and other obstructions (Mouzakiti et al., 2019). Another concept is percolation, which is the movement of water through the soil profile. Percolation is affected by factors such as soil porosity, pore size distribution, and soil depth (Gebremeskel et al., 2017). A third concept is runoff, which refers to the water that flows over the surface of the soil rather than soil rather than infiltrating or percolating through it (Moise et al., 2020). Runoff is affected by factors such as soil surface roughness, vegetation cover, and the slope of the land.

The basic soil physics concepts help to understand how rainwater harvesting affects the movement of water in soils. The most important factor is the storage capacity of the soil. This refers to the amount of water that can be held in the soil before it begins to flow over the surface as runoff. The storage capacity is influenced by the infiltration rate, the porosity of the soil, and the depth of the water table (Moise et al., 2020). Increasing the storage capacity of the soil is one of the main goals of rainwater harvesting practices. The flow rate of water through the soil is also an important factor which affected by the size and number of pores in the soil, as well as the soil's ability to transmit water through the pores. The rate of flow can be increased by increasing the number of pores, increasing the size of the pores, and improving the soil's ability to transmit water. These factors can be influenced by the type of soil, the amount of organic matter in the soil, and the presence of clays and other minerals (Mouzakiti et al., 2019).

The catchment characteristics, such as the slope, vegetation cover, and soil type, can have a significant impact on the movement of water under rainwater harvesting. For example, a steeper slope will result in a faster flow of water, while a flatter slope will allow more time for infiltration (Mouzakiti et al., 2019). Vegetation cover also plays a role, as it reduces runoff and increases infiltration. The soil profile conditions, such as the depth of the soil and the presence of impermeable layers, can also influence the movement of water under rainwater harvesting (Gebremeskel et al., 2017). A steep slope, poor vegetation cover, and shallow soil with an impermeable layer will result in the majority of the rainwater flowing over the surface of the soil and cause erosion, while only a small amount will infiltrate into the soil. The result is a loss of water and nutrients from the system. The water availability to plants is very low because most of the water is lost to runoff and erosion, and the water that infiltrates into the soil is trapped below the impermeable layer, where it is inaccessible to plants (Gebremeskel et al., 2017). A gentle slope, good vegetation cover, and deep soil with no impermeable layer will result in the majority of the rainwater infiltrating into the soil, where it will be stored and gradually released into the atmosphere through evapotranspiration. This results in a reduction of runoff and erosion, and an increase in water and nutrient availability to crops.

Rainwater harvesting can be more effective in sandy soils than in clay soils (Mupangwa et al., 2012a). This is because rainwater can percolate more easily through the loose, porous structure of sand, making it easier to move. In contrast, rainwater can become trapped in the tightly packed structure of clay, making it more difficult to move. However, the high porosity of sand also allows more water to be lost through deep percolation. The rainwater harvesting techniques have gained popularity because of their potential to collect and store runoff. In Zimbabwe, the different rainwater harvesting techniques such as *Fanya juus*, planting basins, infiltration pits, and tied ridges are being used by smallholder farmers to improve soil moisture (Nyagumbo et al., 2019). The techniques improve water infiltration rate, water retention, reduce evaporation, increase surface storage, and the time available for infiltration to occur.

Although nutrient limitations set stronger ceilings on yield than water availability in many dryland regions (Molden et al., 2010), investments in soil nutrients and related production enhancing inputs are less likely due to risks of crop failure by erratic rainfall and long dry spells (Rockström et al., 2010). Infield rainwater harvesting through tied contours and contour infiltration pits are some of the many climate change adaptation strategies that semi-arid farmers can adopt in Zimbabwe (Nyamadzawo et al., 2013). With improved rainwater harvesting, rainfall can sustain crop production during the mid-season dry spells and this will reduce crop failures and may ultimately lead to household food security (Nyagumbo et al., 2019). Integrated water and soil nutrient management particularly focused on rainwater harvesting for dry-spell mitigation and soil fertility improvement can substantially improve yields and water productivity (Mhaka et al., 2012). Hence, lowering these risks through investments in appropriate tied contour and infiltration pits rainwater harvesting, and nutrient management techniques can improve sorghum yield (Rockström et al., 2010). However, only a few studies have been undertaken to understand the effect of rainwater harvesting and nutrient management as resilient adaptive agro-ecological crop intensification techniques on sorghum productivity in dryland agricultural systems.

1.7 PROBLEM STATEMENT AND JUSTIFICATION

Rainwater harvesting either through runoff collection from a catchment area upslope or through conservation of rainfall where it falls in the cropped area has received limited attention in rain-fed systems of semi-arid farming regions of Zimbabwe (Ali, 2016). Early research by Elwell (1997) on the effects of contour farming on soil erosion found that contour farming can reduce the rate of soil erosion by up to 70% compared to conventional farming practices. In addition, contour farming was found to increase crop yields and reduce the loss of nutrients from the soil. Contour farming works by breaking up the flow of water and slowing its movement down the slope, which helps to reduce the amount of soil that is carried away by the water. They focused on reducing soil erosion without investigating the potential of contours as rainwater harvesting structures. Despite water harvesting techniques showing some positive impact of both macro and micro-catchment rainwater harvesting on soil moisture regimes and crop yields, they lacked a holistic approach to problems currently facing the smallholder farming community (Kahinda & Masiyandima, 2014; Tirivangasi & Nyahunda, 2019). Micro-catchment water harvesting techniques that have been promoted throughout southern Zimbabwe include dead-level contours with or without infiltration pits and graded contour ridges (< 5% slope) (Biazin et al., 2012). However, smallholder farmers in semi-arid regions still rely on guesswork on appropriate rainwater harvesting practices to improve crop productivity in the face of climate change making farming a risky business, especially with the advent of erratic rainfall and uneven distribution. Farmers need to invest their scarce labour resources in technologies likely to benefit them in the long run (Barbier, 2012). There is a growing body of knowledge on water harvesting techniques and integrated nutrient management, but knowledge on applicability to diverse farming systems is still scanty. In many semi-arid smallholder farming sector contour ridges exists which mainly serve a function in reducing soil erosion and downward particle transport, but knowledge of how the contours can be used for rainwater harvesting through improving rainwater infiltration is limited among the smallholder farmers.

Most studies on in-situ rainwater harvesting systems overlooked the problem of soil fertility, which can curtail the benefits associated with improved soil water status. Lack of response to soil water management is sometimes compounded by poor soil fertility. Early studies conducted by Nyakatawa et al. (1996) and (Nyamudeza, 1999) investigated the interaction of tied ridge/furrow systems and soil fertility at Chiredzi Research Station while later studies by Motsi et al. (2004), Mugabe (2004), Mupangwa et al. (2006), Mupangwa et al. (2012a), Mhizha & Ndiritu (2013) and Nyakudya et al. (2014) focused on soil moisture management on maize and very little work has been done on sorghum under the rainwater harvesting practices. The answer to the question, to what extent can rainwater harvesting improve nutrient use and vice versa is still scanty, and extension staff is poorly informed to tackle the question when posed to them by farmers, a situation that often results in inappropriate recommendations being forwarded to farmers (Nyagumbo et al., 2019). Therefore, the is a need to exploit synergies and interaction effects between rainwater harvesting practices, soil fertility management options, and sorghum varieties in rain-fed semi-arid smallholder farming systems to determine grain yield, water, and nutrient productivity under such practices. Successful adaptive agro-ecological and sustainable crop intensification options require the synergistic provision of water and nutrients. Water and nutrients are key elements needed to support effective plant growth and to reduce crop failure. Substantial knowledge needs therefore to be explored particularly the impact of combining soil fertility management especially inorganic nitrogen and organic sources of nitrogen with contour-based rainwater harvesting techniques on water and nutrient productivity in semi-arid rain-fed farming systems. This will generate a basket of options for the resource-constrained smallholder farmers in semi-arid farming areas. And by conducting more research on these practices at the farmer level, smallholder farmers in semi-arid regions will be at the forefront of a sustainable revolution in agriculture. Water harvesting practices and nutrient management options need to be constantly examined in contrasting agro-ecological zones to determine their potential as resilient crop intensification strategies to mitigate climate change and variability in agriculture to improve crop yield and food security. The study carried out a meta-analysis on sorghum yield response to in-situ rainwater harvesting practices (tied ridges, basin planting, ripper planting), and explored the effect of contour-based rainwater harvesting techniques (tied contours, infiltration pits) and nutrient management options (inorganic and organic fertilizer) on soil moisture, sorghum yield, rainwater and nutrient use efficiency in semi-arid regions.

1.8 CONCEPTUAL FRAMEWORK

Figure 1.1 shows the relationships between the different variables that may affect sorghum grain yield in semi-arid smallholder farming systems. The rainwater harvesting and nutrient management practices are the independent variables, meaning that they are the variables that be manipulated in the study. The dependant variable is sorghum grain yield. The control variables such as soil type, soil moisture and rainwater harvesting method which influence the effectiveness of rainwater harvesting and nutrient management practices. The research intends to determine the effect of contour based RWH practices (Tied contour and infiltration pits) on two sorghum varieties (Macia and Sc Sila) under varying nutrient management practices.

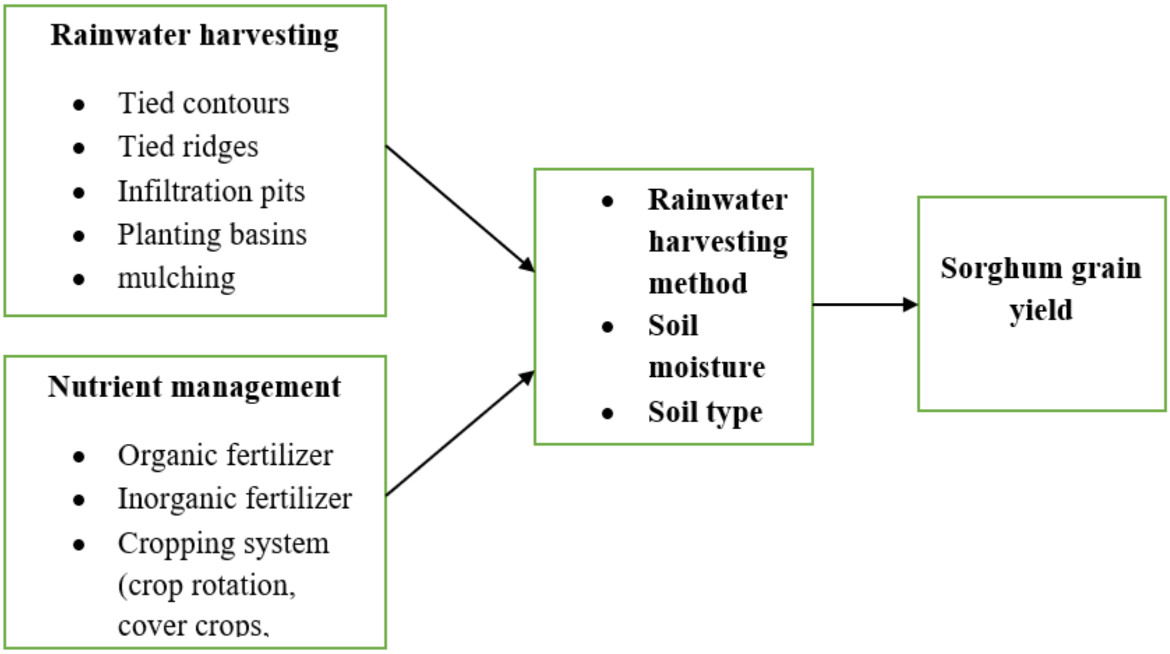

Figure 1. 1: Conceptual framework

1.9 MAIN RESEARCH OBJECTIVE

To evaluate the effect of rainwater harvesting and nutrient management crop intensification options on soil moisture, sorghum grain yield, nutrient use efficiency, and rainwater use efficiency in semi-arid smallholder farming systems.

1.9.1 Specific objectives

1. To determine sorghum grain yield response under *in-situ* rainwater harvesting practices (tied ridges, basins, and ripper planting) in the semi-arid smallholder farming systems.
2. To evaluate sorghum grain yield response under contour-based rainwater harvesting practices (tied contour, infiltration pits) and inorganic nitrogen nutrient management options in the semi-arid rain-fed farming systems.

3. To evaluate the effect of contour-based rainwater harvesting (tied contour, infiltration pits) and organic nutrient management on sorghum grain yield in the semi-arid rain-fed farming systems.
4. To evaluate sorghum grain yield response under contour-based rainwater harvesting (tied contour, infiltration pits) and integrated nutrient management in smallholder rainfed farming systems.
5. To evaluate nitrogen and rainwater use efficiency in contour-based rainwater harvesting (tied contour, infiltration pits) and inorganic nitrogen fertiliser management in semi-arid smallholder farming systems.

1.9.2 Hypotheses

1. Sorghum grain yield is higher under in-situ rainwater harvesting practices (basins, tied ridges, ripper planting) than under conventional farming practices in semi-arid rain-fed farming systems.
2. Sorghum grain yield is higher under contour-based rainwater harvesting (tied contour, infiltration pits, standard contour) with inorganic nutrient management practices than under conventional faming system with inorganic nutrient management in semi-arid smallholder farming systems.
3. Sorghum grain yield is higher under contour-based rainwater harvesting (tied contour, infiltration pits, standard contour) with organic nutrient management than under conventional farming practice with organic nutrient management in semi-arid smallholder farming systems.
4. Sorghum grain yield is higher under contour-based rainwater harvesting (tied contour, infiltration pits, standard contour) with integrated nutrient management than under conventional farming practice with integrated nutrient management in semi-arid smallholder farming systems.

5 There is no significant difference in sorghum nutrient-use efficiency under contour rainwater harvesting (tied contour, infiltration pits, standard contour) and inorganic nutrient management practices in semi-arid smallholder farming systems.

CHAPTER 2: *SORGHUM BICOLOR* (SORGHUM) YIELD RESPONSE TO RAINWATER HARVESTING PRACTICES IN THE SEMI-ARID FARMING ENVIRONMENTS OF ZIMBABWE: A META-ANALYSIS

ABSTRACT

Rainwater harvesting practices are increasingly gaining recognition as viable adaptation strategies to overcome rainfall variability caused by climate change in semi-arid regions of Zimbabwe. A meta-analysis was conducted on 14 studies to provide a comprehensive quantitative synthesis of biophysical conditions (rainfall, soil texture, N fertility, mulch) under which basins, ripper, and tied ridges affected sorghum yields in semi-arid areas of Zimbabwe. Sorghum yield response to rainwater harvesting practices was assessed under the categories of rainfall amount (< 600 mm, 600 - 1000 mm, > 1000 mm), soil texture (< 20 % clay, 20 - 35 % clay, > 35 % clay), mulch (basin + mulch, ripper + mulch, tied ridges + mulch) and fertility (0 - 30 kg N/ha, 30 - 100 kg N/ha, > 100 kg N/ha). Grain yield response was compared to the control (conventional practice) using the weighted mean yield difference approach. The results showed comparable sorghum grain yields in all the rainwater harvesting practices across the biophysical conditions except under rainfall and soil textural classes. Tied ridges had a negative ($p<0.05$) sorghum grain yield response (-0.25 t/ha) under < 600 mm rainfall. Ripper planting had a significant negative grain yield response (-0.32 t/ha) under 600 – 1000 mm rainfall. Substantial ($p<0.05$) grain yield reduction (-1.06 t/ha) was also shown by ripper planting under soils with 20 – 35 % clay. The results suggest that basins, ripper, and tied ridges did not improve sorghum grain yield across all agronomic conditions.

Keywords: Basin, ripper, tied ridges, mulch, conventional planting

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2.1 INTRODUCTION

Agriculture remains a source of livelihood and food security for the majority of sub-Saharan Africa's population with about 95% of agriculture being rain-fed (Singh et al., 2011; Unganai & Murwira, 2010) and subsistence-based (Ndlovu et al., 2020). In sub-Saharan Africa agricultural productivity has not increased substantially over the past decades (Giller, 2020), with increases largely due to crop extensification rather than intensification (FAO, 2017). From an agronomic point, poor soil fertility and droughts are the primary factors that limit agricultural productivity. Seasonal and annual rainfalls in semi-arid regions are highly unpredictable and variable with high risk of crop failure (Gissila et al., 2004; Hadebe et al., 2020; Tesfaye & Walker, 2004), which worsens the food, nutrition, and income security among the smallholder farmers (Gernot et al., 2015).

In Zimbabwe more than 70 % of smallholder farmers depend on rain-fed agriculture and live in semi-arid regions, covering about 23% of the total land area (Chuma & Hagmann, 1998) having 40% of the population being food insecure (WHO, 2020). Farming under the semi-arid smallholder system is characterized by low levels of production technology and production is primarily subsistence with a little marketable surplus. Drought causes severe reductions in grain yields and significant economic losses to farmers. In a bid to overcome the deterioration in food security in Zimbabwe the government gave agricultural input aid in form of seeds and fertilizers to communal and resettled farmers as an agricultural recovery strategy (Foti et al., 2007). However, not much benefit has been achieved from the subsidized input scheme especially in the semi-arid regions because input type and variety did not tally with the agro-ecological location of the farmer (Foti et al., 2007; Mukarumbwa & Mushunje, 2010). Production of traditional cereal grain crops and equipping farmers with improved soil, water, and crop management practices can serve as an important strategy to achieve food security in the semi-arid farming regions (Mathew, 2015).

Sorghum bicolor L. (Sorghum) was one of the most important food crops promoted in semi-arid regions where precipitation and fertility are low and highly variable. It is highly adapted to low rainfall environments and contributes significantly to the diversification and resilience of agro-ecologies (Chivenge et al., 2015). Although the crop is widely recognized as well as adapted to semi-arid environments its yield remained low (< 1 t/ha) (Nyamudeza & Maringa, 1992) because production is entirely rain-fed in smallholder farming systems (Ndlovu et al., 2020). The yield of sorghum remained low because smallholder farmers lack adequate sustainable production knowledge to increase yields above subsistence level even in years of good rainfall. Productivity has stagnated below 0.5 t/ha and below the average yield of 3 to 5 t/ha that can be produced under rain-fed agriculture (Ndlovu et al., 2020). To overcome the hydro-climatic risks and soil-related constraints to crop production farmers employed a variety of soil and water management technologies to reduce the yield gap between the actual and maximum yield (Mupangwa et al., 2006; Mupangwa et al., 2012b; Musiyiwa et al., 2017). Increasing water productivity through the adoption of rainwater harvesting practices was an option that focused on manipulating water balance to minimize runoff and soil erosion while enhancing land and crop water productivity (Kahinda et al., 2007; Motsi et al., 2004; Musiyiwa et al., 2017; Rockström et al., 2009). The technologies are classified into systems that prolong the duration of moisture availability in the soil e.g., conservation agriculture and mulching practices; systems that promote infiltration of rainwater into the soil which include pitting, ridging/furrowing, and terracing, and systems that store surface and subsurface runoff water for later use (Mupangwa et al., 2006; Musiyiwa et al., 2017; Rockström et al., 2002). The practices may include improvement of soil fertility to optimize plant water uptake and increase productivity through the addition of organic matter and mulching (Rockström et al., 2009).

In Zimbabwe, water management techniques were developed and promoted by government extension agencies and various non-governmental organizations to improve food and security in smallholder farming systems (Ndlovu et al., 2020). However, the rainwater harvesting studies in sorghum farming systems showed variations in grain yield at different locations and seasons, both on-farm and on-station (Magombeyi et al., 2018; Nyamangara et al., 2014; Nyamudeza, 1993). In the semiarid regions of Zimbabwe, rainwater harvesting practices considered effective include tied ridges/furrows (Motsi et al., 2004; Rockström et al., 2009; Unganai & Murwira, 2010), reduced tillage methods (Mupangwa et al., 2006; Rockström et al., 2009), and infiltration pits (Mupangwa et al., 2008). Dead level contours with and without infiltration pits have also been reported to increase moisture retention and crop yield (Mhizha & Ndiritu, 2013; Mugabe, 2004; Mupangwa et al., 2012a). On the contrary, the use of ridges, and tied ridges reported failures and successes (Nyamudeza, 1993). Early studies by Vogel (1993) reported no advantage to the granite sands of Zimbabwe while Walton (1962) found conflicting results in Uganda. Seasonal experiments at Chiredzi and Chisumbanje done by Nyamudeza (1993) showed varied sorghum yields under tied ridges and flat furrows annually. Minimum moisture benefits were reported on the use of dead level contours with and without infiltration pits (1m upslope and 3m downslope) (Mupangwa et al., 2012a). Contrasting results were also observed by Nyakudya et al. (2014) who showed that combining infiltration pits and planting pits did not improve soil moisture and yields in the Rushinga district of Zimbabwe, a semi-arid farming area with heterogeneous soils. Soko (2012) also reported sorghum grain yield variation among varieties and across locations and seasons due to rainfall variability, soil fertility, and farming systems.

Quantitative data on the contribution of rainwater harvesting practices to grain yield of sorghum and the conditions under which the technologies perform well is not fully explored considering the heterogeneity of the biophysical farming environment and socio-economic factors of the farmers (Magombeyi et al., 2018; Munamati & Nyagumbo, 2010). Despite some studies being conducted globally, to attempt to identify and understand the benefits, challenges, and factors affecting the performance of the rainwater harvesting practices on sorghum grain yield, the results are still fragmented (Mupangwa et al., 2006). Limited research studies exist with significant detail in space and time on sorghum grain yield response under rainwater harvesting practices (Tonitto & Ricker-Gilbert, 2016). The experiments did not permit the determination of robust conclusions on sorghum grain yield under the rainwater harvesting practices due to variability in soil dynamics, nutrients, varieties, management, weather processes, and their interactions. In order to bridge this information gap, a meta-analysis was conducted to quantitatively analyse sorghum yield performance under basin planting, tied ridges, and ripper planting rainwater harvesting practices under variable rainfall, soils, and nutrient fertility.

2.2 MATERIALS AND METHODS

2.2.1 Inclusion criteria for Meta-analysis

Data was collected from articles that were peer-reviewed (journal articles, refereed book chapters and books, and published refereed conference papers). The selection criteria for research studies were based on field experiments that reported sorghum grain yield from a conventional farming-based treatment (control) compared with sorghum grain yield from a water harvesting-based treatment, where at least the effect of tied ridges, planting basins, and ripper have been tested (Table 1). In this study, conventional planting/farmer's practice was defined as a farming system with no rainwater harvesting or water retention techniques being practiced. The experiments conducted in Zimbabwe under rain-fed field conditions were considered, were means, standard deviations or standard errors, and sample sizes of sorghum yield was directly reported or can be calculated from the given data. Data from the same experiment reported in more than one publication was not repeated and the publication with the most complete dataset was used.

2.2.2 Meta-analysis treatments

Rainwater harvesting technologies were selected partly based on Bayala et al. (2012), McCarthy et al. (2001), and Thiombiano & Meshack (2009). These were ripper planting, tied ridges, and planting basins. The conventional farming practice (no rainwater harvesting) was used as the control against which the experimental rainwater harvesting practices (planting, basins, ripper planting, and tied ridges) were compared.

Long-term mean annual precipitation, farming sector, fertilizer type, and soil texture were used as covariate factors (Gotosa et al., 2019; Rusinamhodzi et al., 2011) for the response of sorghum grain yield to rainwater harvesting practice. Seasonal rainfall was categorized into three classes based on Rusinamhodzi et al. (2011) namely low (< 600 mm), medium (600–1000 mm), and high (> 1000 mm). The N application rates were categorized according to Chivenge et al. (2011) into low (0–30 kg N/ha); medium (30–100 kg N/ha), and high (> 100 kg N/ha). Soil texture was categorized according to Chivenge et al. (2011) into Sand (< 20 % clay), Loam (20 – 35 % clay), and Clay (> 35 % clay).

2.2.3 Meta-analysis

The treatment means, standard deviation, and the number of replicates data sets were used to compute the meta-analysis. Where Standard deviations were not reported but standard error of the mean (SE), coefficient of variation (CV, %), and least significant difference (LSD) were reported, Standard deviation was calculated from the SE and CV and LSD as follows (Eq I and II):

$SD = SE \ x \sqrt{n}$ (Merriam & Tisdell, 2015) *I*

$SD = \frac{CV\%}{100} x \ X$ (Nyamangara et al., 2014) *II*

where *X* is the mean of the rainwater harvesting practice and n is the sample size.

In studies where the LSD was not reported, it was estimated from the mean values presented in the papers by taking the smallest difference between the mean values of treatments that will still be significant (Corbeels et al., 2014). In a meta-analysis, continuous or measured variables are often expressed as weighted mean difference (WMD) and for ease of understanding and making inference, mean differences were used for the analysis (Corbeels et al., 2014; Nyamangara et al., 2014; Rusinamhodzi et al., 2011). Mean differences between treatments and control were used (Eq III). Mean differences were weighted to determine overall effect estimates and assess treatment impact consistency across studies (Eq V). The reciprocal of the calculated variance was used to weight individual research (Eq IV) (Gotosa et al., 2019; Rusinamhodzi et al., 2011).

Mean diferrence (MD) = $mean_{treat} - mean_{control}$ (Nyamangara et al., 2014; Rusinamhodzi et al., 2011) III

$Weight_i = \frac{1}{variance_i} = \frac{1}{{SD_i}^2}$ (Gotosa et al., 2019) IV

Weighted mean difference $(WMD)_{overall} = \frac{\sum_{i=1}^{i=n}(weight_i \times MD_i)}{\sum_{n=1}^{i=n}(weight_i)}$ (Ellis, 2010) V

$CI_{95\%} = mean_{overall} \pm [1.96 \times (Variance_{overall})^{0.5}]$ (Merriam & Tisdell, 2015) VI

$Variance_{overall} = \frac{1}{\sum_{n=1}^{i=n}(weight_i)}$ (Gotosa et al., 2019) VII

The random-effect model was used to calculate the effect size because it takes care of both within and between-study variance (Corbeels et al., 2014; Gotosa et al., 2019). In addition, the model can include covariates to reduce heterogeneity. The mean effect size was substantially different from zero for the overall mean effect significance test if its 95 percent confidence interval does not overlap with zero (Eq VI and VII)). Stata/MP 16.0 statistical software was used to perform the effect size meta-analysis.

Table 2. 1: Summary of studies.

Reference	**Season/RF**	**Soil type (%)**	**Rainwater harvesting practice**	**N rate (kg/ha N)/ Mulch (t/ha)**	**Experiment Summary**
Baudron et al. (2012)	2007/8-2009/10 845; 850; 600 mm	Sand 65 Clay 25 Silt 75	Conventional practice, Ripper, Ripper + Mulch	0	6 treatments × 3 reps (n = 18)
Masaka et al. (2019)	2015/16; 2016/17 408; 419 mm	Sand 35 Clay 40 Silt 25	Conventional practice, basins, ripper	0; 2; 4 t/ha (mulch)	3 × 3 factorial × 3 reps (n = 27)
Chiduza et al. (1995)	1984/85;1985/86 790; 580 mm	Sand 90 Clay 5 Silt 95	Conventional practice, Ripper	0;28;56;84 (MN)	5 × 2 factorial × 3 reps (n = 30)
Siambi (2010)	2007/08 410 mm; 380 mm	Sand 65 Clay 10 Silt 90	Conventional practice, tied ridges, Basins	0; 17.5; 35; 52.5 MN	2 × 3 factorial × 3 reps (n = 18)
Dera (2018)	2013/14; 2014/15 403; 417 mm	Sand 60 Clay 15 Silt 85	Conventional practice, ripper, basins	0; 2; 4 t/ha (mulch)	3× 3 factorial × 3 reps (n = 27)
Mashingaidze et al. (2009)	2004/05; 2005/06 290; 800 mm	Sand 25 Clay 35 Silt 65	Mulch residue retention	Mulch – 0; 25; 50; 75; 100 %	5 treatments × 3 reps (n = 15)
Mashingaidze et al. (2012)	2008/09; 2009/10 630; 600 mm	Sand 30 Clay 35 Silt 65	Conventional practice, ripper, basins	Mulch (0; 4 8 t/ha)	3 × 3 × 2 weeding × 3 reps (n = 54)
Mashingaidze et al. (2017)	2006/07 465 mm	Sand 30 Clay 35 Silt 65	Conventional planting, ripper, basin	Mulch (0; 2; 4 t/ha)	3 × 3 factorial × 3 reps (n = 27)

NB: RF – rainfall, MN – mineral nitrogen, n – sample size

Table 2.1 (continued)

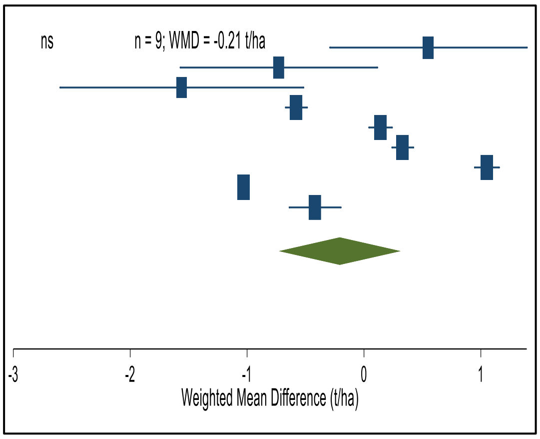
Reference	Season/RF	Soil type (%)	Rainwater harvesting practice	N rate (kg/ha N)/ Mulch (t/ha)	Experiment Summary
Mupangwa et al. (2012b)	2006/07 832 mm	Sand 25 Clay 35 Silt 65	Conventional practice, ripper, basins	Mulch (0; 0.5; 2; 4; 8; 10 t/ha)	3 × 7 factorial × 3 reps (n = 63)
Nyakatawa et al. (1996)	1987/88; 1988/89; 1989/90 117; 203; 504 mm	Sand 90 Clay 5 Silt 95	Conventional practice, tied ridges	0; 58; 66 kg/ha N	3 × 3 factorial × 3 reps (n = 27)
Nyakatawa (1996)	1990/91	Sand 90 Clay 5 Silt 95	Conventional practice, tied ridges	0; 25; 50 75 kg/ha N	3 × 4 factorial × 3 reps (n = 36)
Nyakatawa et al. (2001)	1995/96; 1996/97 540; 905 mm	Sand 90 Clay 5 Silt 95	Conventional practice, tied ridges	N (0; 30; 60; 90 kg/ha N)	2 × 4 factorial × 3 reps (n = 24)
Nyamudeza (1999)	1984/85 – 1990/91	Sand 90 Clay 5 Silt 95	Conventional practice, tied ridges		(n = 18)
Soko (2012)	500 mm; 750-1000 mm	Sand 65 Clay 25 Silt 75	Conventional practice, tied ridges	50; 75 kg/ha N	2×16 factorial × 3 reps (n = 96)

NB: RF – rainfall, MN – mineral nitrogen

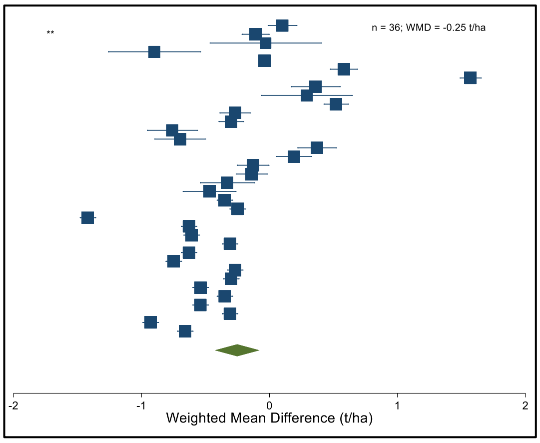
2.3 RESULTS

2.3.1 Sorghum yield responses to rainwater harvesting practices under different rainfall regimes

The results showed that the overall effect size of planting basins did not have significant effects (p>0.05) on grain yield of sorghum in areas receiving less than 600 mm of rainfall (Figure 2.1a), while tied ridges showed a significant negative effect size (-0.25 t/ha) on sorghum grain yield under the same rainfall category (Figure 2.1b). There was no yield advantage of planting basins over conventional planting while tied ridges showed yield depression. There was no experimental data for ripper planting under the rainfall category of less than 600 mm.



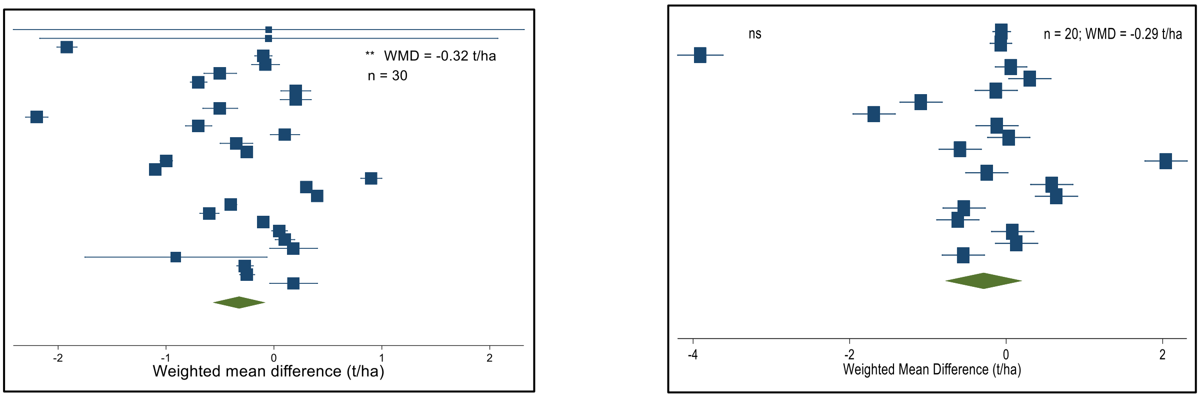
a) Planting basins



b) Tied Ridges

Figure 2. 1: Weighted mean differences in sorghum grain yield in a) Planting basins and b) Tied ridges under rainfall category of < 600 mm. ns denote no significant differences, ** denote significant differences at p<0.05.

Ripper planting showed a significant overall effect size with a weighted mean difference of -0.32 t/ha under medium rainfall (600 – 1000 mm) (Figure 2.2a). The effect size was in favour of conventional practice with no yield advantage of ripper planting over the conventional practice. The overall effect size was not significant on sorghum grain yield under tied ridges in areas under the rainfall category of 600 – 1000 mm (Figure 2.2b). A weighted mean difference of -0.29 t/ha was shown implying no yield difference between tied ridges and conventional planting. There was no experimental data for basin planting under the rainfall category of 600 mm – 1000 mm and no experimental data was found for all the rainwater harvesting practices under the rainfall category above 1000 mm.

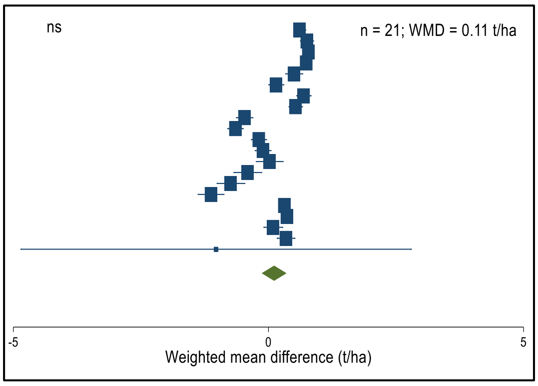


a) Ripper planting **b) Tied ridges**

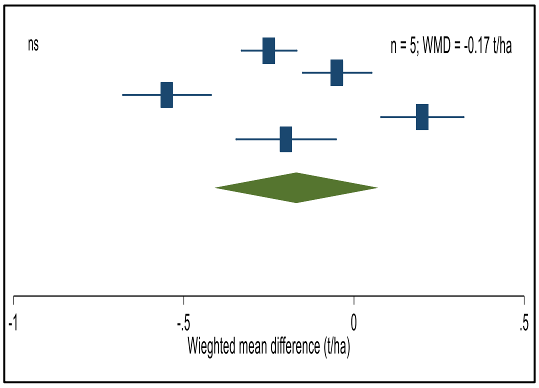
Figure 2. 2: Weighted mean differences in sorghum grain yield in a) Ripper planting and b) Tied ridges under rainfall category of 600-1000 mm. ns denote no significant differences, ** denote significant differences at p<0.05.

2.3.2 sorghum yield response to rainwater harvesting practices under different soil textural classes

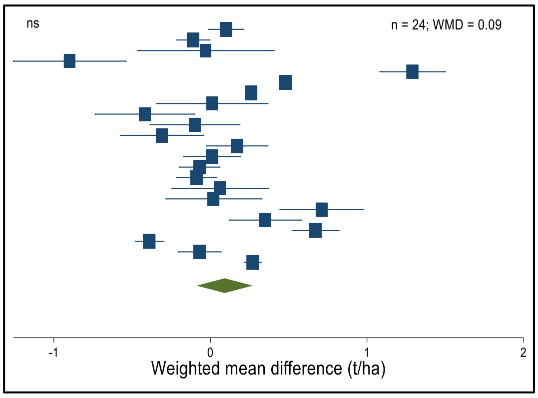
The overall effect size of planting basins, ripper, and tied ridges under the soil textural category of < 20 % clay had no significant effect on sorghum grain yield. Planting basins had a weighted mean difference of 0.11 t/ha (Figure 2.3a,) ripper -0.17 t/ha (Figure 2.3b), and tied ridges 0.09 t/ha (Figure 2.3c).



a) Planting basins



b) Ripper planting



d) Tied ridges

Figure 2. 3: Weighted mean differences in sorghum grain yield in a) Planting basins, b) Ripper planting c) Tied ridges under soil textural category < 20 % clay. ns denotes no significant differences.

A significant (p<0.05) negative overall effect size was shown by ripper planting with a weighted mean difference of -1.06 t/ha under soil textural class of 20-35 % clay (Figure 2.4). There was no experimental data on planting basins and tied ridges under the 20-35 % clay soil textural category.

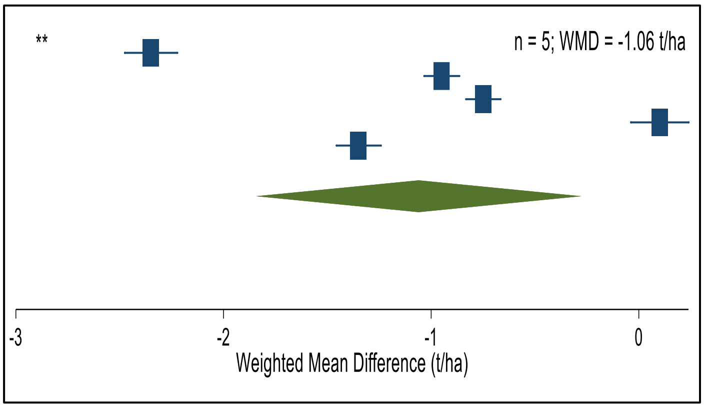
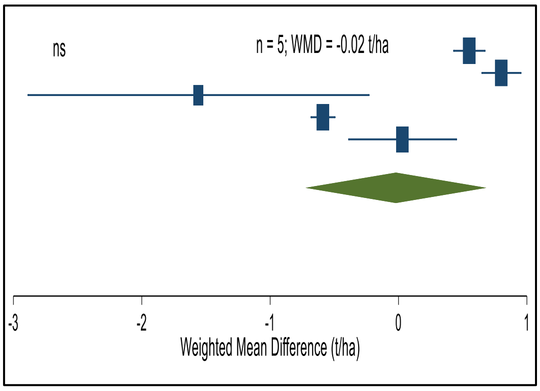
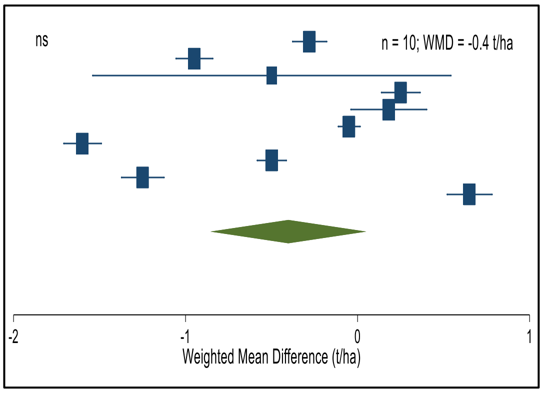


Figure 2. 4: Weighted mean differences in sorghum grain yield in Ripper planting under 20-35 % clay soil textural category. ** denote significant differences at p<0.05.

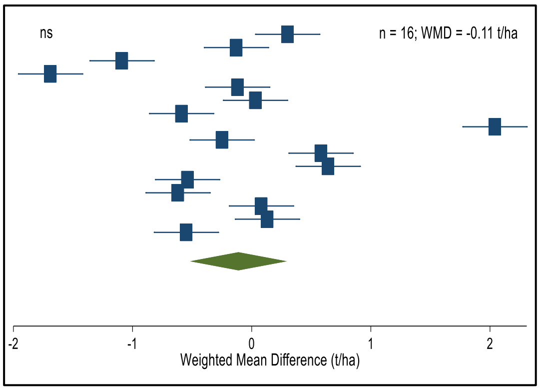
The soil textural category of > 35 % clay showed that planting basins, ripper and tied ridges had no significant effect size with weighted mean differences of -0.02 t/ha (Figure 2.5a), -0.4 t/ha (Figure 2.5b), and -0.11 t/ha (Figure 2.5c) respectively.



a) Planting basins



b) Ripper planting

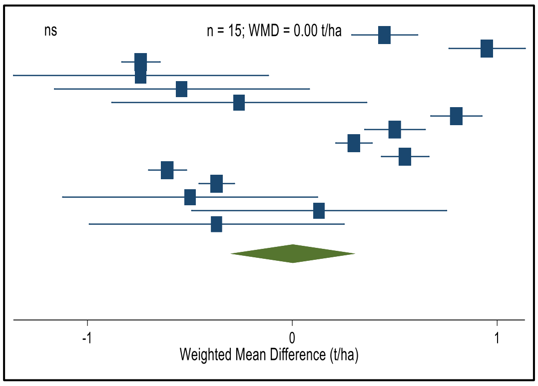


c) Tied Ridges

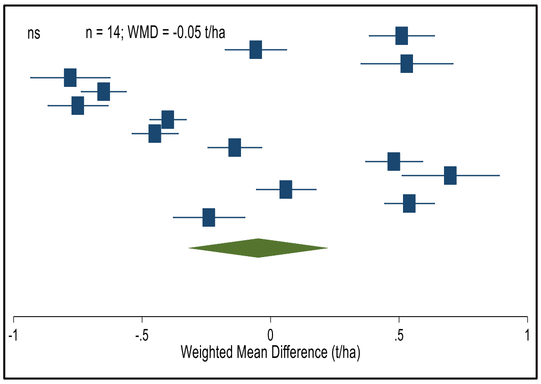
Figure 2. 5: Weighted mean differences in sorghum grain yield in a) planting basins, b) Ripper, c) Tied ridges under soil textural category of >35 % clay. ns denotes no significant differences at p<0.05

2.3.3 Sorghum yield responses to rainwater harvesting practices under mulch

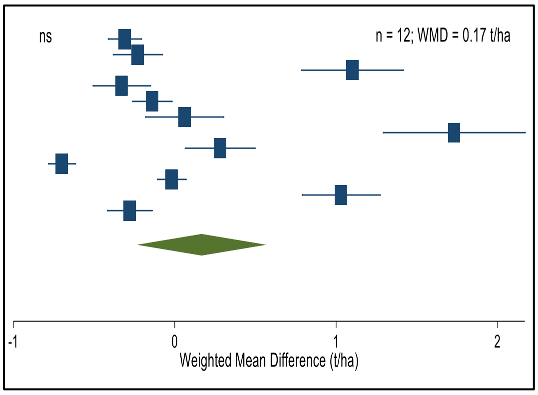
The overall effect sizes were not significant (p<0.05) on sorghum yield under basin planting (Figure 2.6a), ripper planting (Figure 2.6b), and tied ridges (Figure 2.6c) conferring comparable yields hence no yield advantage over conventional planting. The application of mulch to basin planting was neutral with weighted mean difference of 0 t/ha and depressed yields under ripper planting with weighted mean difference (-0.05 t/ha) while tied ridges had positive weighted mean difference (0.17 t/ha) though the effect sizes were not significantly different when compared with conventional farming system.



a) Planting basins + Mulch



b) Ripper + Mulch

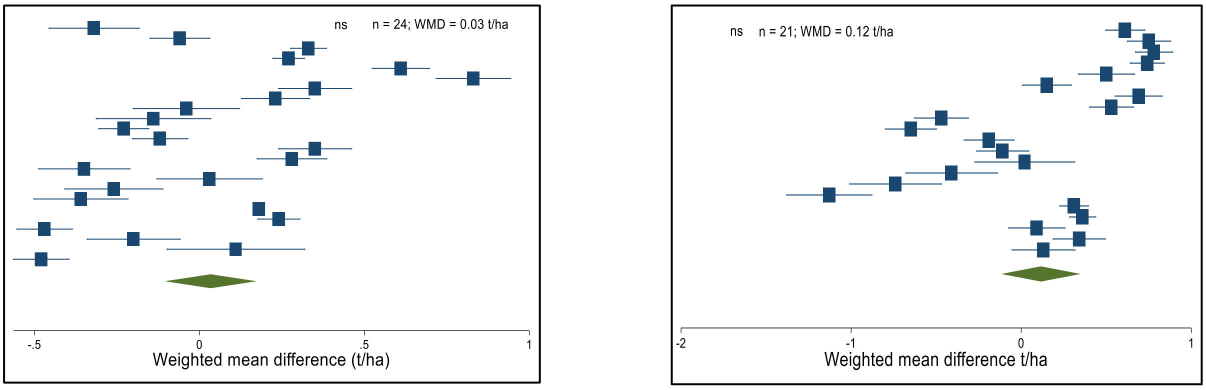


c) Tied ridges + Mulch

Figure 2. 6: Weighted mean differences in sorghum grain yield under a) Basin + Mulch, b) Ripper + Mulch c) Tied ridge + Mulch. ns denotes no significant differences at p<0.05.

2.3.4 Sorghum yield responses to rainwater harvesting practices under different fertility categories

The overall effect sizes of tied ridges were not significantly different ($p<0.05$) on sorghum yield under nitrogen fertility of < 30 N kg/ha (Figure 2.7a) and 30 - 100 N kg/ha (Figure 2.7b) implying no yield advantage over conventional planting. The overall effect sizes for the two fertility categories under tied ridges were low under < 30 N kg/ha with weighted mean difference = 0.03 t/ha and higher at 30 - 100 N kg/ha with weighted mean difference = 0.12 t/ha. There was no experimental data for planting basins and ripper planting under the different fertility categories.



a) 30Kg N/ha **b) 30-100 Kg N/ha**

Figure 2. 7: Weighted mean differences in sorghum grain yield in tied ridges under N fertility categories of a) 30 kg N/ha and b) 30-100 kg N/ha. ns denotes no significant differences at $p<0.05$.

2.4 DISCUSSION

This study demonstrated that planting basins (Figure 2.1a) and tied ridges (Figure 2.1b) showed no sorghum grain yield advantage compared with the conventional farming practice when rainfall was < 600 mm. Sorghum grain yield underplanting basins was comparable to conventional planting. In low rainfall areas (< 600 mm), poor distribution, and low short-duration rainfall intensities affect the performance of rainwater harvesting techniques. This is probably because basins quickly dry up when the rainfall interval is too short, and the rainfall intensity and duration are not sufficient to cause significant runoff collection leading to no grain yield differences between the rainwater harvesting technique and the conventional farming practice. In a meta-analysis, Nyamangara et al. (2014) reported higher weighted mean difference under basin planting when the rainfall pattern was well distributed than when it was poorly distributed, showing that basins do not necessarily address the problems associated with poorly distributed rainfall. Studies by Mupangwa et al. (2008) and Rockström et al. (2009) found that in Zimbabwe, rainfall distribution is the major challenge to crop production rather than lack of it. Tied ridges showed considerable grain yield reduction compared with farmer's practice (conventional practice) when rainfall was < 600 mm suggesting the absence of yield benefits of the rainwater harvesting practice. Tied ridges are made of ridges up to 20 cm high tied at intervals which allow significant water collection. Intense short-duration rainfall patterns which often occur in semi-arid regions cause localized waterlogging making tied ridges undesirable to the crop. In cases where rainfall of 600-1000 mm was received, sorghum yield was significantly depressed under ripper planting (Figure 2.2a) while tied ridges (Figure 2.2b) showed a negative grain yield response although not significant. The negative sorghum yield response is attributed to water collection by the in-situ rainwater retention practice which compromised drainage leading to waterlogging. Waterlogging leads to anaerobic conditions and affects nutrient uptake and crop growth (Manik et al., 2019).

There was no substantial improvement in sorghum grain yield from planting basins, ripper, and tied ridges rainwater harvesting practices compared with conventional farming practices under the different soil textural categories in Zimbabwe. The rainwater harvesting practices of basins, ripper, and tied ridges showed comparable grain yield in soils that had < 20 % clay (Figure 2.3) implying no yield advantage over conventional planting. This may be attributed to high internal drainage exhibited by soils with low clay content rendering the rainwater retention techniques ineffective. Ripper planting showed a significant negative weighted mean difference in soils that had 20-35 % (Figure 2.4) implying significant yield reduction compared with conventional practice. Minimum soil disturbance in ripper planting favours termite activity which depresses yields in smallholder farming systems (Mutsamba et al., 2016). Comparable grain yields were shown by all the rainwater harvesting techniques (basins, ripper, tied ridges) when compared with conventional practice in the soil textural category with more clay content (>35 % clay) (Figure 2.5). However, negative yield responses were noted in all the rainwater harvesting techniques. This was attributed to clay soils exhibiting temporary waterlogging which reduces crop growth. Rainfall intensities in semi-arid areas can cause localized waterlogging and the effects are profound in heavy clays where internal drainage is relatively poor (Nyamangara et al., 2014). The reduction in crop yields on poorly drained soils under rainwater harvesting was also reported by Corbeels et al. (2014). Mupangwa et al. (2008) and Nyengerai (2010) reported the effect of waterlogging under basin planting being more pronounced due to the tendency of water stagnating in plots under heavy rainfall during the early part of the season.

The addition of mulch to rainwater harvesting practices (basins, ripper, tied ridges) did not have substantial grain yield benefits over conventional farming practices (Figure 2.6). The use of mulch depressed yields and this was likely to be a result of the high C/N ratio in the mulch used by smallholder farmers. Micro-fauna activity incorporates the mulch into the soil and immobilizes the available N (Mandal & Neenu, 2012; Truong et al., 2019). The results on ripper + mulch farming practice were in tandem with findings by Masaka et al. (2020) who reported sorghum yield depression compared with the conventional farming practice while Mupangwa et al. (2012b) found no substantial gain in sorghum grain yield under ripper + mulch and basin + mulch compared with the conventional practice. However, contrary to the findings, Masaka et al. (2020) reported substantial sorghum grain yield gains compared with conventional farming practice under basin + mulch farming practice.

Sorghum yield response under tied ridges did not improve despite changes in nutrient regimes (Figure 2.7). The yield remained comparable to conventional planting in all the nutrient categories despite N soil fertility being an important limiting factor in the smallholder farming systems. In low potential areas with very low and poorly distributed rainfall, rainfall may not be enough to cause a significant concentration of water in the furrows when needed by the crops. This causes low crop responses to rainwater harvesting and inorganic fertilizer use resulting in low benefits on crop yields as reflected by the marginal weighted mean difference under the two fertility categories. Due to inadequate soil moisture resulting from low and poorly distributed rainfall, fertilizer applications under rain-fed conditions may require extremely good timing to realize benefits in yield and economic returns under the rainwater harvesting practices. In a meta-analysis, Gotosa et al. (2019) reported that nitrogen application rates of < 100 kg ha^{-1} had fewer advantages than application rates >100 kg N ha^{-1} under high potential conditions.

2.5 CONCLUSION

The rainwater harvesting practices (basins, ripper, and tied ridges) did not improve the grain yield potential of sorghum when compared with conventional farming practices under the different agronomic conditions (rainfall, soil texture, mulch, and nitrogen fertility). The rainwater harvesting practices showed comparable sorghum grain yield responses compared with farmers' practices under the different agronomic conditions. However, sorghum grain yields were depressed under tied ridges and ripper planting at < 600 mm and 600 - 1000 mm rainfall classes respectively. A negative grain yield response was also shown by ripper planting in soils that had 20 - 35 % clay. The variation in yields with varying rainfall intensities implies that farmers have to pay closer attention to soil water management to avoid waterlogging. Similarly, the challenges caused by clay soils and mulch mean that smallholder farmers need better soil management strategies to improve sorghum's yield potential.

CHAPTER 3: FIELD-EDGE RAINWATER HARVESTING AND INORGANIC FERTILIZERS FOR IMPROVED *SORGHUM BICOLOR L. (*SORGHUM) YIELDS IN SEMI-ARID FARMING REGION OF MARANGE, ZIMBABWE

ABSTRACT

Sorghum (*Sorghum bicolor L.*) is mainly cultivated in marginal areas of Zimbabwe, where rainfall is low, erratic, and poorly distributed, leading to low yields. The study aimed to determine the effect of tied contour (TC) and in-contour infiltration pits (IP) rainwater harvesting (RWH) methods and varying nitrogen fertilizer application rates on the yield of two sorghum varieties, Macia and Sc Sila. A split-split plot experiment was laid out, with the main plot factor being the RWH method, the subplot factor being sorghum variety, the sub-sub plot factor being nitrogen application rate, and the sub-sub-sub plot factor being the plant distance from the RWH method. The experiment was done at Mt Zonwe's small-scale farming community in the Mutare district from 2016/17 to 2018/19. Soil moisture and sorghum grain yield data were subjected to analysis of variance (ANOVA) to determine treatment differences. The results revealed that TC and IP increased the gravimetric water content (gwc) of the soil. The gwc decreased gradually as the distance from the rainwater RWH method increased (0-5 m > 5-10 m > 10-15 m), with the 2016/17 season having the maximum gwc. In all seasons, TC and IP yielded more sorghum grain than modified standard contour (SC). Sorghum grain yield was significantly greater at all nitrogen application rates and consistently higher at all plant distances from the RWH method in the 2016/17 season with more rainfall. In comparison to TC and IP, the SC had significantly lower grain yield at all nitrogen application rates. At all plant distances from the RWH method, TC and IP had significantly higher grain production than SC in both sorghum varieties.

Keywords: rainwater harvesting, tied contour, infiltration pits, sorghum, semi-arid, rain-fed.

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3.1 INTRODUCTION

Sorghum (*Sorghum bicolor L.*) is a key food crop in Southern Africa, accounting for 22% of total cereal land after maize (*Zea mays*) (Macauley & Ramadjita, 2015). It is a major cereal grown for food and beverages by resource-poor farmers in sub-Saharan Africa (SSA) and has been regarded as a future crop due to its ability to withstand climate change-induced stress (Nciizah et al., 2020). The crop has the potential to boost food security, but due to its low competitiveness in mainstream agriculture with commodity crops like maize and wheat, its full potential has not been realized (Mabhaudhi et al., 2016; Ulian et al., 2020). Its production is progressively declining in terms of area under production and yield, limiting its ability to contribute in reducing food insecurity in semi-arid areas (Chanza, 2018; Nhemachena et al., 2014). The grain yields have steadily declined because cultivation is being pushed into areas with poor soils and drought-prone.

In the context of climate change and variability, increasing small grain yield is critical for food and nutrition security (Mathew, 2015; Ndlovu et al., 2020). Droughts and low soil fertility are common in semi-arid regions, trapping smallholder farmers in a cycle of poverty (Nciizah et al., 2020). Drought is a primary sorghum production constraint and is the leading cause of yield decrease (Gruber, 2017). Sorghum cultivation in Zimbabwe's marginal agro-ecological regions IV (450-650 mm) and V (650-950 mm) is entirely dependent on rainfall (Mukarumbwa & Mushunje, 2010) and vulnerable to moisture stress at key stages of crop development (Weldeslassie et al., 2016). Small-scale farmers in semi-arid agro-ecologies obtain meagre yields (0.5 t/ha) which are below subsistence level (Musara et al., 2019) resulting in high yield gaps compared to commercial farms (3 t/ha) located in agro-ecological region III (250-450) and II (450 to 650 mmm) ((Macauley & Ramadjita, 2015).

Rainfall in the semi-arid areas is relatively low, often poorly distributed, and highly variable (Mhizha & Ndiritu, 2013). There is a high coefficient of variation of quantity, onset, and cessation of rainfall. In addition, the long dry spells may coincide with the vegetative and grain production crop growth stages (Mamombe et al., 2017). Moisture stress is a common phenomenon that leads to low, unreliable grain output (Mupangwa et al., 2012a). This makes crop production in dry-land locations highly risky due to the high value of potential evapotranspiration (Chianu et al., 2012; Mahinda et al., 2018). The low rainfall received in the semi-arid rain-fed farming areas reduces the rate of nutrient uptake efficiency affecting nutrient demand at critical crop growth stages (Mahinda et al., 2018). If the entire spectrum of advantages from soil nutrient additions is to be achieved, cultural adaptive sustainable crop intensification strategies that preserve and increase the time of moisture availability to the plants are required to enhance sorghum productivity in low rainfall environments (Mundia et al., 2019). The primary constraint is the lack of suitable adaptive low-cost water and nutrient management technologies for sorghum production under relatively low and erratic rainfall (Lian et al., 2017; Mupangwa et al., 2016).

Field edge and in-contour rainwater harvesting (RWH) methods are promising low-cost ways of supplementing soil moisture in rainfed farming systems (Nyagumbo et al., 2019; Velmurugan et al., 2018). Rainwater captured through the field edge and channelled through a modified graded contour (modified standard contour) (SC) tied at intervals to form miniature ponds (tied contour) (TC) have received little research under sorghum production. Most of the studies o RWH focused on tied ridges (Mandumbu et al., 2020), planting basins (Mupangwa et al., 2019), dead level contours, and in-field infiltration pits (IP) (Mhizha & Ndiritu, 2013; Mupangwa et al., 2012a). However, few researchers investigated the possibility of converting standard contours into tied contours and contour-infiltration pits for rainwater harvesting.

The research aimed to determine the effect of tied contours and in-contour infiltration pits RWH methods and mineral nitrogen fertilizers on soil moisture and grain yield of two sorghum varieties (Macia and Sc Sila) in a semi-arid rain-fed farming system. We hypothesiszed that i) the RWH methods (TC, IP) have no soil moisture difference at varying distances from the RWH methods. ii) the varieties of sorghum (Macia and Sc Sila) have no grain yield difference in the RWH methods (TC, IP) at varying inorganic nitrogen application rates and distance from RWH methods.

3.2 MATERIALS AND METHODS

3.2.1 Description of the study site

The field trial was done in Mutare, at Mt Zonwe smallholder farming community found in natural region IV of Zimbabwe (19º 11'30" S; 32º 3'28" E, 835 m above sea level) (Figure 3.1). The experiment was run for three seasons from 2016/17 to 2018/19. The agro-ecological region is characterised by low, erratic, and poorly distributed rainfall. The unimodal rainfall pattern begins in October and ends in March. The seasonal rainfall ranges from 450 - 650 mm and the soils are predominantly sandy, and poor in nitrogen and phosphorus (Table 3.1). The trial field was on a general slope of 3 %. The catchment area was characterised by some rock outcrops capable of generating runoff. The underlaying material was gravelly at depth of 0.9 m which may enhance water retention but a limiting factor for root extension. The farming enterprises consist of a crop-livestock farming system and the predominant crops grown include crops like maize, sorghum, millets (*Pennisetum glaucum (L.) R. Br.).* and *(Eleusine coracana (L.) Gaertn*) and cotton (*Gossypium hirsutum L.*).

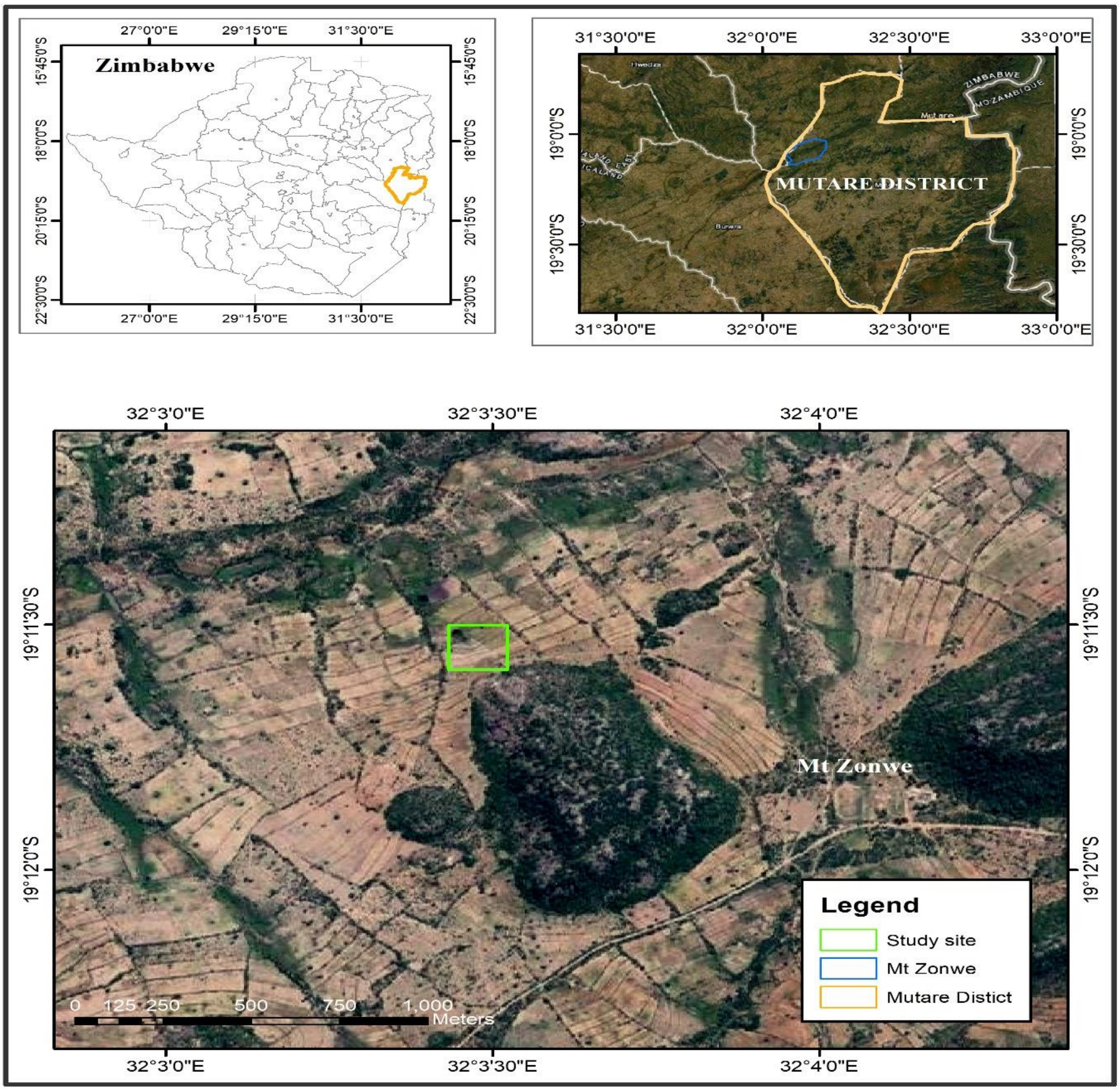

Figure 3. 1: Experimental study site

3.2.2 Soil sampling and characterization

Before planting, random soil samples in the 30 cm layer were collected using a soil auger from a 90 x 45 m experimental field. To evaluate the physicochemical parameters of the experimental site, composite samples were prepared for analysis. The composite samples of soil were dried in the open air, pulverized, and passed via a 2 mm screen. Total N was analysed following the Kjeldahl procedure (Cottenie, 1980), soil pH following the 0.01 M $CaCl_2$ method (Henderson & Bui, 2002), organic C following the wet digestion method (Walkley & Black, 1934), available P_2O_5 following the Olsen method (Olsen, 1954), and soil texture following Bouyoucons Hydrometer method (Bouyoucos, 1962). Table 3.1 shows the physical and chemical parameters of the soil at the research site.

Table 3. 1: Soil physicochemical properties of the research site

Soil composition			
Clay (%)	4		
Silt (%)	14		
Sand (%)	82		
Soil texture	Sandy loam		
	2016/17	**2017/18**	**2018/19**
pH ($CaCl_2$)	5.3	5.6	5.7
Organic C %	1.41	1.43	1.42
Total N %	0.1	0.17	0.19
P_2O_5 mg/kg	4.21	5.32	5.40

3.2.3 Experimental layout

Three successive modified standard contours measuring 90 m and spaced 15 m apart were identified on the farmer's field. The modified standard contours were graded contour ridges that were made to properly discharge runoff water from the field to prevent soil erosion (Mhizha & Ndiritu, 2013). The modified standard contours were made of a trench (contour channel) of 1 m (width) × 0.4 m (depth) with dug soil placed down the slope (Mhizha & Ndiritu, 2013). The contour lengths were split into 3 × 30 m lengths of RWH methods namely TC, IP, and SC. A factorial experiment was established in a split-split plot configuration. The RWH methods were the main plot factor. The TC constituted a modified SC channel tied across with earth material constructed along the graded contour channel after every 5 m to form small ponds (Figure 3.2). The constructed ponds measured 5 m (length) × 1 m (width) × 0.4 m (depth). IP were made by digging pits measuring 2 m (length) × 0.5 m (width) × 0.5 m (depth) after every 1 m along the graded contour channel (Figure 3.2). The dimensions of TC and IP were partly based on Mhizha & Ndiritu (2013), Mupangwa et al. (2012a), Mwenge Kahinda (2004), and Nyakudya et al. (2014). The SC was the control which measured 30 m in length. The RWH methods were separated by a distance of 2 m along the contour channel (Figure 3.2).

Sorghum variety was the subplot factor. Two sorghum varieties, Macia and Sc Sila were randomly allocated to the subplot factor with each variety plot measuring 15 m (length) × 4.5 m (width). Nitrogen treatments (0, 50, 70, 100 130, and 170 kg N/ha) were randomly assigned as sub-sub plot factor in each variety of sorghum measuring 2 m (length) × 4.5 m (width) (Figure 3.2). The sub-sub plot factors were replicated downslope within each RWH method at distances of 0-5 m, 5-10 m, and 10-15 m measured from the centre of the RWH method.

3.2.4 Experimental procedure

The field was ploughed using an ox-drawn mouldboard plough in July every year. Planting furrows were made by an ox-drawn mouldboard plough with an inter-row spacing of 0.75 m in all the treatments. The varieties of sorghum Sc Sila and Macia were planted under each RWH method (TC, IP) and SC on 10 th of December every year. Sorghum varieties were planted at a seed rate of 12 kg/ha into the furrows and a basal NPK (7:6:6) fertilizer was applied along the furrows at 200 kg/ha in all the treatments. The plants were thinned to leave plants spaced at 10 cm in all the plots. The top dressing was done with Ammonium nitrate fertilizer (34.5 %) at 5 weeks after planting. The amount of nitrogen topdressing fertilizer used for each treatment was determined by the difference between nitrogen treatments (50, 70, 100, 130, and 170 kg N/ha) and N applied as basal (14 kg N/ha). In all the sub-plot factors, top-dressing a 0 kg N/ha treatment was used as a control. Hand hoeing was used to control weeds, while the control of Fall armyworm (*Spodoptera frugiperda*) was done with Ecoterex (*Deltamethrin* and *Pirimiphos methyl*) insecticide. Quelea birds (*Quelea quelea*) were controlled at the booting stage by scaring during the day to prevent grain loss until harvesting maturity.

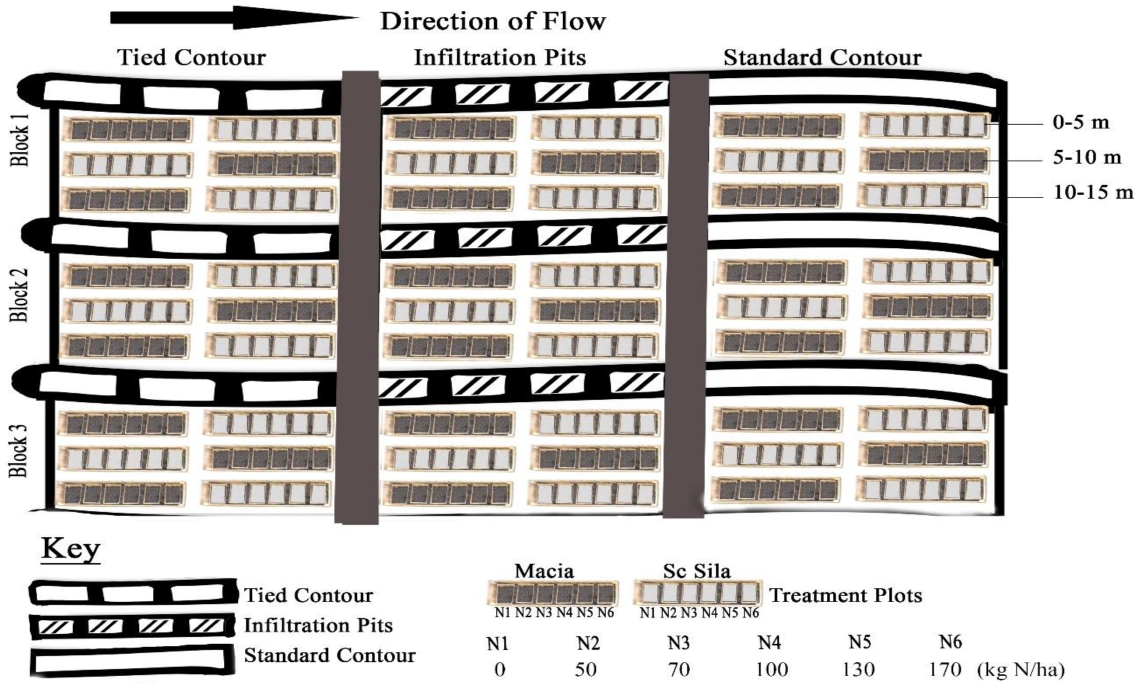

Figure 3. 2: Experimental Layout

3.2.5 Planting material

The varieties of sorghum Macia and Sc Sila were used as the planting material. Macia is widely grown in the study area, owing to its relative stable yield. It is an open-pollinated low-tannin variety with flowering on set at 60-65 days and an early to medium maturity index (60–65 days). The variety has remarkable drought resistance traits (250–750 mm rainfall), stays green after harvest, and yields a potential of 3–6 t/ha (Gasura et al., 2015). The commercial sorghum variety Sc Sila is a medium maturing hybrid with a high grain yield potential (8 t/ha) in optimum conditions. It has good heat and drought stress characteristics ideal for the marginal areas of natural regions IV and V (Gasura et al., 2015).

3.2.6 Moisture content

The gravimetric method was used to determine the soil water content (Nyagumbo et al., 2019). Samples of soil were taken using an auger up to a depth of 0.6 m in each RWH method (TC, IP) and SC at varying distances of 0-5 m, 5-10 m, and 10-15 m from all the RWH methods. A total of 5 soil samples were collected diagonally at each distance from RWH practice and SC once a month irrespective of rainfall event or no rainfall at the time of collection. Before calculating gravimetric water content (gwc), samples of soil were oven-dried for 48 hours at 105°C. The procedure outlined by Ingram & Anderson (1993) was used to calculate the gwc. Soil bulky density was not measured hence the volumetric water content was not calculated.

3.2.7 Grain yield

The yield of grain was determined by cutting sorghum heads at harvest maturity from the two middle rows of 1 m in each treatment. The cut sorghum heads were sun-dried for easy threshing. A moisture meter - Dickey-john (United States) was used to determine grain moisture and the grain yield (t/ha) was corrected to 12.5 % moisture for analysis.

Grain yield after moisture correction = Grain yield before moisture correction × (100-P)/(100-Q); Where P, was the moisture content of grain measured and Q was the specified grain moisture content (12.5%) (Mulvaney & Devkota, 2020).

3.2.8 Statistical analysis

Normality and homoscedasticity tests were done using Kolmogorov-Smirnov and Bartlett tests respectively in SPSS version 26. The data met the criteria of normality and homoscedasticity. To examine the interaction effects over the seasons, data on soil water content and grain yield were not studied independently in all the seasons. The analysis of variance (ANOVA) was done using GenStat and mean separation was performed using the least significant difference test at 5 %.

3.3 RESULTS

3.3.1 Seasonal Rainfall

According to the Zimbabwe agro-ecological region classification, the growing period in each year received more rainfall than the amount prescribed for the region (450 - 650 mm) (Figure

3.3). The 2016/17 season was the wettest and received 35% more rainfall than normal for agricultural region IV. The rainfall was fairly distributed at crop establishment and vegetative crop growth stage with severe dry spell coinciding with grain filling and ripening crop growth stages (Table 3.2). The seasons 2017/18 and 2018/19 were fairly similar with February being the wettest month coinciding with the vegetative and flowering period crop growth stages (Table 3.2). Despite the high rainfall totals in all the seasons, the rainfall was not evenly distributed across all crop growth stages as shown in table 3.2.

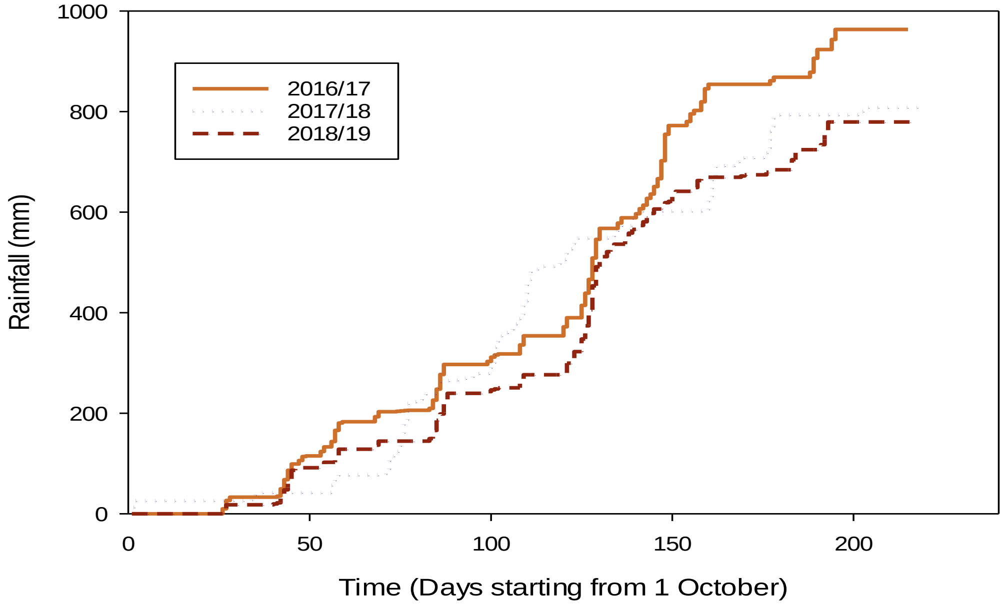

Figure 3. 3: Cumulative rainfall distribution during the course of the trial

Table 3. 2: Occurrence of rainy and dry pentads during different sorghum phenological growth stages in 2016/17 – 2018/19 growing seasons

Month	Season		
	2016/17	2017/18	2018/19
December	**3^{e},4^{e},5^{e},6^{e}**	4^{e},**5^{e},6^{e}**	4^{e},**5^{e},6^{e}**
January	**1^{e},2^{v},3^{v},4^{v},5^{v},6^{v}**	**1^{e}**,2^{e},3^{v},4^{v},**5^{v},6^{v}**	**1^{e}**,2^{e},3^{v},4^{v},5^{v},**6^{v}**
February	**1^{v},2^{v},3^{v},4^{f},5^{f}**,6^{f}	**1^{v},2^{v},3^{v},4^{v},5^{f},6^{f}**	**1^{v},2^{v},3^{v},4^{v},5^{f}**,6^{f}
March	1^{f},2^{g},3^{g},4^{g},5^{g},6^{r}	**1^{f}**,2^{f},3^{g},4^{g},**5^{g},6^{g}**	**1^{f},2^{f}**,3^{g},4^{g},5^{g},6^{g}
April	1^{r},2^{r},3^{r}	**1^{r},2^{r}**,3^{r}, 4^{r}	**1^{r},2^{r}**,3^{r},4^{r}

NB. 1. Sorghum planting dates were: 11/12/16 (3rd pentad of December 2016), 16/12/17 (4th pentad of December 2017), 4 th pentad of December 2018. 2. The superscripts after the pentad number indicate the phenological growth stages, i.e., e=establishment, v=vegetative, f=flowering, g=grain filling, r=ripening. Pentads in bold were rainy. A rainy pentad (bold) was defined as the centre one of three five-day periods (pentad) which together receives at least 40 mm of rainfall and two of the pentads receive a minimum of 8 mm of rainfall. The numbers 1–6 represent the numbered pentads in each month.

3.3.2 Soil moisture content

The RWH method showed a statistically significant effect ($p<0.05$) gwc. The gwc for TC and IP rainwater harvesting methods was significantly higher than the SC (Table 3.3). The TC and IP had comparable gwc of 8.74 % and 8.46 % respectively. Gravimetric water content was significantly influenced by distance from the RWH method ($p<0.05$), with a substantial gradual decrease in gravimetric water content as the distance from the RWH method increased (Table 3.3). The distance of 0-5 m from the RWH method had the highest gwc (8.62 %) while 10-15 m distance from the RWH method had the least gravimetric water content (7.15%). The gwc varied significantly across the years with the highest gwc in 2016/17 and the gwc in 2018/19 (Table 3.3). The RWH methods significantly improved predicted gwc at field capacity, wilting point and saturation point compared to SC (Figure 3.4) and the effectiveness of the RWH method in water retention decreased with an increase in distance from the RWH method (Table 3.4)

Table 3. 3: Effects of RWH method, distance from rainwater harvesting method, and season on gravimetric water content.

Treatment	Gravimetric water content (%)
RWH method	
Tied-contour	8.74a
Infiltration-pits	8.46a
Standard contour	6.48b
LSD	0.61
Distance from RWH method	
0-5 m	8.62a
5-10 m	7.91b
10-15 m	7.15c
LSD	0.61
Season	
2016/17	8.70a
2017/18	7.86b
2018/19	7.11c
LSD	0.61
RWH method × distance from RWH method	ns
RWH method × season	ns
Distance from RWH method × season	ns
RWH method × distance from RWH method × season	ns

Means in the same column followed by the same letter are not significantly different at $p<0.05$. LSD – least significant difference at 5 %, ns – not significantly different at $p<0.05$. RWH – rainwater harvesting method.

Table 3. 4: Predicted gravimetric water content at field capacity, wilting point and saturation point at different distances from rainwater harvesting practices

Distance from rainwater harvesting	Gravimetric water content (%)		
	Field capacity	Wilting point	Saturation point
0-5 m	2.96[a]	-1.13[a]	11.14[a]
5-10 m	3.32[b]	-1.14[b]	12.27[b]
10-15 m	3.75[c]	-1.15[c]	13.58[c]
p-value	<0.001	<0.001	<0.001
LSD	0.26	0.008	0.78

Means in the same column followed by the same letter are not significantly different at p<0.05.

LSD – least significant difference at 5 %.

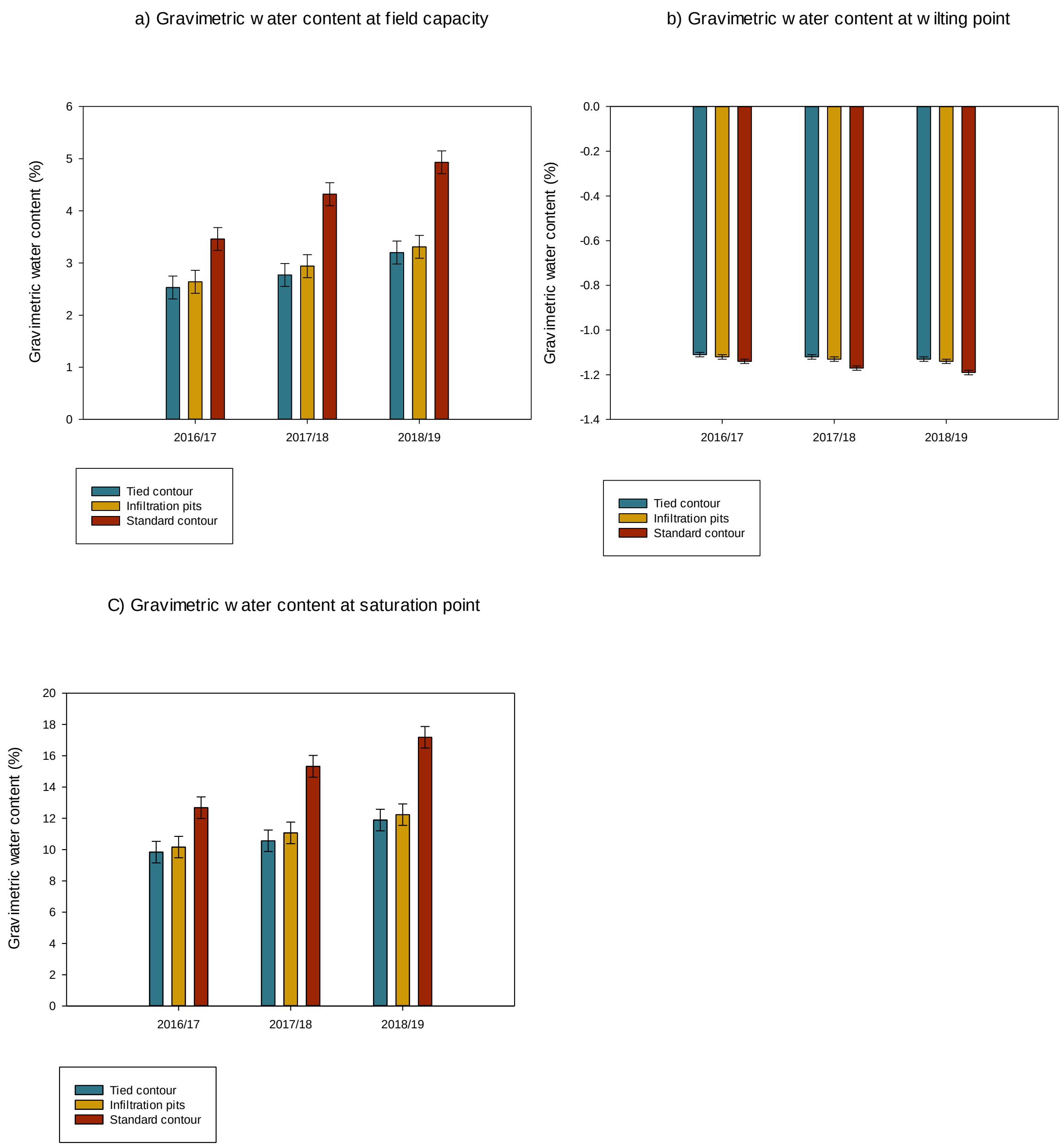

Figure 3. 4: Effect of rainwater harvesting practices on predicted gravimetric water content at field capacity, wilting point and saturation point

3.3.3 Sorghum grain yield

Table 3.3 summarizes the analysis of the variance of grain yield of two sorghum varieties (Macia and Sc Sila) under RWH methods and varying nitrogen application rates over three seasons (2016/17 - 2018/19). The grain yield of sorghum was significantly influenced ($p<0.05$) by the main treatment effects (RWH method, variety, nitrogen application rate, season, and distance from RWM method). However, considerable interaction ($p<0.05$) between the treatments, on the other hand, explains the grain yield discrepancies (Table 3.3).

Table 3. 5: Summary of ANOVA of sorghum grain yield under RWH methods and nitrogen application rates across three seasons (2016/17 to 2018/19)

Source of variation	P-value
RWH method	*
Variety	*
N	*
Season	*
Distance from RWH method	*
RWH method × sorghum variety	ns
RWH method × N	*
Sorghum variety × N	*
RWH method × season	*
Variety × season	ns
N ×season	*
RWH method × distance from RWH method	*
Variety × distance from RWH method	*
N × distance from the RWH method	*
Distance from RWH method × season	*
RWH method × variety × N	ns
RWH method × variety × season	ns
RWH method × N × season	ns
Variety × N × season	ns
RWH method × Variety × distance from RWH method	*
RWH method × N × distance from RWH method	ns
Variety × N × distance from RWH method	ns
RWH method × season × distance from RWH method	ns
Variety × season × distance from RWH method	ns
N ×season × distance from RWH method	ns
RWH method × variety × N x season	ns
RWH method × variety × N × distance from RWH method	ns
RWH method × variety × season × distance from RWH method	ns
RWH method × N × season × distance from RWH method	ns
Variety × N × season × distance from RWH method	ns
RWH method × variety × N × season × distance from RWH method	ns

* Significant at $p<0.05$; ns – not significant; RWH – rainwater harvesting method; N - nitrogen

The interaction effect of the RWH method and season significantly influenced ($p<0.05$) grain yield of sorghum (Table 3.5). In all the seasons, the RWH methods - TC and IP had considerably higher ($p<0.05$) sorghum grain yield than the SC (Figure 3.5). TC and IP had comparable grain yields across all seasons (Figure 3.5).

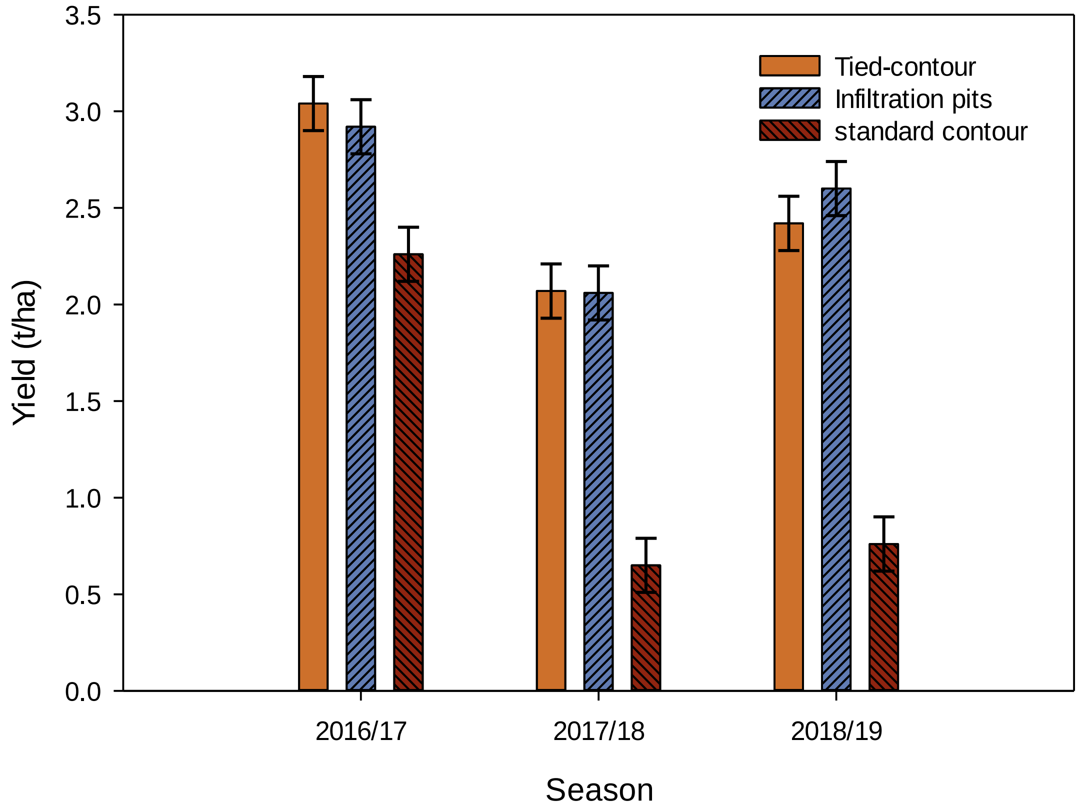

Figure 3. 5: The interaction effect of RWH method × season on grain yield of sorghum. Vertical bars represent standard error.

A significant interaction effect ($p<0.05$) between nitrogen application rate and season influenced sorghum grain yield (Table 3.5). The highest sorghum grain yield was in the 2016/17 season at all nitrogen application rates, while the lowest yield was in the 2018/19 season at all nitrogen application rates except at 0 kg N/ha. In all seasons, the treatments with 0 kg N/ha had considerably lower sorghum grain production than the nitrogen-applied treatments (Figure 3.6). Nitrogen application rate of 50 kg N/ha significantly ($p<0.05$) increased sorghum grain yield in all the seasons. An increase in nitrogen up to 100 kg N/ha boosted sorghum grain yield in the 2016/17 season, after which there was no substantial improvement in yield. Nitrogen application greater than 50 kg N/ha had no substantial grain production advantage in all the seasons.

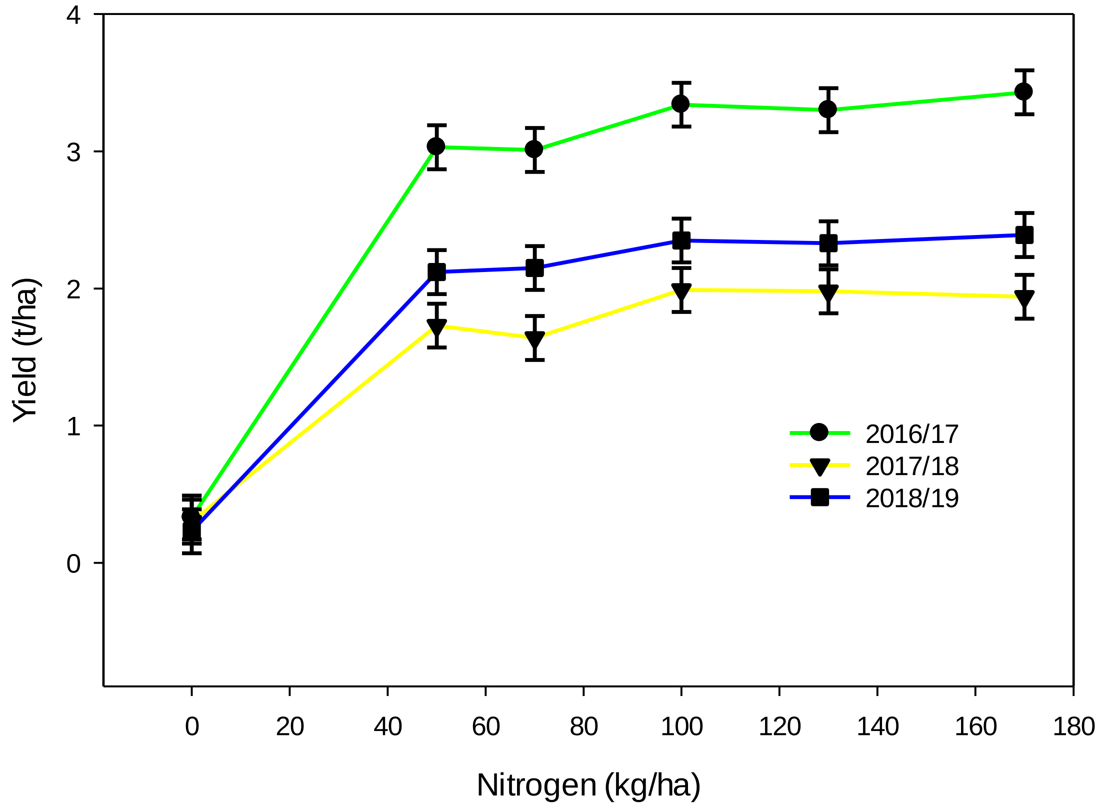

Figure 3. 6: The interaction effect of nitrogen application × season on grain yield of sorghum. Vertical bars represent standard error

The effect of distance from the RWH method on grain yield of sorghum significantly varied ($p<0.05$) with the season (Table 3.5). Grain yield from RWH methods was comparable at all distances in the 2016/17 season, and the season had the highest grain output at all distances when compared to the 2017/18 and 2018/19 seasons (Figure 3.7). In the 2017/18 and 2018/19 seasons, the effect of distance from the RWH method was more apparent. Distances of 0-5 m and 5-10 m from RWH methods yielded comparable grain yields in both seasons 2017/18 and 2018/19, but significantly greater than 10-15 m. In all the seasons, the distance of 10-15 had significantly lower sorghum grain yield than distances of 0-5 and 5-10 m.

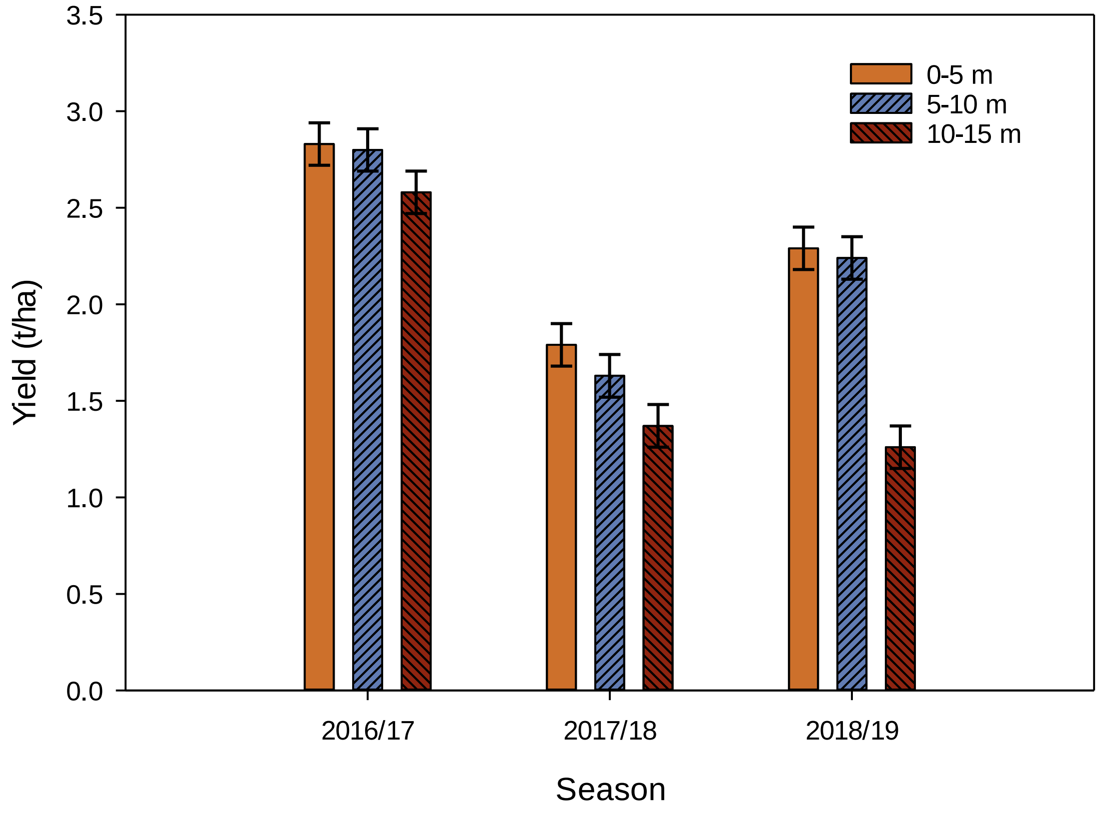

Figure 3. 7: Interactive effects of plant distance from RWH method × season on grain yield of sorghum. Vertical bars represent standard error.

The RWH method and nitrogen application rate had a significant interaction effect ($p<0.05$) on grain yield (Table 3.5). The results showed that the SC had a considerably lower ($p<0.05$) grain yield than the TC and IP at all nitrogen application rates except at 0 kg N/ha (Figure 3.8). At 0 kg N/ha, there was no considerable variation in sorghum grain yield between the RWH systems and the SC. In all the RWH methods, nitrogen-applied treatments had considerably higher ($p<0.05$) sorghum grain yield than the 0 kg N/ha treatment. Nitrogen application increased sorghum grain yield in the TC and IP (Figure 3.8), compared to the SC. Sorghum grain yield increased considerably up to 50 kg N/ha in the SC, beyond which there was no significant improvement.

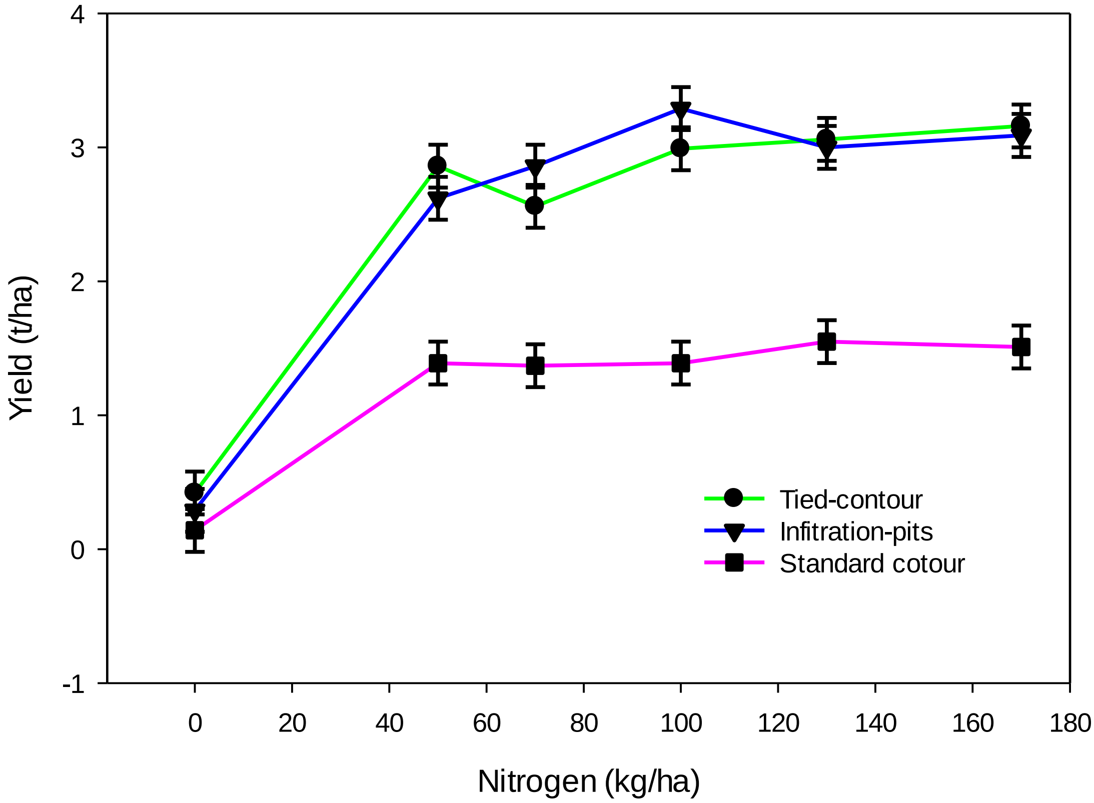

Figure 3. 8: Interactive effects of RWH method × nitrogen application on grain yield of sorghum. Vertical bars represent standard error.

The interaction effect of sorghum variety and nitrogen application on sorghum grain yield was significant ($p<0.05$) (Table 3.5). At all the nitrogen application rates, the sorghum variety Macia had significantly greater yield than the sorghum variety Sc Sila at nitrogen application rate of 50, 70, 100, and 130 kg N/ha, while no grain yield significant differences were observed at 0 and 130 kg N/ha (Figure 3.9). At 0 kg N/ha, there was no substantial difference in yield between the sorghum cultivars. Treatments of 50, 70, 100 and 130, 170 kg N/ha had significantly higher ($p<0.05$) grain yields than 0 kg N/ha each sorghum variety. The grain yield did not differ significantly in all the varieties when nitrogen addition was greater than 50 kg N/ha.

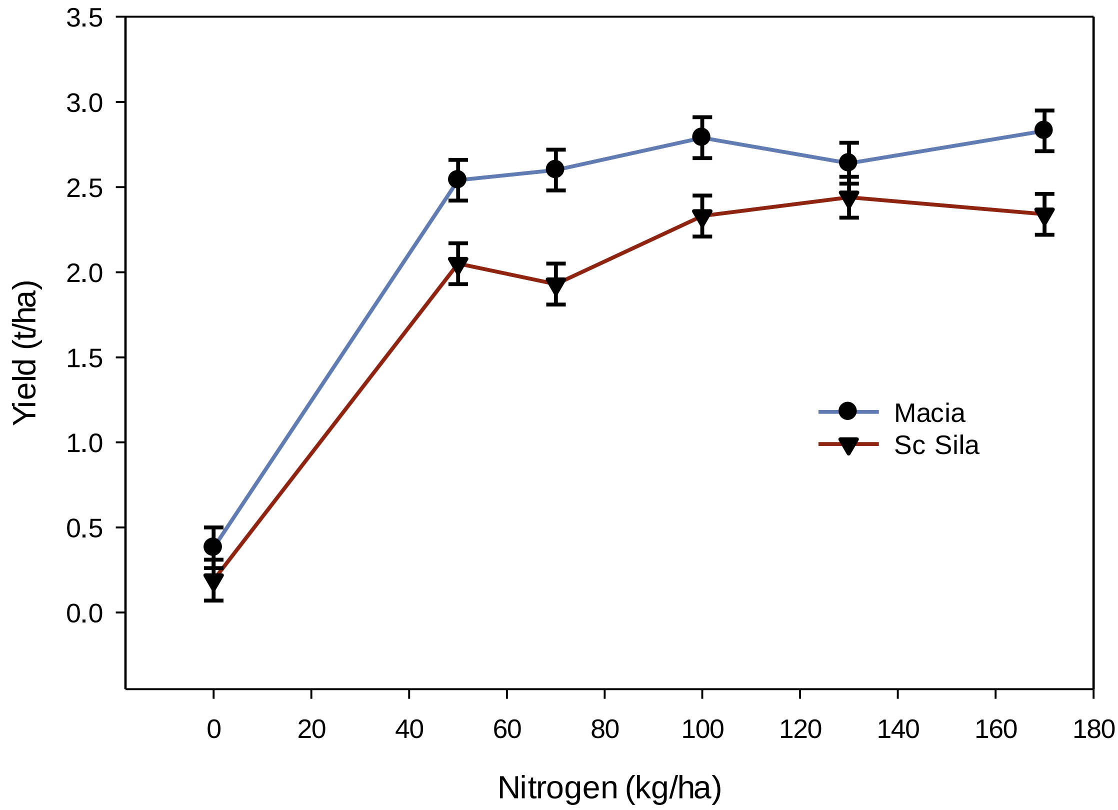

Figure 3. 9: The interaction effect of sorghum variety × nitrogen application on grain yield of sorghum. Vertical bars represent standard error.

The yield of sorghum grain was significantly influenced ($p<0.05$) by the interaction of nitrogen application and distance from the RWH method (Table 3.5). Treatments with 0 kg N/ha had considerably lower grain yield than treatments with nitrogen rates more than 50 kg N/ha, and this trend was consistent at all distances from the RWH method (Figure 3.10). The distance from the RWH method of 10-15 m had consistently lower grain yields at all nitrogen application rates except for the control (0 kg N/ha) where there was no grain yield difference.

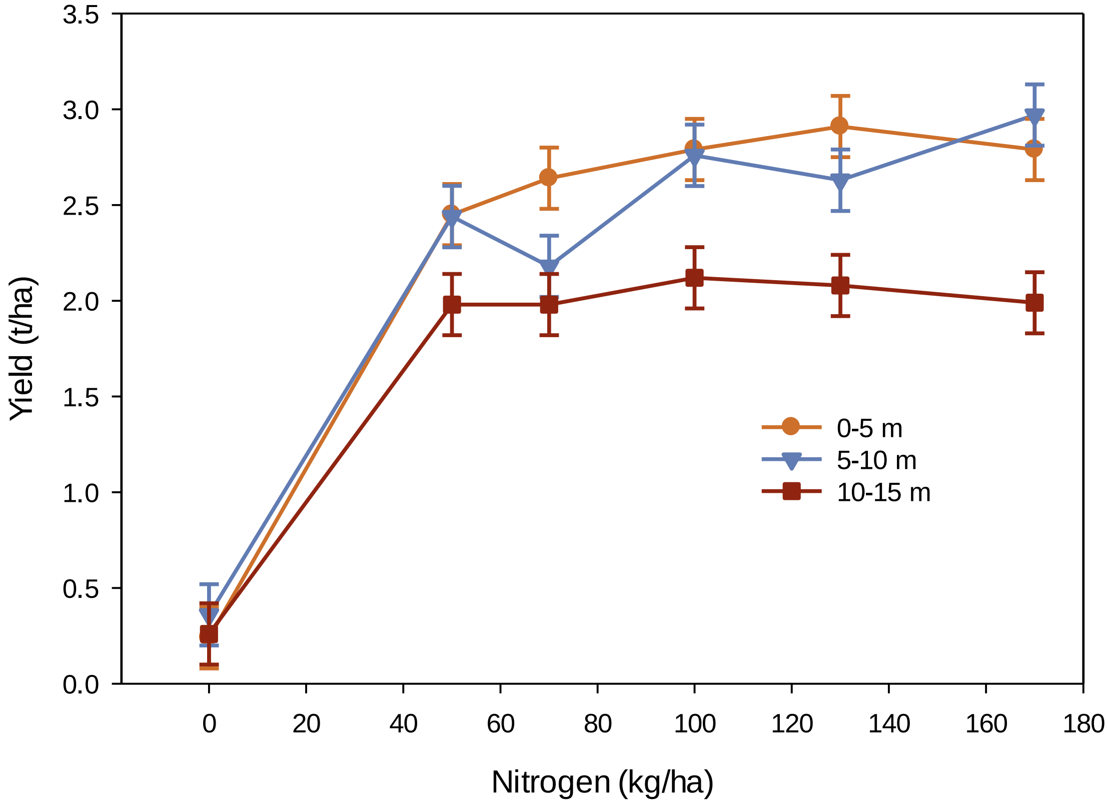

Figure 3. 10: Interactive effects of plant distance from RWH method × nitrogen application on sorghum grain yield. Vertical bars represent standard error.

The interaction between RWH, sorghum variety, and distance from RWH influenced sorghum grain yield considerably ($p<0.05$) (Table 3.5). Grain yield response to RWH methods in all sorghum varieties showed that TC and IP had higher grain yields than the SC at all distances (Figure 3.11). However, at all distances from RWH methods, TC and IP had comparable grain yields under the sorghum varieties (Macia and Sc Sila), except at 5-10 m distance under the sorghum variety Sc Sila. Yield varied in the order IP>TC>SC at a 5-10 m distance from the RWH method in the sorghum variety Sc Sila (Figure 3.11).

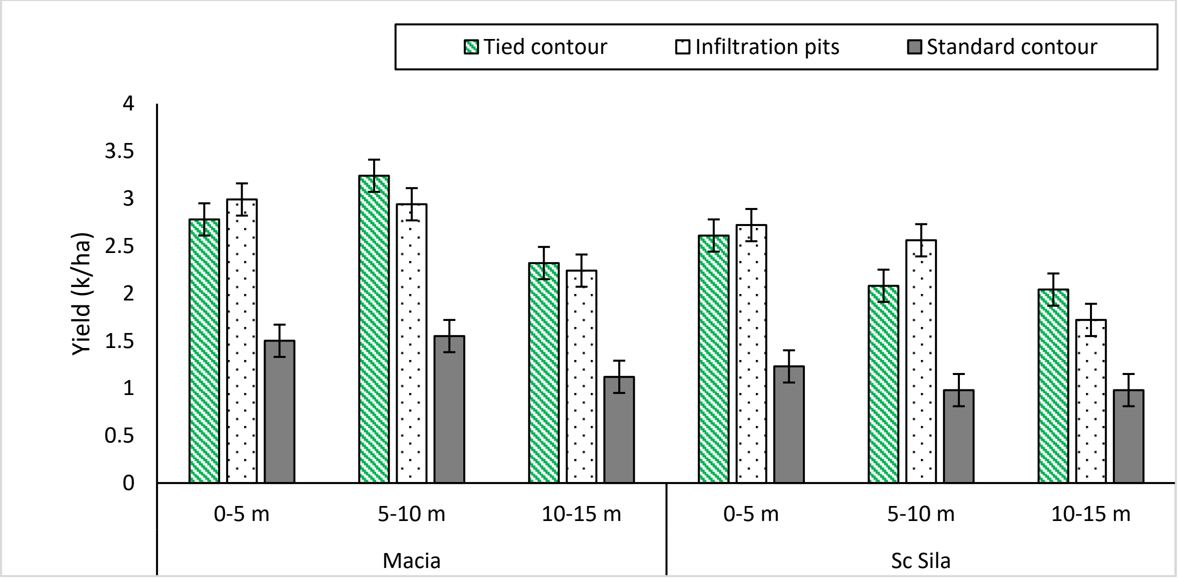

Figure 3. 11: Interactive effects of RWH method × variety × plant distance from RWH method on grain yield. Vertical bars represent standard error.

3.4 DISCUSSION

3.4.1 Soil moisture

The RWH methods TC and IP improved the actual measured gwc (Table 3.3) and the predicted gwc at field capacity, wilting point, and saturation point of the soil (Figure 3.4). It implies that the RWH methods improved the water retention properties of the soil. This was due to their capacity to collect more runoff water from the catchment area creating a moisture reservoir resulting in more moisture under the cultivated area down the slope. The comparable gravimetric water content shown by tied contour and infiltration pits may be due to their similar principle of operation in water collection and storage. Nyagumbo et al. (2019) found that the use of tied contours and infiltration pits increased soil water content by up to 40% compared to traditional farming methods. Another study conducted by Mupangwa et al. (2012a) found that RWH techniques improved soil water content by up to 60% compared to a control plot. However, not all studies have found such a significant improvement. Some studies have found smaller increases in soil water content, or no significant difference. For example, a study conducted by Nyakudya et al. (2014) found that tied contours and infiltration pits did not have a significant impact on soil water content, likely due to the high clay content of the soil. Similarly, a study from South Africa conducted by Mugabe (2004) found that RWH techniques had only a small impact on soil water content. It is worth noting that the studies were conducted in different locations and used different methods, so it is difficult to draw definitive conclusions. However, they do suggest that the impact of tied contours and infiltration pits on soil water content may vary depending on the soil type, slope catchment characteristics and other environmental factors. The standard contour had the least gwc due to water loss through runoff. The results concur with the findings by Nyamadzawo et al. (2013) who found that about 50 % of water is los as runoff from standard contours. The actual measured gravimetric water content and the predicted gravimetric water content at field capacity, wilting point and saturation point decreased with increase in distance (Table 3.3; 3.4). It implies that the effectiveness of the RWH practices decreased with increase in distance from RWH practice. The decrease in soil moisture content with increase in distance from source of moisture is best explained by Richards (1931)'s equation. According to Richards equation, the rate of change of moisture content with distance is proportional to the capillary pressure. In other words, the further the distance from moisture source, the lower the capillary pressure and the lower the rate of change of moisture content. This is because the further away from moisture source, the water has to overcome more resistance from the soil, and it is likely to evaporate. The 2016/17 season characterized by high rainfall (Figure 3.3) had the highest gwc (Table 3.3). Despite the high rainfall total in 2016/17, the season was characterized by well-distributed rainfall during the greater part of the season which encouraged water infiltration resulting in high gwc. The low gwc in the 2018/19 season might be attributed to the poor quality of the season which was marked by high-intensity rainfall within a small period in the months of January and February.

This could have resulted in water loss due to runoff, as rainfall intensity may have exceeded the soil's infiltration capacity.

3.4.2 Grain yield

The TC and IP RWH methods improved the grain yield of sorghum compared with the SC in all the seasons (Figure 3.5) showing their potential to serve as climate change resilient strategies in semi-arid regions. This was attributed to the ability of the RWH methods in collecting runoff water from the catchment area creating a large moisture reserve. This was evidenced by higher gwc (Table 3.3) and predicted gwc at field capacity, wilting point and saturation point in the RWH practices (Figure 3.4). The soil moisture will probably later used by the crops to evade dry spells. The results corroborate with those of Mandumbu et al. (2020) and Nyagumbo et al. (2019) who found higher grain yields under improved RWH techniques compared with the conventional farming system (graded standard contour). Earlier findings by Mupangwa et al. (2012a) also revealed that RWH techniques tied ridges, infiltration pits, and dead level contours with and without infiltration pits improved the soil moisture and crop yields. Water retention by TC and IP improves soil moisture and subsequently higher grain yield. In the SC, runoff water was disposed of leaving little water reserve in the contour for groundwater recharge resulting in low yield. This was evidenced by the low gwc (Table 3.3) and predicted gwc at field capacity, wilting point and saturation point attained by the SC (Figure 3.4). Results support work by Nyamadzawo et al. (2012) and Nyamadzawo et al. (2013) who reported water losses up to 50% being lost as runoff from croplands and disposed of through contour channels. Mahinda et al. (2018) and Mupangwa et al. (2018) reported that soil water availability is critical for effective grain filling and hence yield. Thus, RWH structures can sustain crop production during dry periods under rain-fed crop production systems in semiarid regions.

In all the seasons the addition of mineral nitrogen increased sorghum grain yield. The yield was highest in 2016/17 at all nitrogen application rates while the 2017/18 season had the least sorghum grain yield at all nitrogen application rates except for the zero-nitrogen application rate (Figure 3.6). This was attributed to differences in rainfall pattens. The season 2016/17 was characterized by above-average rainfall (900 mm) (Figure 3.3) and wetter rainfall pentad (Table 3.2) which improved groundwater recharge resulting in more soil moisture (Table 3.3), hence higher grain yield response to nitrogen. Despite the seasons 2017/18 and 2018/19 showing above-average rainfall, they were characterized by high-intensity short-duration rainfall (Table 3.2) generating more runoff resulting in low plant response to nitrogen. Soil moisture has a direct effect on nitrogen uptake on the production of assimilates and partitioning to economic sink (Sharma & Bali, 2017). Thus, the season's rainfall characteristics play a vital role in the effect of nitrogen on crop productivity. Nitrogen application greater than 50 kg N/ha had no substantial grain production advantage in all the seasons. This implies that application rate of 50 kg N/ha is probably the optimum.

The season 2016/17 was characterized by wetter rainfall pentads and high rainfall (900 mm) (Figure 3.3) which resulted in more moisture content evidenced by higher gwc in the season (Table 3.3) and high soil water retention capacity in terms of predicted gravimetric water content at field capacity, wilting point, and saturation point (Table Figure 3.4). This probably resulted in higher grain yield at each distance (Figure 3.7). The greater moisture sphere of influence resulted in no grain yield difference at each distance in the 2016/17 season due to higher rainfall totals. In seasons with above-average rainfall, Mupangwa et al. (2012a) found comparable soil moisture in the soil profile, resulting in no variation in yield. The effect of plant distance from the RWH method was apparent in the 2017/18 and 2018/19 seasons. However, the rainfall totals were comparatively moderate and above-average rainfall (Figure 3.3) but poorly distributed across the seasons. A gradual drop in yield observed as plant distance increased from the RWH method (Figure 3.7) in all seasons was attributed to a considerable drop in gwc as plant distance increased from the RWH method (Table 3.3). Results corroborate with findings by Nyakudya et al. (2014) and Mupangwa et al. (2012a) who found moisture benefits at access tubes placed closer to the rainwater harvesting technique while those further away had little moisture benefits which result in differential plant growth. Moisture gradients created as distance increase results in differential moisture interception and uptake for plant development and hence yield (Lian et al., 2017; Mhizha & Ndiritu, 2013; Mupangwa et al., 2012a). The decrease in soil moisture with increase in distance was explained by Richards (1931)'s theory.

Grain yields were greater in TC and IP than in SC at all nitrogen applications rates greater than 50 kg N/ha (Figure 3.8). The RWH methods showed higher gwc which may have a bearing on better grain yield response to nitrogen addition. Studies by Mishra & Patil (2015), Shamme et al. (2016), and Sharma & Bali (2017) showed a significant positive association between nitrogen and soil moisture on sorghum grain yield. Mahinda et al. (2018) also found that the integration of the RWH method and nitrogen application rates improves crop productivity. The low grain yield response to nitrogen addition in the SC was due to low moisture content evidenced by the low gwc (Table 3.3) and low soil water retention capacity (Figure 3.4). Higher sorghum grain yield at 50, 70, 100, 130 and 170 kg N/ha compared with no 0 kg N/ha treatment in the RWH methods (Figure 3.8) explains the importance of nitrogen addition in crop growth. Water and nitrogen availability are important in the production of photo-assimilates and partitioning at the economic sink for the production of grain (Lian et al., 2017).

The sorghum variety Macia showed significantly greater grain yield than variety Sc Sila across all nitrogen application rates except at nitrogen addition of 130 kg N/ha with no significant variation in grain output (Figure 3.9). The effect of sorghum variety on yield was mainly attributed to varietal differences. Contrary to the high yield potential of a hybrid sorghum variety Sc Sila, the variety showed a low grain yield response to nitrogen application compared to Macia. Macia is an open-pollinated sorghum cultivar with a quiescent growth habit and better environmental adaptability, giving it an advantage in grain yield response to nitrogen over Sc Sila a hybrid sorghum variety. Hadebe et al. (2017a) found yield advantage of open-pollinated varieties over hybrids. Higher sorghum grain yield in the treatments 50, 70, 100, 130 and 170 kg N/ha compared with 0 kg N/ha treatment in each sorghum variety (Figure 3.9) indicates the importance of nitrogen in crop growth.

The influence of nitrogen on grain yield varied with distance from the RWH method. Distances from the hydraulic structure of 0-5 m and 5-10 m showed higher sorghum grain yield than 10-15 m at all nitrogen application rates (Figure 3.10). The positions were closer to the moisture discharge point, which experienced moist conditions where moisture was easily intercepted by plants. This subsequently improved grain yield response to nitrogen than positions further away. This was shown by significantly higher gwc at 0-5 m and 5-10 m distances from rainwater harvesting practices closer to moisture discharge point than the 10-15 m distance further away (Table 3.3). Hence, the reduced grain yield at a 10-15 m distance from the RWH method was related to lower water availability which resulted in low grain yield. The findings are supported by Richards (1931)'s equation. The theory explains that the rate of change of moisture content with distance is proportional to the capillary pressure. This means that further the distance from moisture source, the lower the capillary pressure and the lower the rate of change of moisture content. As water moisture moves further away from moisture source, it encounters resistance from the soil, and it is likely to evaporate and intercepted by plants. Therefore, distances closer moisture source exhibit higher gwc and soil water retention capacity hence higher grain yield. According Mandumbu et al. (2020), soil moisture content close to field capacity provides the optimum pores for the diffusion of oxygen, the highest nutrient content in insoluble forms, and the largest sectorial region for ion and mass movement of water, and the optimum soil environment for root growth.

Nitrogen application above 50 kg N/ha across RWH methods, varieties, distance from RWH method, and seasons had no grain yield benefits. Results support work by Shamme et al. (2015) and Mupangwa et al. (2018) who found no yield response in cereal grain crops to high nitrogen fertilizer inputs under a rain-fed production system. Mupangwa et al. (2018) suggest that some soil variables may become limiting leading to no substantial variation in yield. Other soil variables, such as micronutrient deficiencies and nitrogen leaching, might affect crop growth at pH levels below 5.0 (Madamombe et al., 2018). However, there was evidence of stunting when nitrogen fertilizer was not applied resulting in yield reduction in each season confirming the importance of nitrogen application on crop yield (Lian et al., 2016).

Higher grain yield attained by TC and IP at each distance from the RWH method and sorghum varieties (Figure 3.11) may be attributed to the higher capacity of TC and IP in capturing runoff water for later use by the crops. Water captured influenced infiltration and lateral flow downslope improving grain yields at all distances from RWH methods across all varieties compared with SC. This was shown by higher water content being attained by TC and IP while the SC had the least water content (Table 3.2; Figure 3.4). Mahinda et al. (2018) and Mupangwa et al. (2016) reported that the RWH techniques have the potential to mitigate crucial water deficit periods through moisture retention in the rhizosphere.

3.5 CONCLUSION

The RWH methods (TC and IP) improved sorghum grain yield by storing more available soil water, evading critical moisture stress periods. This was demonstrated by the high soil water content exhibited by the RWH methods. However, with increasing plant distance from RWH systems, there was a variation in moisture content in a decreasing trend. The SC had low crop productivity, evidenced by low gwc and grain yield. Grain yield response to N was improved by TC and IP RWH methods. A substantial grain yield response to nitrogen was attained by sorghum variety Macia revealing its adaptation and yielding ability. The nitrogen application rate of 50 kg N/ha was more beneficial and recommended under the RWH methods, sorghum varieties, distance from RWH methods, and in all seasons. The findings suggest that TC, IP and application of nitrogen are climate change resilient crop intensification practices which can improve soil moisture and sorghum grain yield in semi-arid farming systems. However, the research was carried out in a typical sandy soil characterized by high seepage which may reduce the capacity of TC and IP RWH methods. Further study needs to conducted on how to improve water storage capacity of RWH methods. Smallholder farmers are also resource constraint, therefore future work may need to be carried out to investigate the economic benefits of using TC and IP as RWH methods.

CHAPTER 4: INTERACTIVE EFFECTS OF CONTOUR-BASED RAINWATER HARVESTING AND ORGANIC FERTILIZERS ON GRAIN YIELD OF *SORGHUM BICOLOR L.* (SORGHUM) IN RAINFED DRYLAND FARMING SYSTEMS, ZIMBABWE

ABSTRACT

Rainfall variability in semi-arid rain-fed smallholder farming systems affects sorghum grain yield with prolonged dry spells, especially during critical crop growth stages. This is aggravated by low soil fertility because inorganic fertilizers are beyond the reach of most smallholder farmers. The objective of the research was to investigate the effect of contour-based rainwater harvesting (C-RWH) systems and cattle manure as a source of nutrients, on the grain yield of sorghum. A factorial experiment was laid out in a split-split plot design and replicated three times. Infiltration pits (IP) and tied contours (TC) were two rainwater harvesting (RWH) systems that were compared with the control, the modified standard contour (SC). The sorghum varieties used in the experiment were Macia and Sc Sila. Soil moisture and sorghum grain yield data were subjected to analysis of variance (ANOVA) to determine treatment differences. The findings from this study showed that in each RWH system sorghum grain yield increased with an increase in cattle manure application up to 20 t/ha and differed in the order TC > IP > SC at each cattle manure application rate. The use of cattle manure increased sorghum grain yield in each sorghum variety and across seasons with sorghum variety Macia showing a higher grain yield than Sc Sila at all cattle manure application rates. However, the two seasons showed no significant sorghum grain yield differences at all cattle manure application rates. In the two sorghum varieties, TC and IP had higher sorghum grain yields compared with SC at all distances from the RWH system in both seasons (2016/17 and 2017/18). According to the findings, using C-RWH practices (TC and IP), and cattle manure increase sorghum grain yields in rain-fed smallholder agricultural systems.

Keywords: Rainwater harvesting, cattle manure, sorghum, rainfall variability, soil fertility

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4.1 INTRODUCTION

Sorghum is primarily cultivated as a rain-fed grain crop in subtropical Africa in places with low, inconsistent, and extremely variable annual rainfall totals ranging from 400 to 650 mm (Naba et al., 2020). Despite its resilience to adverse ecological conditions, research has shown that in semiarid parts of Africa, the production potential of grain sorghum is severely constrained by soil water deficit and low fertility (Wang et al. 2020). Low and erratic rainfall (Mupangwa et al., 2018) compounded by runoff loss (Nyamadzawo et al., 2013), and low fertility (Masvaya et al., 2017) are the major causes of low crop output in the semiarid smallholder farming systems in Zimbabwe. The availability of adequate soil water and plant nutrients, particularly N, is a critical component of effective sorghum production in semi-arid smallholder farming systems. To meet the expanding population's demand for food Agriculture in dryland areas must be improved by making better use of rainwater and implementing low-input, low-nutrient management practices (Naba et al., 2020). As a result, in semi-arid smallholder farming systems, water and nutrient management is a critical entry point for long-term agricultural productivity and poverty reduction. Integrating contour based rainwater harvesting (C-RWH) and organic fertilizers into crop production are effective agronomic management strategies for increasing sorghum yields (Kugedera et al., 2022). The benefits of integrating organic fertilizers with rainwater harvesting (RWH) practices in restoring water and soil fertility, as well as improving agricultural yields, have been demonstrated by Kubiku et al. (2022a) and Vanlauwe & Zingore (2011). Research by Kugedera et al. (2020) and Wang et al. (2020) found that using organic and RWH techniques resulted in significant increases in both nirogen uptake and yield.

The significance of organic matter in maintaining the sustainability of cropping systems is indisputable. Organic matter's primary function in the soil is to stabilize soil aggregates, making it simpler to cultivate, enhancing soil water-holding and buffering capacities, and releasing plant nutrients upon mineralization (Fageria, 2012; Mapfumo and Giller, 2001). Mapfumo et al. (2007) found that sandy soils are typically more responsive to organic amendments than other soil types, due to their low cation exchange capacity and low organic matter content. When manure is applied to growing crops, it is possible to eliminate the need for mineral nitrogen fertilizer (Fageria, 2012). However, under organic fertilizer management, one issue that remains to be of concern is the optimum application rate under moisture deficit environments. Because of slow mineralization, greater N immobilization, denitrification, and volatilization, organic fertilizers frequently have suppressed yields (Vanlauwe et al., 2001). All of these challenges in organic fertilizer management indicate that further research is needed to optimize organic fertilizer use in semiarid smallholder farming systems. The effectiveness and profitability of organic fertilizers as agronomic inputs are improved by determining the management techniques that will provide long-term agronomic use.

Cattle manure is a common organic nutrient source for crops in smallholder farming systems, although its efficiency among most farming systems is limited by low moisture. Low soil moisture makes the amount of nutrients provided by the cattle manure insufficient to meet crop demands in a semi-arid smallholder farming system (Chivenge et al., 2011). Low soil moisture tends to slow mineralization and the subsequent release of nutrients causing nutrient asynchrony with crop demand (Vanlauwe & Zingore, 2011). Moisture status differences explain the differential yield responses following organic application in cropping systems (Tittonell et al., 2005). Manipulating the mineralization of the organic fertilizers to promote synchrony between nitrogen release and plant uptake is a challenging task (Rufino et al., 2011). Adopting rainwater harvesting measures that reduce the effects of dry spells caused by seasonal variation in rainfall can help to synchronize water and nutrient availability in the root zone (Chivenge et al., 2011; Naba et al., 2020). Research is still being done in semi-arid areas to develop sustainable water management practices and promote the use of organic fertilizer recommendations for dryland grain sorghum production systems. Some rainwater harvesting techniques, on the other hand, have gained popularity due to their ability to recharge groundwater by collecting runoff water and concentrating it in the rhizosphere via subsurface flow and capillary action (Kubiku et al., 2022b; Nyamadzawo et al., 2015). The theory of subsurface flow was developed by Richards, (1931) which describes the movement of water through a porous medium and take into consideration both the pressure head and capillary pressure.

Rainfall harvesting systems based on contours have not been fully exploited in increasing the sustainability and reliability of rain-fed agriculture by optimizing rainwater use and organic nutrient release (Kugedera et al., 2022; Nyagumbo et al., 2019). The substantial contribution to this development in rainfall collection and subsequent provision of moisture to crops in dryland farming systems during prolonged dry spells has not been fully investigated (Mohammedien et al., 2018). In addition, the synergy between the combined effects of C-RWH and organic fertilizers in increasing sorghum grain yield through soil water supply and nutrient release is still limited. Contour-based rainwater harvesting may be an entry point and viable opportunity to improve the productivity of organic fertilizers in moisture deficit environments in a long-term sustainable manner. The objective of this study was to determine the effects of tied contour and infiltration pits C-RWH techniques and cattle manure on sorghum yield in semiarid rain-fed smallholder farming systems.

4.2 MATERIALS AND METHODS

4.2.1 Description of the study area

The study was undertaken during the 2016/17 and 2017/18 cropping seasons, at Mt Zonwe's small-scale farming area in Mutare district, Zimbabwe (19^{o} 11\` 30\`\` S $32^{o}$ 03\` 28\`\` E 835 m above sea level). The small-scale farming community is located in natural farming region IV characterized and marginal annual rainfall ranging from 450 to 650 mm. The rainfall pattern is unimodal starting in October and ending in March. The landform was composed of sandy soils overlaying gravel at a depth of 0.9 m and on a general slope of 3 % which requires soil conservation practices. Rock outcrops were also predominant stretching to the cultivated area with potential to generate runoff and serve as bedrock for water retention. The cropping season experiences periodic dry spells, particularly in January. The farming area consists of a dry season that spans from May to September. Sorghum, millets, and cotton are the principal crops grown in monoculture, and maize production is very poor as a result of recurrent droughts. Data for the initial soil physicochemical characteristics of the study sites and nutrient content in the study are presented in Table 4.1.

4.2.2 Soil sampling and analysis

Soil samples were randomly taken across the experimental field measuring 90 x 45 m up to a depth of 30 cm. The samples were composited, air-dried, ground, and sieved through a 2 mm sieve. The physical soil properties were determined following the Bouyoucons Hydrometer method (Bouyoucos, 1962), soil pH following 0.01 M $CaCl_2$ method (Henderson and Bui, 2002), organic C following wet digestion method (Walkley and Black, 1934), total nitrogen following Kjeldahl method (Cottenie, 1980), and available P_2O_5 following the Olsen method (Olsen, 1954) (Table 4.1).

Table 4. 1: Physico-chemical characteristics of the soil on the experimental site

Physical properties		
Sand %	82	
Silt %	14	
Clay %	4	
Textural Class	Sand	
Chemical properties	**2016/17**	**2017/18**
pH	5.5	5.6
Organic C %	1.01	1.03
Total N %	0.1	0.17
Available P_2O_5 mg/kg	4.21	4.32

4.2.3 Experimental design

A factorial experiment was laid out in a split-split plot design and replicated three times over two seasons. The experimental design was partly based on Kubiku et al. (2022a), where a field with at least three 90 m consecutive modified standard contours (SC) spaced at 15 m intervals was selected. Each 90 m SC lengths was divided into 3 × 30 m RWH systems (Figure 4.1). Earth ties spaced at intervals of 5 meters along the contour channel were constructed forming micro ponds that were 0.5 meters broad and 0.4 meters deep. The earth ties measured 0.5 m wide × 0.5 m long × 0.4 m deep. The modified SC channel with the micro ponds was called tied contour (TC). Infiltration pits consist of miniature dams dug along the SC channel measuring 2 m long x 0.5 m wide x 0.5 m deep spaced at intervals of 0.5 m along the contour channel. The RWH systems - tied contour, infiltration pits and standard contour were the main plot factor. As a control, a SC of 30 m length was left. The RWH systems were demarcated by a 2 m wide buffer strip along the contour channels. Under each RWH system, subplot factors of the sorghum varieties Macia and Sc sila were planted. Cattle manure application rates of 0; 5; 8; 10; 15; and 20 t/ha were superimposed as sub-sub plot components, each measuring 2 m long and 4.5 m wide. The cattle manure application rates were based on farmers' practice and cattle manure nutrient composition. The cattle manure treatments in each sorghum variety were replicated three times downslope in each RWH system at varying distances of 0-5 m, 5-10 m, and 10-15 m measured from the center of the RWH method (Figure 4.1).

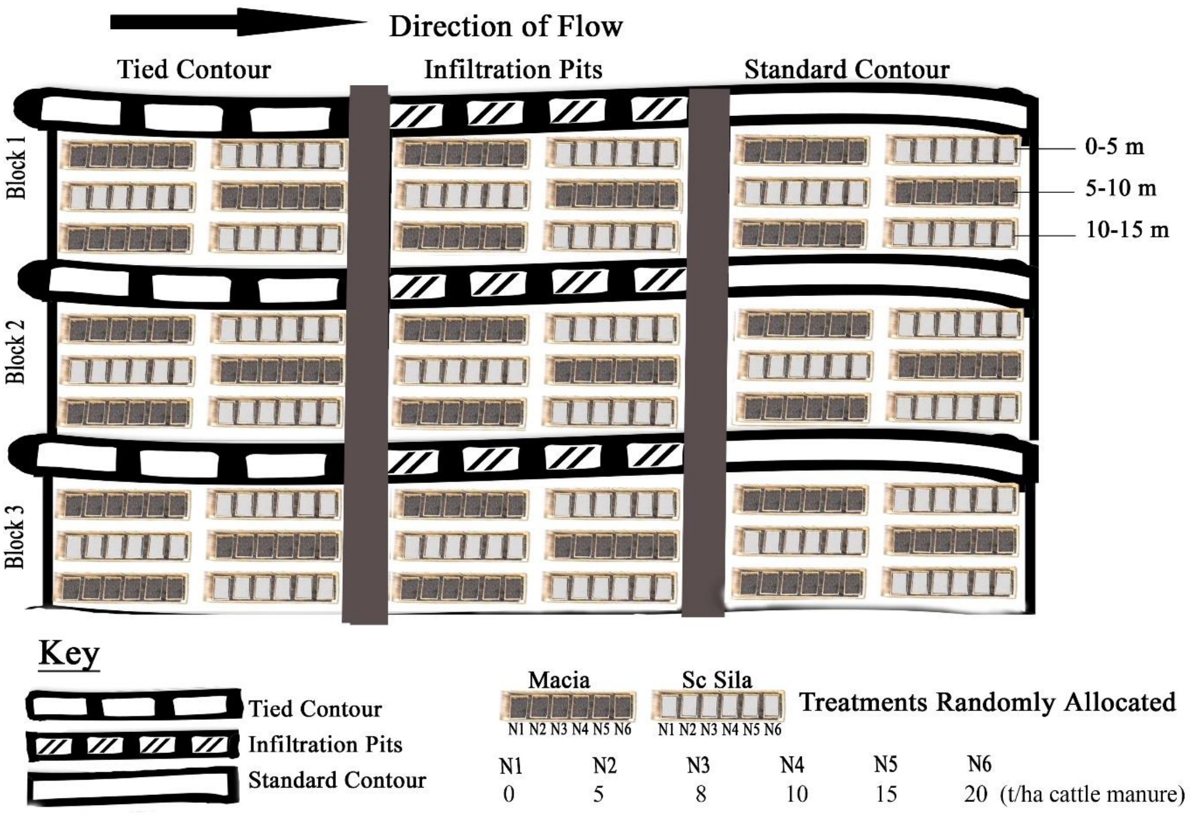

Figure 4. 1: Experimental Layout

4.2.4 Experimental Procedure

In the month of December, ox-drawn plough was used to plough the field to a depth of 20 cm. In all the treatments, furrows were opened with an interrow spacing of 0.75 m. Cattle manure application rates of 0; 5; 8; 10; 15 and 20 t/ha were randomly applied as basal organic fertilizer into the sub-sub plots under the three rainwater harvesting systems. The nutrient content of cattle manure was determined before spreading (Table 4.2). In both seasons the varieties of sorghum, Macia and Sc Sila were drilled at a seed rate of 12 kg/ha. Plants were thinned to leave individual sorghum plants spaced at 10 cm along the furrow after crop emergence to achieve a population of 133 333 plants/ha. Planting commenced after receiving the first effective rainfall of the season and was completed by mid-December every season. Experimental plots were weeded to control weeds as they emerged in all the seasons. To prevent grain loss, the pesticide Ecoterex (*Deltamethrin and Pirimiphos methyl*) was used to suppress the Fall armyworm (*Spodoptera frugiperda*) while Quelea birds were kept under control from the time flowers began to bloom until harvest maturity. A rain gauge was installed at the study site and the farmer recorded the rainfall.

Table 4. 2: Composition of nutrients in applied cattle manure

Parameter	**Composition**	
	2016/17	**2017/18**
Organic C (%)	10	12
Total N (%)	0.81	0.73
Available P (mg/kg)	0.003	0.002
Available K (%)	0.5	0.5
Moisture Content (%)	17	18

4.2.5 Data collection

4.2.5.1 Moisture content

Soil samples were collected with an auger up to a depth of 0.6 m in each RWH method at varying distances of 0-5 m, 5-10 m, and 10-15 m from the RWH method. Soil samples were taken once in every month regardless of whether there had been a rainfall event or not at the time of collection. The soil samples were oven-dried at 105 ℃ for 48 h before determining gravimetric water content. The gravimetric water content was determined using the method described by Ingram & Anderson (1993) and (Nyagumbo et al., 2019). The volumetric water content was not determined since the bulk density of the soil was not assessed. Pedofunctions were used to predict gravimetric water content at field capacity, wilting point and saturation point to determine the effectiveness of the RWH practices in soil moisture retention.

4.2.5.2 Grain yield

Sorghum heads were removed from the two centre rows, each measuring 1 m in length, when they were ready for harvest. For threshing, the sorghum heads were sun-dried, and the seed yield was adjusted to a moisture content of 12.5%. Grain moisture was measured with a moisture meter (Dickey-john model). The moisture-adjusted grain yield was determined as follows:

Moisture corrected grain yield (t/ha) = Actual grain yield (t/ha) × (100-W)/(100-Z);

Where W, is the grain moisture and Z is the assigned grain moisture content (12.5%).

4.2.6 Data Analysis

The Kolmogorov-Smirnov test was used to determine the normality of grain yield and moisture content data, and the Bartlett test was used to determine the homogeneity of variances. Because the error of the variances for the two seasons was homogenous, the data for each season was not examined separately. The GenStat statistical programme was used for the analysis of variance (ANOVA), and significant treatment means were separated using the least significant difference test at 5%.

4.3 RESULTS

4.3.1 Rainfall

The two seasons were characterized by a relatively high rainfall total greater than the long-term average rainfall (650 mm) for the area (Figure 4.2). The season 2016/17 received more rainfall than the 2017/18 season. Intermitted dry spell conditions were experienced in the seasons despite high rainfall total. The dry spell conditions coincide with grain filling which are critical growth stages (Table 3.2) as explained in chapter 3

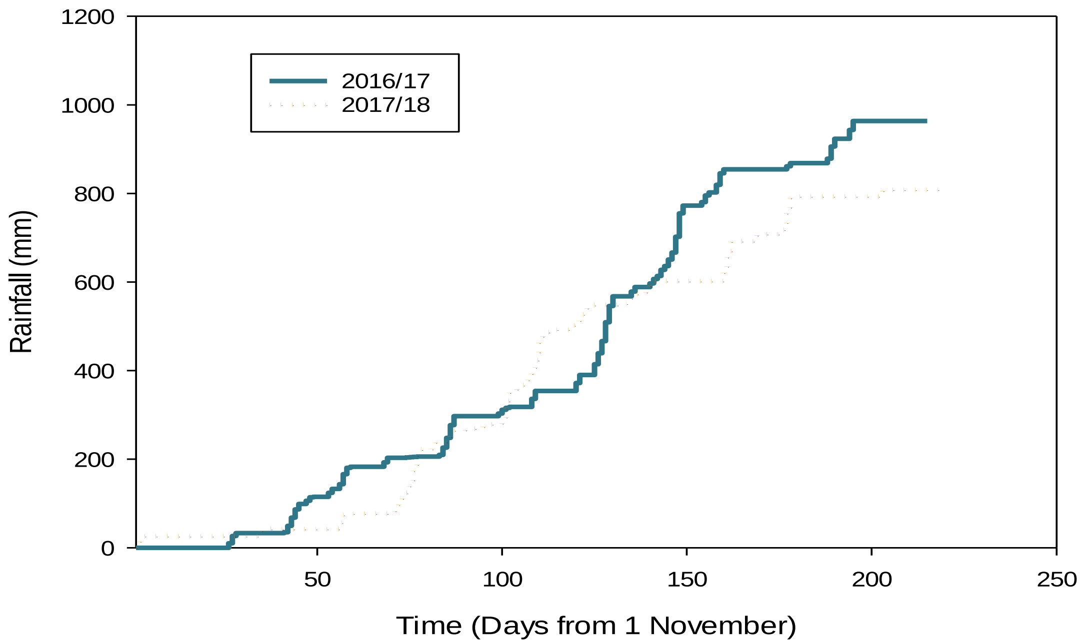

Figure 4. 2: Cumulative rainfall distribution during the course of the trial

4.3.2 Moisture content

When compared to the conventional farming method (standard contour), contour-based TC and IP had considerably higher soil moisture content ($p<0.05$) (Table 4.3). However, there was no discernible difference in moisture content between the RWH techniques of TC and IP. The amount of soil moisture differed significantly ($p<0.05$) as the distance from a RHW system increased in the following order: 0-5 m > 5-10 m > 10-15 m (Table 4.3). The moisture content between the two seasons 2016/17 and 2017/18 differed significantly ($p<0.05$) (Table 4.3). On soil moisture, there were no notable interaction effects among the treatments.

Table 4. 3: The Effects of rainwater harvesting method, distance from RWH method, and season on soil water content.

Treatment	Gravimetric water content (%)
Rainwater harvesting practice	
Contour-based tied contour	8.67[a]
Contour based infiltration pits	8.55[a]
Standard contour	6.84[b]
LSD	0.61
Distance from RWH system	
0-5 m	8.73[a]
5-10 m	7.99[b]
10-15 m	7.32[c]
LSD	0.41
Season	
2016/17	8.30[a]
2017/18	7.74[b]
LSD	0.31
Rainwater harvesting × distance from RWH	ns
Rainwater harvesting × season	ns
Distance from RWH × season	ns
Rainwater harvesting × distance from RWH × season	ns

Means followed with the same letter are not significantly different at $p<0.05$. ns – means are not significantly different at $p<0.05$.

The RWH practice, distance from the RWH practice, and season significantly influenced ($p<0.05$) the water retention capacity of the soil (Table 4.4). Tied contour and infiltration pits improved the water retention of the soil in terms of gwc at field capacity, wilting point, and saturation point compared to SC. The ability of the soil to retain water significantly decreased with an increase in distance from the RWH practice (Table 4.4). The results showed that the two seasons 2016/17 and 2017/18 had significantly different ($p<0.05$) predicted gwc at field capacity, wilting point and saturation point. The soil showed higher soil water retention capacity in 2016/17 season.

Table 4. 4: Predicted gravimetric water content at field capacity, wilting point and saturation point

Treatment	**Predicted gravimetric water content (%)**		
Rainwater harvesting	**Field capacity**	**Wilting point**	**Saturation point**
Tied contour	3.21[a]	-1.28[a]	11.10[a]
Infiltration pits	3.28[a]	-1.28[a]	11.31[a]
Standard contour	4.38[b]	-1.36[b]	14.49[b]
p-value	0.009	0.009	0.009
LSD	0.59	0.04	1.69
Distance from rainwater harvesting			
0-5 m	3.24[a]	-1.28[a]	11.19[a]
5-10 m	3.63[b]	-1.31[b]	12.34[b]
10-15 m	4.00[c]	-1.33[c]	13.38[c]
p-value	<0.001	<0.001	<0.001
LSD	0.02	0.02	0.74
Season			
2016/17	3.46[a]	-1.30[a]	11.82[a]
2017/18	3.79[b]	-1.32[b]	12.78[b]
p-value	<0.001	<0.001	0.01
LSD	0.24	0.02	0.70

Means in the same column followed with the same letter are not statistically different at $p<0.05$.

LSD – Least significant difference at 5 %

4.3.3 Yield

4.3.3.1 Effect of rainwater harvesting x cattle manure on sorghum grain yield

The interaction effect of RWH and cattle manure significantly influenced ($p<0.05$) sorghum yield. The grain yield response to RWH differed in the order TC>IP >SC at each application rate except at 5 and 15 t/ha (Figure 4.3). At cattle manure application rate of 5 and 15 t/ha, TC and IP had comparable yields which were significantly higher than SC. Highest sorghum grain yield (2.51 t/ha) was attained by TC at cattle manure application rate of 20 t/ha while the SC had the lowest grain yield (1.49 t/ha) at the same application rate. However, in all the RWH systems, there was an increase in grain yield with an increase in cattle manure application. Cattle manure application showed a strong correlation with grain yield in each RWH practice.

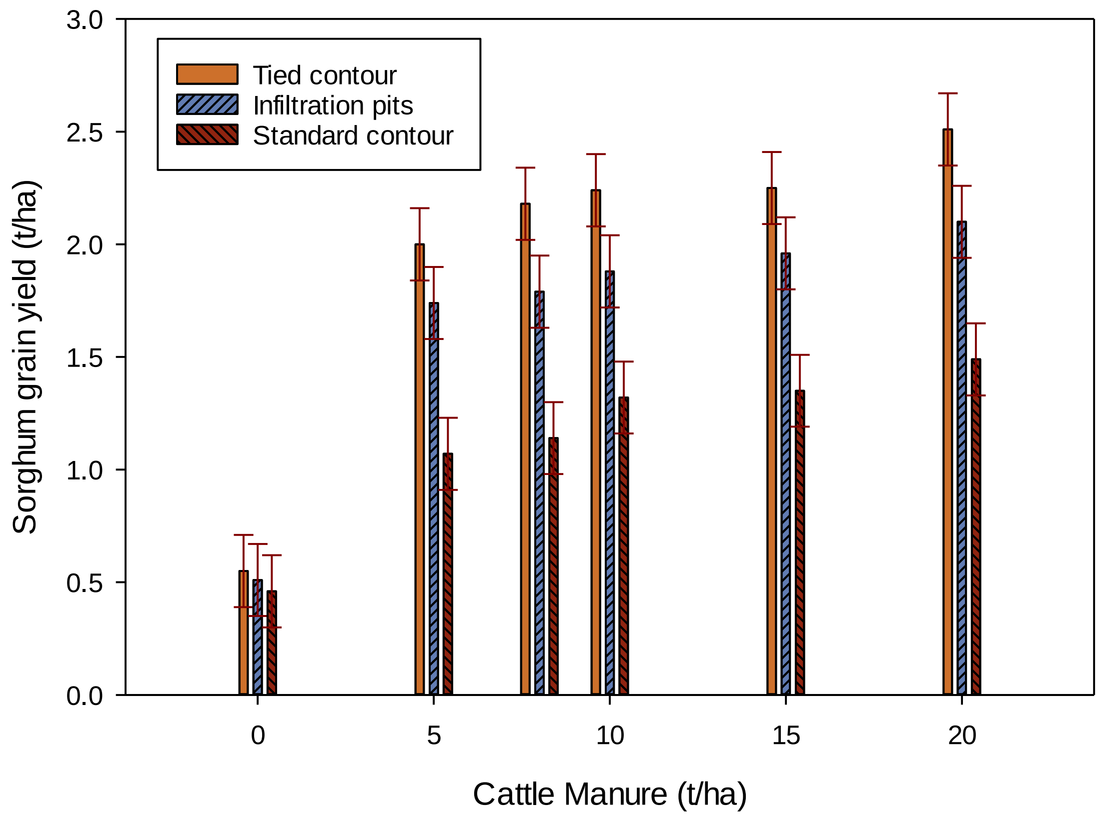

Figure 4. 3: Interaction effects of rainwater harvesting and cattle manure on sorghum yield

4.3.3.2 Effect of sorghum variety x cattle manure on yield

Sorghum variety and cattle manure showed a significant interaction effect on sorghum grain yield ($p<0.05$). Significant differences were observed between the sorghum varieties at all cattle manure application rates with sorghum variety Macia showing a higher yield than Sc Sila (Figure 4.4). However, no substantial grain yield differences were observed between the varieties at 0 kg/ha cattle manure. A strong correlation between cattle manure application rate and yield in both varieties was observed. The two sorghum varieties, Macia and Sc Sila attained the highest yield of 2.29 and 1.78 t/ha respectively at cattle manure application of 20 t/ha. Grain yield in both sorghum varieties was considerably low when cattle manure was not applied.

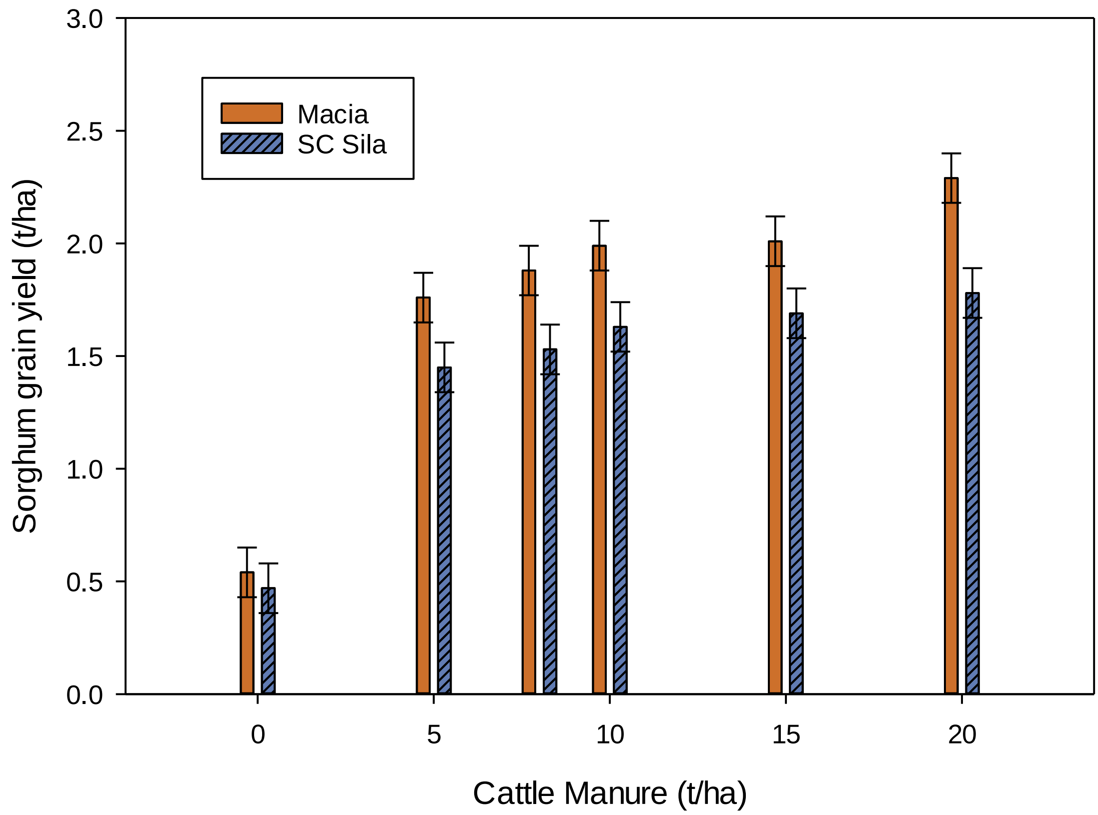

Figure 4. 4: Effect of sorghum variety and cattle manure application on yield

4.3.3.3 Effects of cattle manure x season on sorghum yield

Significant interaction effects ($p<0.05$) of cattle manure and season were observed. Significant grain yield differences between the seasons were apparent at cattle manure application of 5 and 15 t/ha, and on the other hand, the seasons exerted a similar influence on grain yield at all other cattle manure application rates (Figure 4.5). The yield was significantly low in both seasons when cattle manure was not applied. There was a substantial increase in grain yield with an increase in cattle manure application rate up to 20 t/ha in both seasons and yields of 1.97 and 2.10 t/ha were attained in the 2016/17 and 2018/19 seasons respectively.

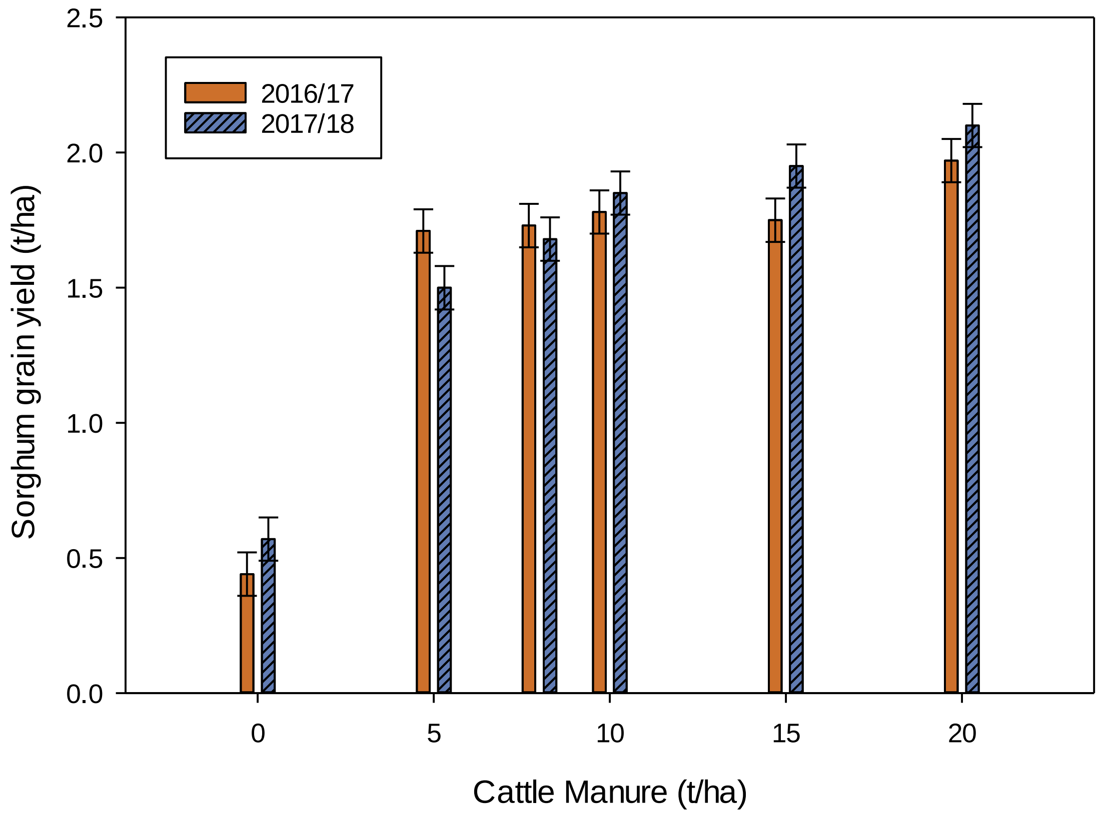

Figure 4. 5: Interaction effects of cattle manure and season on sorghum grain yield

4.3.3.4 Effects of sorghum variety x season on yield

The grain yield of sorghum was significantly influenced by the interactive effects of variety and season. In all the seasons, grain yield was considerably greater in sorghum variety Macia than Sc Sila. Yields of 1.77 and 1.72 t/ha were attained by Macia in the 2016/17 and 2017/18 seasons respectively while variety Sc Sila attained 1.35 and 1.5 t/ha for the same seasons (Figure 4.6). However, the grain yield performance of both varieties across seasons was not substantially different.

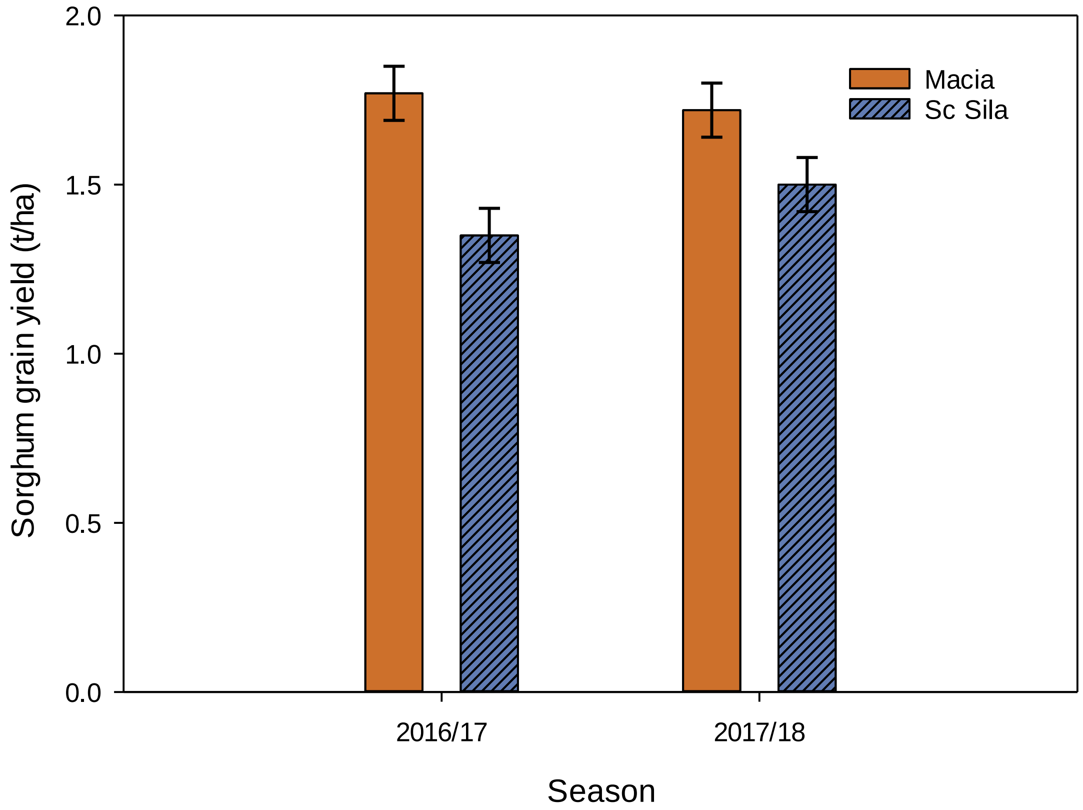

Figure 4. 6: Effects of sorghum variety and season on yield

4.3.3.5 Effects of RWH system × sorghum variety × distance from rainwater harvesting system on yield

The TC and IP had substantially higher grain yield ($p<0.05$) than the SC across all distances from the RWH practices and sorghum variety (Figure 4.7). Generally, yields were higher in sorghum variety Macia compared to Sc Sila at each distance from RWH practice under each RWH system.

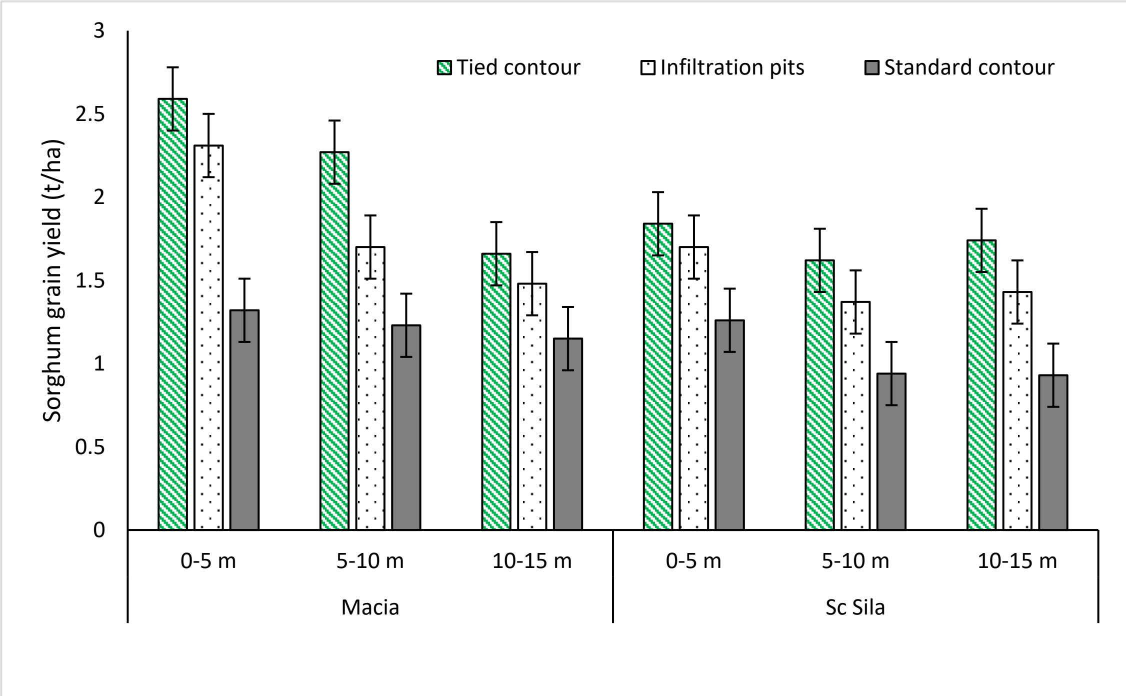

Figure 4. 7: Effect of rainwater harvesting, sorghum variety, and distance from rainwater harvesting practice on yield

4.3.3.6 Effects of RWH system × distance from RWH system × season on grain yield

In the 2016/17 cropping season, TC and IP had significantly higher ($p<0.05$) yields across all distances from rainwater harvesting practices. The SC had considerably lower grain yield than tied contour and infiltration pits at all distances from RWH practice in 2016/17 season, while in 2017/18 season grain yield was not differently different at 10-15 m distance from RWH practice (Figure 4.8).

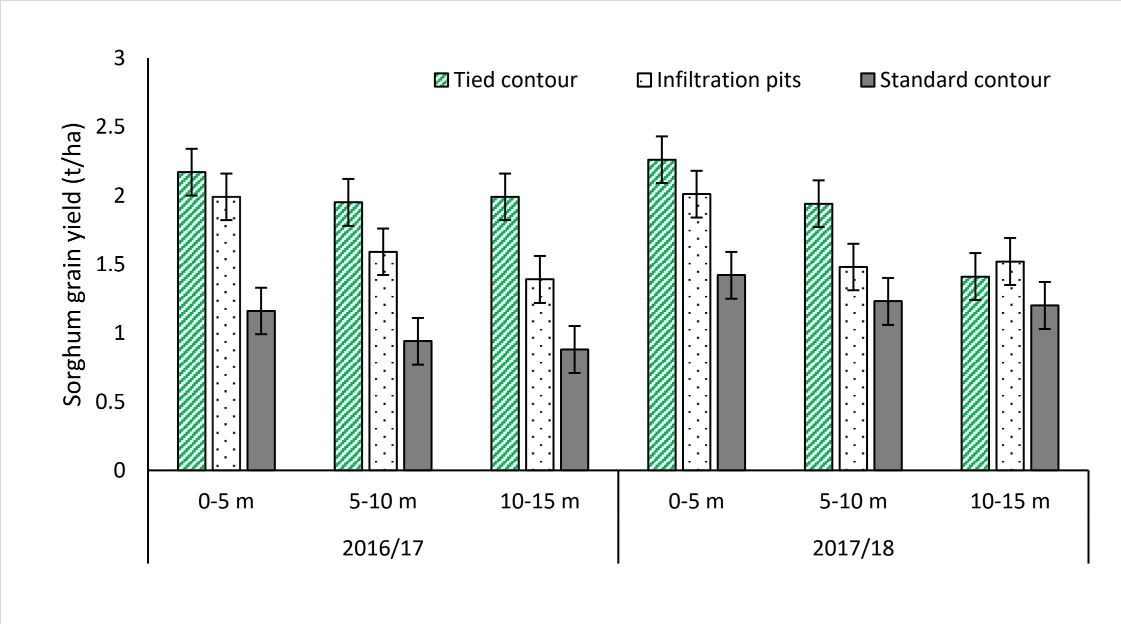

Figure 4. 8: Effect of rainwater harvesting and distance from rainwater harvesting across seasons on yield of sorghum

4.4 DISCUSSION

4.4.1 Soil moisture content

The improvement in soil moisture (Table 4.3) and soil moisture retention capacity (Table 4.4) under TC and IP compared to SC was probably due to the high rainwater collection and storage of the RWH practices, while the low moisture content (Table 4.3) and retention capacity (Table 4.4) shown by standard contour due to lack of water collection and storage capacity. The comparable water content shown by TC and IP may explain their similar operational principle in water retention. Manyanga et al. (2022) found similar results where RWH techniques improved soil moisture availability. Although many studies have found that tied contours and infiltration pits can improve soil water content, Nyakudya et al. (2014) found that these techniques did not have a significant impact on soil moisture levels. The study examined the impact of water harvesting techniques on soil moisture in the semi-arid areas of Zimbabwe and showed that while these techniques could have a small effect on soil moisture in some cases, they did not lead to a significant improvement overall. One of the possible reasons for the different findings in the two studies is the location of the research sites. The first study was conducted in the semi-arid region of Zimbabwe, while the second study was conducted in a more arid area. It is possible that the semi-arid region receives more rainfall, which would allow the tied contours and infiltration pits to have a greater effect on soil water content. The findings of these studies show that the effectiveness of these techniques may depend on the local climate and environmental conditions. A considerable, steady drop in the actual measured soil moisture (Table 4.3) and predicted water retention capacity (Table 4.4) as the distance from a rainwater gathering capacity increases shows that the distance from the moisture discharge point had an impact on the movement of moisture. This phenomenon is explained by the Richards (1931)'s equation, the further the distance from moisture source, the lower the capillary pressure and the lower the rate of change of moisture content. Significantly greater soil water content and soil retention capacity in terms higher predicted gwc at field capacity, wilting point, and saturation point exhibited in the 2016/17 season compared with the 2017/18 season (Table 4.3) may be attributed to higher rainfall total received in the 2016/17 season compared with the 2017/18 season. Higher rainfall total received during the season results in greater soil moisture profile recharge. The findings concur with Mupangwa et al. (2011) and Kubiku et al. (2022a) who found that seasons with more rainfall total had more soil water content.

4.4.2 Grain yield

The combined effect of RWH and cattle manure (organic fertiliser) increased sorghum grain yield at all cattle manure application rates under contour-based TC and IP compared with the SC (Figure 4.3). The C-RWH techniques (TC and IP) improve the provision of water in the soil profile through runoff collection, recharging groundwater as evidenced by greater soil profile moisture content (Table 4.3). This prolongs the provision of water in the root zone decreasing the consequences of dry periods caused by the seasonal variation of rainfall. The moist soil environment due to rainwater harvesting could have resulted in more nutrient release from mineralization of cattle manure, hence more yield at each cattle manure application rate compared with the conventional farming practice (Figure 4.3). Results corroborate findings by Kugedera et al. (2020), and Naba et al. (2020) who found increased grain yields under RWH practices in combination with cattle manure. The SC showed the least sorghum grain yield at all cattle manure application rates (Figure 4.3) due to less moisture retention (Table 4.3) as most of it was lost through runoff (Nyamadzawo et al., 2013). The low moisture status in the standard contour could have reduced the mineralization of cattle manure to provide a ready form of nitrogen (Wortmann et al., 2020) resulting in a low response in grain yield at each cattle manure application rate (Figure 4.3). The difference in sorghum grain yield between cattle manure applied treatments (5, 8, 10, 15, 20 t/ha) and the treatment with 0 kg/ha cattle manure, and successive increases in grain yields with an increase in cattle manure application in all RWH systems explain the importance of organic manure in contributing toward grain production.

The application of cattle manure as an organic fertilizer up to 20 t/ha increased sorghum grain yields in both sorghum varieties (Macia and Sc Sila) (Figure 4.4) and in both seasons (2016/17 and 2017/18) (Figure 4.5). This substantial increase in grain yield with an increase in cattle manure application was attributed to the role organic materials play in improving chemical and physical properties ideal for crop growth and grain yield (Kugedera et al., 2018; Kugedera et al., 2020; Mahmood et al., 2017). Other studies have shown that cattle manure application improved soil moisture status by enhancing soil physical properties and hence yield (Mahmood et al., 2017; Papini et al., 2011; Wang et al., 2020). A positively strong correlation of grain yield with organic matter in each sorghum variety indicates that cattle manure addition affects yield directly. Similar studies were reported by Kubiku et al. (2022a) and Mahmood et al.

(2017) who found that the incorporation of organic manures improves soil physicochemical properties that may have a direct effect on plant growth and grain yield. Higher grain yield response of Macia than Sc Sila at all cattle manure applications indicates the variety's ability to utilize organic nutrient sources more than Sc Sila.

The higher sorghum grain yields shown by sorghum variety Macia compared to Sc Sila regardless of seasons (Figure 4.6) explains the significant role adapted sorghum varieties play in mitigating climate change and variability. The yield differences were explained by varietal differences in that Macia is an open pollinating variety of sorghum and exhibits quiescent growth habit (Hadebe et al., 2017a) while Sc Sila is a hybrid variety that proved to be less adapted. In addition, the sorghum variety Macia also exhibits a shorter growth maturity index (104 days) compared to Sc Sila (120 days) making it more adapted to semi-arid regions with high rainfall variability. Results concur with Hadebe et al. (2017a) and Shamme & Raghavaiah (2016) who found higher grain yield in landraces than hybrids under semiarid environments.

Sorghum grain yield was also influenced by the RWH method at each distance from the RWH system in both sorghum varieties (Figure 4.7) and seasons (Figure 4.8). Higher grain yield under TC and IP than SC in both varieties, and seasons at each distance suggests that the RWH techniques have a high capacity to collect runoff water influencing moisture at a greater distance though in a decreasing manner. Similar results were demonstrated by (Kubiku et al. (2022a) who reported higher grain yield under TC and IP due greater moisture content at all distances from RWH methods. All distances in SC had considerably low yields which were attributed to the low capacity to collect water and influence moisture at greater distances. Kubiku et al. (2022b) and Nyamadzawo et al. (2013) attributed this to more runoff experienced by standard contour resulting in poor water retention and groundwater recharge hence low plant growth and yield.

4.5 CONCLUSION

The study has shown synergies between RWH practices and cattle manure application resulting in improved sorghum grain yields. Tied contour and IP showed high potential in improving sorghum yields which were attributed to improved soil moisture content thereby evading mid-season dry spells. The synergy increased nutrient release from organic complexes and availability for plant uptake for growth hence yield. Application of cattle manure results in a substantial increase in sorghum grain yields up to 20 t/ha of cattle manure signifying the importance of organic fertilizers in crop production. Sorghum variety Macia, is ideal for improving yields compared with Sc Sila across all cattle manure application rates and seasons. At each distance TC and IP had a higher yield advantage compared with farming system under SC. We concluded that TC and IP rainwater harvesting systems and cattle manure application can improve sorghum yields. Thus, the rainwater harvesting systems can serve as alternative sustainable climate change resilient crop intensification practices in a semi-arid smallholder farming system.

CHAPTER 5: EFFECT OF CONTOUR RAINWATER HARVESTING AND INTEGRATED NUTRIENT MANAGEMENT ON SORGHUM GRAIN YIELD IN SEMI-ARID FARMING ENVIRONMENT OF ZIMBABWE

ABSTRACT

The application of insufficient amounts of mineral fertilizer coupled with unreliable precipitation has caused a drastic reduction in the yield of sorghum in the smallholder farming areas of Zimbabwe. This calls for innovative interventions to improve production under changing climatic conditions. This study evaluated the effect of two contour-based RWH practices and the use of cattle manure + N nutrient amendment on soil moisture and sorghum grain yield. A 3×2×6×3 factorial experiment was laid down in a split-split plot design where RWH practice was the main plot factor, sorghum variety subplot factor, cattle manure + N sub-sub plot factor and distance from rainwater harvesting practice sub-sub-sub plot factor. Analysis of variance (ANOVA) was used to determine treatment differences on sorghum grain yield and soil moisture data. The results showed that the yield of sorghum was significantly higher under tied contour and infiltration pits compared to modified standard contour at all distances from RWH practices and across seasons. In all the seasons sorghum varieties Macia and Sc Sila showed higher yield under tied contour and infiltration pits compared to modified standard contour. However, regardless of the distance from RWH practice and season sorghum variety, Macia showed a higher grain yield than Sc Sila. At each incremental level of nitrogen application to cattle manure, Macia had a higher grain yield than Sc Sila, and no significant yield benefits were shown in each variety at nitrogen applied to cattle manure above 50 kg N/ha. It was concluded that contour-based RWH practices and cattle manure + nitrogen improve sorghum grain yield and nitrogen application of 50 kg N/ha can be recommended.

Keywords: rainwater harvesting; semi-arid; cattle manure; sorghum; rain-fed; climate change

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5.1 INTRODUCTION

Smallholder agriculture is facing significant challenges in increasing food production without significantly increasing the area under cultivation (Stevenson et al., 2013). Even the production and grain yields of crops that are traditionally recommended for semi-arid regions such as sorghum has been on the decline. This decline in yields has been attributed to the reduction in soil fertility and droughts as a result of climate change (Nyamangara et al., 2014). In addition, poor agronomic practices, particularly the inadequate application of both mineral and organic fertilizers, have also resulted in a drastic reduction in yields (Chianu et al., 2012). The use of livestock manure remains an integral component of soil fertility management in southern Africa, with the potential to increase crop productivity in the smallholder farming sector. It is widely accepted that the addition of livestock manure is essential to maintain soil fertility (Mapfumo et al., 2007). Occasionally the positive effects of using livestock manure are limited due to the poor quality of organic materials used by smallholder farmers and also limited moisture conditions as a result of unreliable rainfall.

Organic inputs are a major source of energy and nutrients for soil microbial communities which promote soil aggregation and nutrient buffering capacity (Lal et al., 2007). However, the use of organic materials to increase nutrient reserve requires large amounts of annual additions. Rufino et al. (2011) suggested that between 7 and10 t/ha/year are required to maintain soil organic carbon and sufficient nutrient level for crop production. In addition, it is difficult to build or maintain adequate soil organic matter levels for nutrient provision under smallholder farming conditions due to competing uses like livestock and firewood (Mhlanga & Muoni, 2014). More so crop responses to manure application observed in the farmers' fields are highly variable because of the differences in the chemical composition of manure, rates, and frequency of manure application (Chivenge et al., 2011). The nutrient contents of manure differ because of variations in animal diet and ways in which manure is collected and stored. Many crop residues and animal manure are of low quality as they fall below critical nitrogen contents of 1.8-2.0%, hence they immobilize nitrogen temporarily potentially exacerbating the nitrogen deficiency (Nyamangara et al., 2005).

The addition of low-quality organic inputs may over time, increase soil organic carbon, but without necessarily increasing the productivity of the cropping systems (Rufino et al., 2011). Low-quality organic materials do not provide soluble carbon and nitrogen to enhance soil microbial activity and may immobilize nitrogen, markedly reducing crop production compared to levels before the addition of the organic materials (Nyamangara et al., 2005). To address and offset these potentially negative effects, an option can be to combine organic manures with mineral nitrogen fertilizer, a practice called integrated nutrient management (INM).

Integrated nutrient management can improve soil fertility status, water infiltration, and nutrient availability (Lal, 2004; Mahajan et al., 2008). Research findings have shown that neither mineral fertilizers nor organic sources alone can result in sustainable productivity (Godara et al., 2012). A combination of both inorganic and organic fertilizers is the best remedy for soil fertility (Chivenge et al., 2011; Woldesenbet & Tana, 2014). The inorganic fertilizer provides readily available nutrients and the organic fertilizer mainly increases soil organic matter and improves soil structure and soil pH buffering capacity of the soil (Godara et al., 2012). This will narrow the carbon to nitrogen ratio and increase soil microbial activity thereby increasing nutrient availability and soil buffering capacity. The application of livestock manure, in combination with small amounts of mineral nitrogen fertilizer inputs, can be used to enhance nitrogen availability and nutrient cycling efficiency (Chivenge et al., 2011). Apart from improving the physical and chemical properties of soils integrated nutrient management does not have only additive effects but real interaction, which significantly affects crop yield and water-use efficiency (Ouedraogo & Mando, 2010).

Several researchers e.g., (Angachew, 2009; Chivenge et al., 2011; Farah et al., 2014; Kugedera et al., 2018; Kugedera et al., 2020; Mahajan et al., 2008; Mahinda et al., 2018; Masvaya et al., 2017) demonstrated the beneficial effect of INM in mitigating the deficiency of nutrients, however its productivity in semi-arid regions is lowered by low soil moisture status due to unreliable rainfall (Mahinda et al., 2018; Masvaya et al., 2017). Hence there is a need to identify soil water management practices and inorganic nitrogen fertilizer application rates that are agro-ecologically specific. Contour-based rainwater harvesting (RWH) practices can offer an opportunity to enhance the productivity of integrated nutrient management, but their contribution has not been fully exploited (Nyamadzawo et al., 2013). Information regarding the effects of contour RWH and cattle manure + nitrogen fertility management on sorghum productivity in smallholder farming systems is still limited. Thus, the objective of this study was to determine the effect of two contour-based RWH techniques (tied contour and infiltration pits) and the use of cattle manure + nitrogen on sorghum production in smallholder semi-arid farming areas.

5.2 MATERIALS AND METHODS

5.2.1 Study Site

The experiment was conducted in Mt Zonwe smallholder farming area of Mutare district in Zimbabwe (19^{o} 11\` 30\`\` S 32$^{o}$ 03\` 28\`\` E 835 m above sea level) during the 2016/17 - 2018/19 cropping seasons (Figure 3.1 chapter 3). The area is located in agro-ecological region IV characterized by low and erratic rainfall. The rainfall pattern is unimodal with October – March rain season receiving long term annual average rainfall of <650 mm. The mean annual temperature of the area is 27 ^{0}C. The soils are chiefly sand on a general slope of 3 % and soils are inherently deficient in nitrogen and phosphorus. The catchment characteristics were similar to chapter 3 and 4 with gravel at depth of 0.9 and predominant rock outcrops stretching toward cultivated area. The predominant cropping pattern is mainly monoculture of sorghum, millets

(*Pennisetum glaucum (L.) R. Br.)* and *(Eleusine coracana (L.) Gaertn*) and cotton (*Gossypium hirsutum L.*).

5.2.2 Soil sampling and analysis

A total of 15 soil samples were collected before planting in the experimental field measuring 90 x 45 m from a depth of 0-30 cm in a zig-zig manner using a soil auger. A composite sample was prepared for analysis to determine selected physicochemical properties of the experimental site. The composited soil sample was air-dried, ground, and sieved to pass through a 2 mm sieve. Total nitrogen was determined following the Kjeldahl procedure, soil pH by 0.01 M $CaCl_2$ method, organic carbon by wet digestion method, available phosphorous by Olsen method, and soil texture by Bouyoucos Hydrometer method. Summary data for soil Physico-chemical characteristics of the study site are presented in Table 5.1.

Table 5. 1: Physico-chemical characteristics of soil from experimental sites

Textural Composition %			
Sand	80		
Silt	10		
Clay	10		
Textural Class	Sandy loam		
	2016/17	**2017/18**	**2018/19**
pH (0.01 M $CaCl_2$)	5.2	5.3	5.3
Organic carbon %	1.36	1.93	1.97
Total nitrogen %	0.13	0.17	0.19
Available phosphorus $mgkg^{-1}$	3.91	5.32	5.40

5.2.3 Experimental design

A split-split plot experimental design replicated three times over three years was used. The experimental units consisted of three successive contour channels spaced at 15 m intervals each measuring 90 m long. The contour length was divided into three 30 m lengths of RWH practices namely tied contour (TC), infiltration pits (IP), and modified standard contour (SC) (Figure 5.1). The RWH practices were the main plot factor. The TC was made of cross ties made at intervals of 5 m along the contour creating miniature dams measuring 5 m long × 0.5 m wide × 0.5 m deep. The IP were dug along the contour channel measuring 2 m long × 0.5 m wide × 0.5 m deep spaced at intervals of 0.5 m along the contour. A 30 m length SC was left as a control. A distance of 2 m wide was left between each RWH method along the contour marking the end of a RWH method. Subplot factors consisted of two sorghum varieties Sc Sila and Macia grown under each RWH method. Each sub-plot factor measured 15 m long and 4.5 m wide where cattle manure + nitrogen rates were used as sub-sub plot factors. The sub-sub plot factor of cattle manure + nitrogen measured 2 m long × 4.5 m wide and replicated three times down the slope within each RWH method. The replications were categorized into three distances from RWH method namely 0-5 m, 5-10 m, and 10-15 m measured from the centre of the RWH method. Sub-sub plot treatment factor of cattle manure (t/ha) + N (kg N/ha) was as follows 5+0N; 5+50N; 5 + 70N; 5+100N; 5+130N and 5+170N kg N/ha (Figure 5.1).

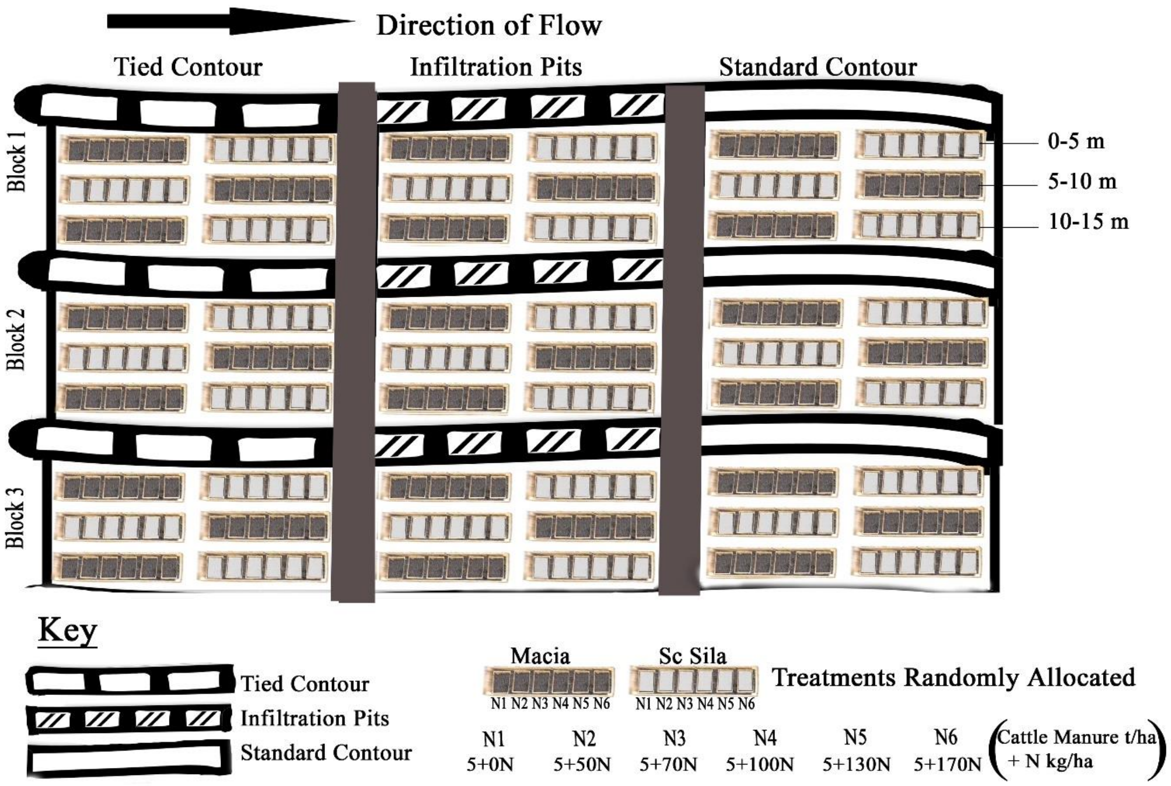

Figure 5. 1: Field experimental layout.

5.2.4 Experimental Procedure

The experimental field was ploughed using an ox-drawn plough to a depth of 20 cm in all seasons and planted on the 10th of December after receiving effective rainfall of the season. Furrows were opened by an ox-drawn plough spaced at 0.75 m in each treatment and cattle manure was spread along the furrow as basal organic fertilizer at 5 t/ha. Cattle manure was analysed before spreading to determine nutrient content (Table 5.2). Sorghum varieties Macia (open-pollinated) and Sc Sila (hybrid) were planted into the furrows at a seed rate of 12 kg/ha and two weeks after crop emergence thinning was done leaving individual sorghum plants spaced at 10 cm along the furrow, giving a target plant population of 133 333 plants/ha. The nitrogen levels of 0; 50; 70; 100; 130 and 170 kg N/ha were randomly applied as sub-sub plot factors in each sorghum variety using ammonium nitrate (34.5 %) top dressing fertilizer 5 weeks after planting. A 0 kg N/ha treatment was left as a control in each subplot factor. Weed control was done using hand hoes in all the plots as weeds emerged. Incidence of fall armyworm (*Spodoptera frugiperda*) was recorded and controlled using Ecoterex (*Deltamethrin* and *Pirimiphos methyl*) pesticide and bird scaring was done at the heading stage to harvest maturity. Rainfall was recorded by the farmer using a rain gauge installed at the experimental site.

Table 5. 2: Nutrient composition of cattle manure applied

Parameter	Cattle Manure		
	2016/17	**2017/18**	**2018/19**
Organic C %	11	10	9.87
Total N %	0.71	0.83	0.91
Available P (%)	0.1	0.2	0.2
Available K (%)	0.4	0.48	0.5
Moisture Content (%)	19	17	18

5.2.5 Data Collection

Monthly soil moisture measurements were done using the gravimetric method in the field under each RWH method. Soil moisture was assessed to a depth of 30 cm at varying plot distances of 0-5 m, 5-10 m, and 10-15 m from RWH methods. A total of 5 soil samples were taken diagonally in each plot distance from RWH method. Pedofunctions were used to predict gravimetric water content at field capacity, saturation point and wilting point using the Rawls et al. (1982) equation. Sorghum heads were cut from the two middle rows of each plot at harvest maturity and sun-dried for threshing. Grain yield (kg/ha) was recorded after harvesting from the net plot of 1 m × 1 m = 1 m^2. Grain yield was adjusted to 13.5% moisture content after measuring moisture using a digital moisture meter (Dickey-john model) and converted to t/ha for statistical analysis.

Adjusted yield = Actual yield × (100-M)/(100-D);

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

5.2.6 Data Analysis

Soil moisture content and sorghum grain yield data were subjected first to normality and homoscedasticity tests using Kolmogorov-Smirnov and Bartlett tests respectively in SPSS version 26. The data was subjected to statistical analysis of variance for split-split plot design using the GenStat statistical package. The least significant difference test at 0.05 was performed to separate significant treatment means.

5.3 RESULTS

5.3.1 Rainfall

The total rainfall received during the growing seasons ranged from 780 to 964 mm which was above the long-term average of 650 mm for the agro-ecological region (IV). The highest rainfall was recorded in 2016/17 while the 2018/19 season had the least rainfall total (Figure 5.2). Despite high rainfall totals during the seasons, intermittent dry spell periods were experienced during the season evidenced by dry pentads discussed in table 3.2 of chapter 3.

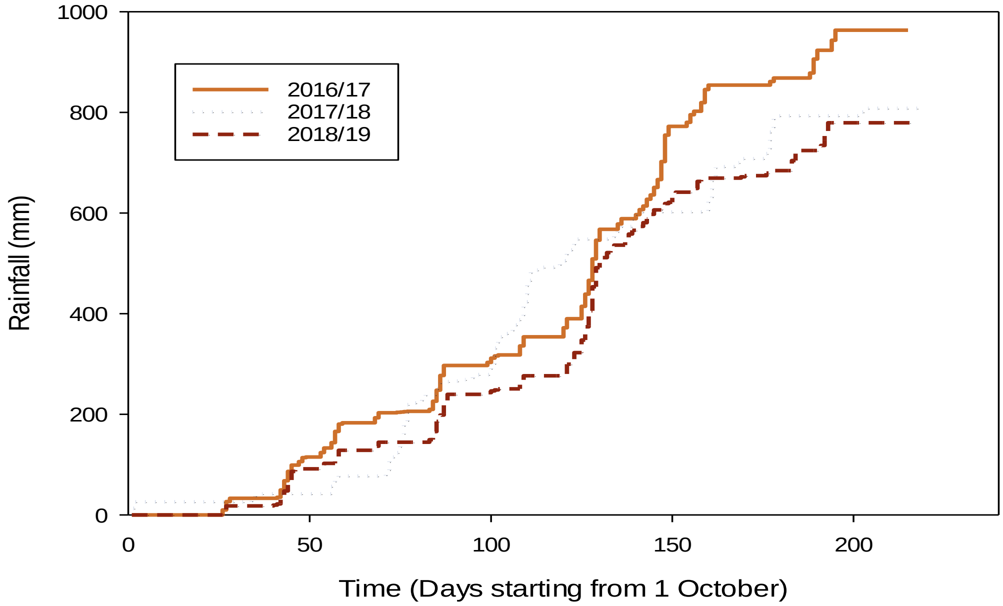

Figure 5. 2: Cumulative rainfall distribution during period of experimentation

5.3.1 Soil moisture content

Significant ($p<0.05$) soil moisture reduction was observed as the distance from RWH practices increased. Soil moisture conditions under the RWH methods at distances of 0-5 m and 5-10 m significantly ($p<0.05$) decreased in the order TC > IP > SC, while there was no soil moisture difference between the RWH methods at 10-15 m distance from the RWH method (Figure 5.3). Soil moisture decreased in the order 0-5 m > 5-10 m > 10-15 m under TC and IP while there were no soil moisture differences between the distances from RWH practices under the SC.

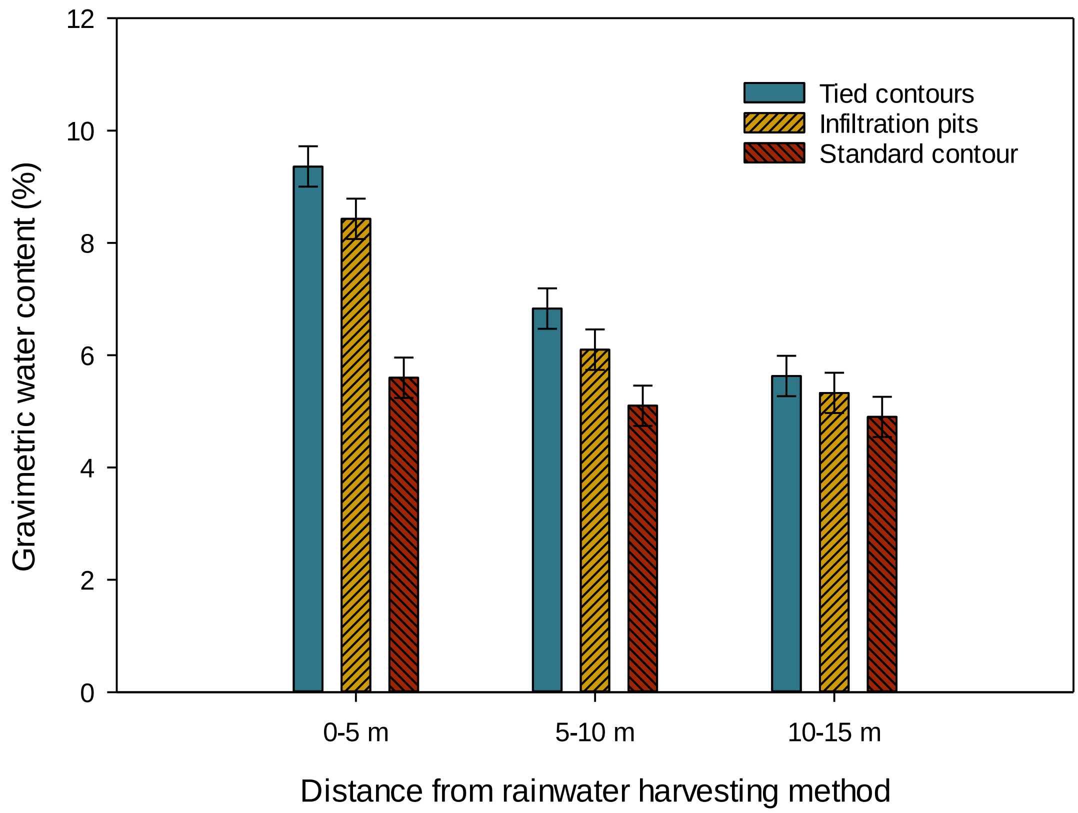

Figure 5. 3: Effect of rainwater harvesting × distance from rainwater harvesting method on soil moisture content

The gravimetric water content at field capacity, saturation point and wilting point significantly varied with the type of RWH practice, distance from RWH, and season (Table 5.3). The gravimetric water content at field capacity varied in the order IP>TC>SC while gravimetric water content at saturation point and wilting point was in the order TC>IP>SC. There was also significant difference in gravimetric water content at field capacity, saturation point and wilting point at each distance from RWH practices. The variation was in the order TC>IP>SC. The further the distance from RWH the less effective the RWH practices in water retention capacity (Table 5.3). The 2016/17 season had the most effective water retention capacity while the 2018/19 season had the least water retention capacity (Table 5.3).

Table 5. 3: Gravimetric water content at field capacity, saturation point and wilting point

Treatment	Gravimetric water content at field capacity (%)	Gravimetric water content at saturation point (%)	Gravimetric water content at wilting point (%)
RWH practice			
Tied Contour	1.51[a]	1.47[a]	-1.9[a]
Infiltration pits	1.83[b]	1.55[b]	-1.97[b]
Standard contour	2.11[c]	2.37[c]	-2.28[c]
Distance from RWH			
0-5 m	1.59[a]	1.55[a]	-1.97[a]
5-10 m	1.83[b]	1.79[b]	-2.06[b]
10-15 m	2.11[c]	2.06[c]	-2.16[c]
Year			
2016/17	1.54[a]	1.56[a]	-1.95[a]
2017/18	1.84[b]	1.80[b]	-2.06[b]
2018/19	2.15[c]	2.10[c]	-2.16[c]
P value	<0.001	<0.001	<0.001
LSD	0.13	0.06	0.02

Means in the same column followed with the same letter are not significantly different at p<0.05. LSD - Least significant difference at 5 %.

5.3.2 Gain yield

The results showed a significant effect ($p<0.05$) of all the main treatments on sorghum yield (Table 5.4). Significant interaction effects ($p<0.05$) on sorghum yield were observed among the treatments and were used to explain the grain yield differences.

Table 5. 4: Effects of RWH practice, sorghum variety, cattle manure + nitrogen, distance from RWH practice and season on sorghum grain yield.

Treatment	Grain yield (t/ha)
Rainwater harvesting	
Tied contour	1.54
Infiltration pits	1.29
Standard contour	0.76
P-value	p<0.001
SED	0.06
Sorghum variety	
Macia	1.68
Sc Sila	0.71
P-value	p<0.001
SED	0.08
Cattle manure+Nitrogen	
5+0N	0.40
5+50N	1.18
5+70N	1.34
5+100N	1.41
5+130N	1.45
5+170N	1.39
P-value	p<0.001
SED	0.1
Distance from RWH	
0-5 m	1.33
5-10 m	1.26
10-15 m	1.00
P-value	p<0.001
SED	0.07
Season	
2016/17	1.38
2017/18	1.20
2018/19	1.00
P-value	p<0.001
SED	0.07

SED – Standard error of differences

5.3.2.1 Effect of rainwater harvesting × distance from rainwater harvesting method × season on sorghum grain yield

Significant interaction effect ($p<0.05$) of RWH method × distance from RWH method × season was shown on sorghum grain yield. The TC and IP had no yield difference with a significantly higher yield than standard contour at 0-5 m distance from RWH method in the 2016/17 season (Figure 5.4). As the distance from RWH method increased to 5-10 m in the same season, a different trend was shown with TC exhibiting higher yield while IP and SC had no yield differences. In 2016/17 season, TC and IP had significantly higher sorghum grain yield at 0-5 m distance from RWH method, while at 5-10 m distance TC had significantly higher sorghum grain yield than IP and SC. In the same year (2016/17) IP had significantly higher sorghum grain yield than the SC at 10-15 m distance from RWH method. In the 2017/18 season TC and IP had no yield difference with a significantly higher yield than the SC at each distance from the RWH practice (Figure 5.4). In the 2018/19 season, at 0-5 m distance from RWH practice sorghum yield significantly decreased under the RWH practices in the order TC > IP > SC. When the distance from RWH practice was > 5 m TC showed higher yield while IP and SC had no yield differences (Figure 5.4).

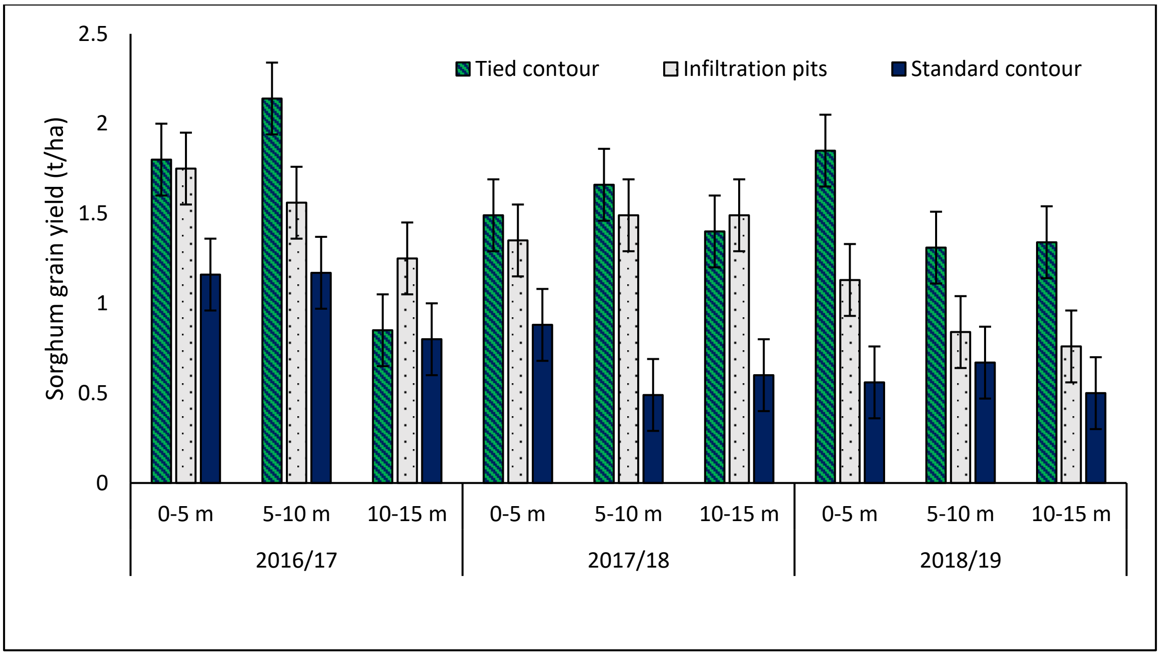

Figure 5. 4: Effect of rainwater harvesting on sorghum yield at different distances from rainwater harvesting practice and season

5.3.2.2 Effect of rainwater harvesting × sorghum variety × season on sorghum grain yield

The influence of RWH practice on yield varied with sorghum variety and season. The TC and IP had no yield difference in 2016/17 and 2017/18 under sorghum variety Macia while in 2018/19 yield response to RWH decreased in the order TC > IP > SC (Figure 5.5). Under sorghum variety Sc Sila, TC had significantly higher yield than IP and SC in the 2016/17 season. The TC and IP had no yield difference in the 2017/18 season with significantly higher yields than SC in the same variety. The effect of RWH practice on yield was not significant in the 2018/19 season under sorghum variety Sc Sila. The SC showed significantly ($p<0.05$) low grain yield across all seasons in the same sorghum variety and the yield of Macia was generally higher than Sc Sila in each rainwater harvesting practice across all seasons.

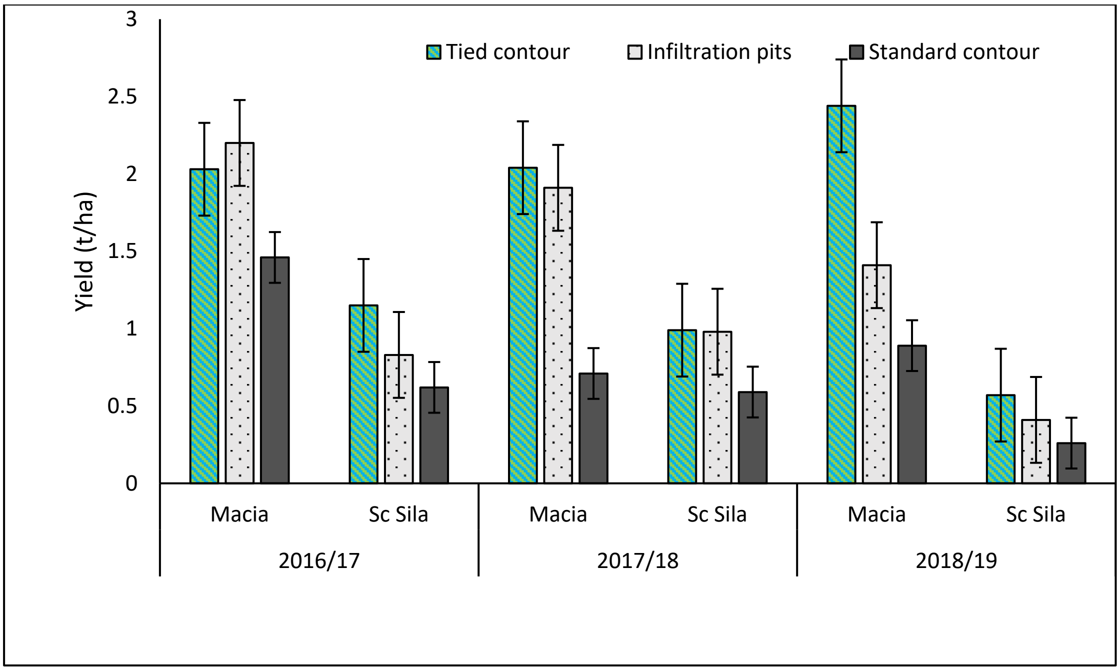

Figure 5. 5: Effect of rainwater harvesting × variety × season on sorghum grain yield

5.3.2.3 Effect of sorghum variety × distance from rainwater harvesting practice × season on sorghum grain yield

Sorghum variety × distance from RWH practice × season had a significant interaction effect on yield ($p<0.05$). Regardless of the season and distance from RWH practice sorghum variety, Macia showed a higher yield than Sc Sila at each distance from RWH practice except in the 2016/17 season where there was no yield difference at 10-15 m distance from RWH practice (Figure 5.6). The yield of Macia at each distance from RWH practice was in the range of 0.96 – 2.4 t/ha while the yield of Sc Sila ranged from 0.36 – 0.99 t/ha across the treatment combinations.

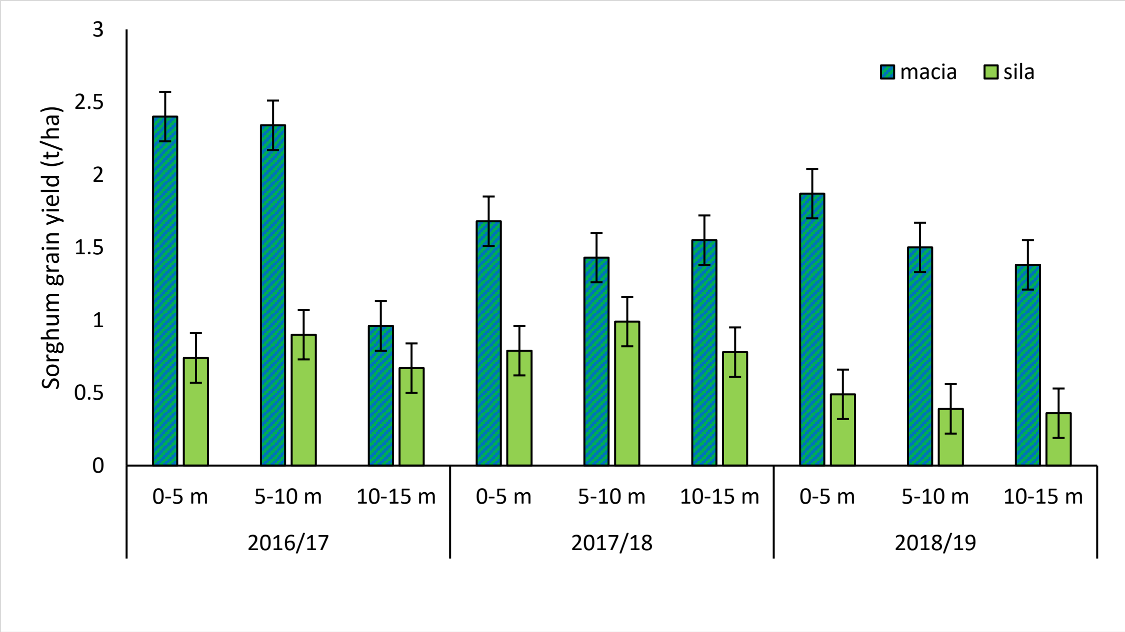

Figure 5. 6: Effect of sorghum variety × distance from rainwater harvesting practice × season on sorghum grain yield

5.3.2.4 Effect of sorghum variety x fertility amendment (cattle manure + nitrogen) on sorghum grain yield

Significant interactive effects of variety and cattle manure + nitrogen on yield ($p<0.05$) were observed. Cattle manure with no nitrogen had a low yield in both sorghum varieties compared with 5 + 50, 5 + 70, 5 + 100, 5 + 130, and 5 + 170 (cattle manure t/ha + nitrogen kg/ha) (Figure 5.7). Sorghum variety Macia had a higher yield than Sc Sila at each incremental level of nitrogen application under the integrated nutrient management system. However, the addition of nitrogen > 50 kg N/ha to 5 t/ha of cattle manure resulted in no yield benefit in both varieties and there was a strong correlation shown in each sorghum variety between fertility management (cattle manure + nitrogen) and yield.

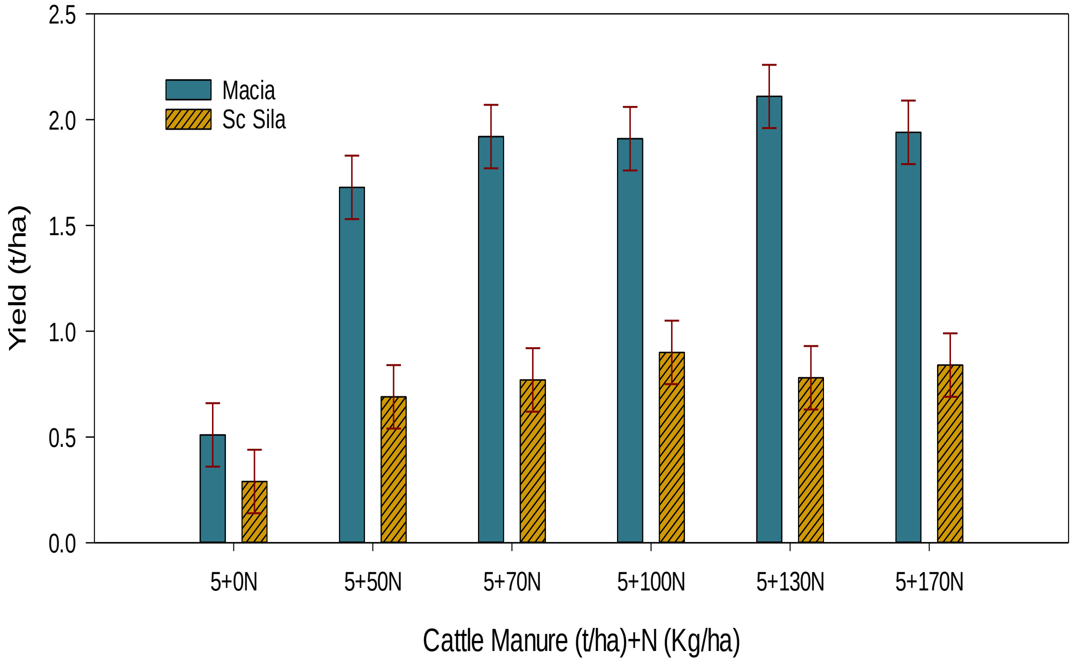

Figure 5. 7: Effect of sorghum variety × cattle manure × nitrogen on sorghum grain yield.

5.4 DISCUSSION

5.4.1 Soil moisture content

Rainwater harvesting using TC and IP improved soil moisture compared to SC (Figure 5.3). Significantly higher moisture benefits shown by TC and IP at distance from RWH practices up to 10 m were attributed to their ability to collect water making it available to crops. The SC had low moisture at all distances due to water lost through runoff. The higher gravimetric water at field capacity, saturation point and wilting point in TC and IP compared to SC implies that they are effective in water retention. The results concur with a study conducted by Nyagumbo et al. (2019) who found that TC and IP can improve soil moisture at all three points: field capacity, saturation point, and wilting point. Overall, the study concluded that the RWH were an effective way to improve soil moisture levels in semi-arid areas. Another study conducted by Mhizha and Ndiritu (2013) in Zimbabwe reported higher moisture content under RWH practices compared to the conventional farming systems. Alseekh and Ghaleb (2009) looked at the impact of tied contour and infiltration pits on soil moisture and runoff and reached a different conclusion. The researchers in this study found that TC and IP did not have a significant impact on soil moisture at saturation point, and that they only had a small impact on soil moisture at field capacity and wilting point. They concluded that these techniques may not be effective in all circumstances, and that further research is needed to determine their effectiveness in different locations. A significant gradual decrease in moisture content was shown by the RWH practices (Figure 5.3). This was probably due to water interception and the resistive nature of soil particles to the lateral flow of water resulting in differential moisture content with an increase in distance from RWH practices (Mhizha & Ndiritu, 2013; Mupangwa et al., 2012a). The predicted gravimetric water content at field capacity also showed the same trend implying that as distance increase from the RWH practice the RWH practices become ineffective in water retention capacity. The higher water retention capacity of year 2016/17 compared to other seasons 2017/18 and 2018/19 may be attributed to differences in season quality in terms of rainfall distribution.

5.4.2 Grain yield

Higher sorghum grain yield attained under TC and IP at all distances and in most seasons compared with SC (Figure 5.4) may be attributed to greater water storage capacity shown by the TC and IP as evidenced by high water content compared to the standard contour (Table 5.4). Water collected by the RWH practices infiltrates the soil increasing subsurface soil water storage thereby allowing crops to evade the dry spell period of the season. Similar findings were reported by Mandumbu et al. (2020), Mhizha & Ndiritu (2013), and Nyagumbo et al. (2019) who reported the efficiency of RWH practices in concentrating water to the root zone through lateral flow, improving water availability and yield. The low sorghum grain yield in the SC at each distance and season (Figure 5.4) was due to low water retention (Figure 5.3).

Similar results were reported by Nyamadzawo et al. (2013) who found 50 % water loss in standard contours.

The improve grain yield of sorghum variety Macia under TC and IP rainwater harvesting method compared with the SC in all season explains the potential of RWH methods to store and distribute rainwater more efficiently, reducing water stress on the crop (Table 5.2). Hadebe et al. (2017a) and Purushothaman et al. (2016) attributed differences in grain yielding ability of sorghum varieties Macia and Sc Sila under the RWH methods across seasons to differential response to moisture as a result of genetic differences among the varieties.

The seasons had rainfall totals above average. Regardless of season and distance from RWH method the sorghum variety, Macia had a significantly higher yield than Sc Sila (Figure 5.6). However, the yield of sorghum variety Macia was higher than Sc Sila in each RWH method (Figure 5.5), which may attributed to the variety Macia having an early flowering index than Sc Sila. Mandumbu et al. (2020) and Mupangwa et al. (2016) reported that sorghum varieties that flower earlier may be more efficient at utilising water resources, leading to higher yield. This confirms the importance of varietal selection to realize the full benefits of RWH in semi-arid farming environments (Singh, 2017). In studies by Hadebe et al. (2017b) farmers indicated that an ideal sorghum variety must be able to mature within sixty to ninety days. The sorghum variety Macia is an open-pollinated variety resilient to semi-arid conditions compared to Sc Sila a hybrid variety that showed no resilience to the prevailing environmental conditions. This concurs with the findings by Li et al. (2010), Srinivasarao et al. (2014), and (Mitran et al., 2016) who concluded that the use of adapted sorghum varieties improves grain yield and facilitates the translocation of nutrients to the economic part of the crop, thus increasing use efficiency of the applied nutrients (Ghosh et al., 2015).

The addition of mineral nitrogen fertilizer to cattle manure increased sorghum yield, however, there was a significant interactive effect of sorghum variety and cattle manure + nitrogen nutrient amendment on grain yield (Figure 5.7). The greater grain yield observed in sorghum variety Macia than Sc Sila at each cattle manure + nitrogen nutrient amendment was probably due to varietal differential response to nutrient uptake and utilization due to genetic differences. Yield differences between 5 t/ha (41 kg/ha total nitrogen) cattle manure with no nitrogen applied and treatments with cattle manure + nitrogen applied indicates the importance of nitrogen addition to cattle manure in both varieties (Figure 5.7). The results concur with findings by Mahinda et al. (2018), where the addition of Nitrogen to farmyard manure resulted in a remarkable increase in sorghum yield in the above-average rainfall season, and Nyamangara et al. (2005) reported higher nitrogen uptake by maize under cattle manure and mineral nitrogen treatment than the no nitrogen treatment. Kumar et al. (2017), Parihar et al. (2010), and Woldesenbet & Tana (2014) also reported similar results where the incorporation of inorganic to organic fertilizers significantly increased grain yield in rice, food barley, and pearl millet by improving the physical and chemical properties of the soil. Studies by Chivenge et al. (2009) showed that the application of mineral nitrogen fertilizer provides start-up nitrogen for use by plants and microbial nitrogen for mineralization of cattle manure. This reduces net immobilization of nitrogen as microbial nitrogen uptake is faster than plant uptake of nitrogen which induces temporary nitrogen deficiency in the plants (Chivenge et al., 2011). The slow nitrogen mineralization rate from the manure (Murwira & Kirchmann, 1993) means that some mineral nitrogen should be applied at planting to prevent N deficiency during early plant growth (Nyamangara et al., 2003).

Increasing nitrogen application rate above 50 kg N/ha to cattle manure showed no significant yield difference between sorghum varieties (Figure 5.7) because other factors may have been limiting resulting in no increase in grain yield with an increase in nitrogen fertilizer application to cattle manure. Soil factors such as soil pH < 5.0 may limit micronutrient availability limiting plant growth and yield (Mapfumo & Giller, 2001). Woldesenbet & Tana (2014) found out that application of 5 t/ha farmyard manure combined with 75% recommended inorganic nitrogen (23 kg N/ha) and phosphorous (46 kg P_2O_5/ha produced better yield and beyond this caused yield decline in food barley (*Hordeum vulgare* L.).

5.5 CONCLUSION

It can be concluded that TC and IP improved soil moisture and sorghum yields in the integrated nutrient management system compared with standard contour. The moisture provided by the RWH practices (TC and IP) at all the distances from RWH practice (0-5, 5-10, and 10-15 m) improved rainwater productivity and hence yield. Higher yield benefits in sorghum variety Macia suggests that it was better variety compared to Sc Sila. The addition of mineral nitrogen fertilizer to cattle manure was more beneficial at the nutrient amendment of 5 t/ha (cattle manure) + 50 kg N/ha. Mineral nitrogen fertilizer above 50 kg N/ha added to 5 t/ha cattle manure had no yield benefits because an increase in nitrogen application did not result in a corresponding increase in sorghum yields. The use of TC, IP and cattle manure + nitrogen nutrient amendment can be recommended as climate change resilient crop intensification practices to improves soil moisture and sorghum grain yield in semi-arid farming systems.

CHAPTER 6: ENHANCING NITROGEN AND RAINWATER USE EFFICIENCY THROUGH RAINWATER HARVESTING IN SEMI-ARID SMALLHOLDER *SORGHUM BICOLOR* (SORGHUM) FARMING SYSTEMS

ABSTRACT

Nitrogen and rainwater productivity in semi-arid smallholder farming systems is low due to low soil fertility and low and unreliable rainfall. The objective of this study was to evaluate the effect of rainwater harvesting and mineral nitrogen fertilizer on nitrogen and rainwater use efficiency under two *Sorghum bicolor* (sorghum) varieties. A split-split plot experiment, replicated three times was conducted in Mt Zonwe smallholder farming area in Zimbabwe from 2016/17 to 2018/19 rain seasons. Agronomic efficiency (AE) and rainwater use efficiency (RWUE) data were subjected to analysis of variance to determine treatment differences. The results showed that tied contour (TC) and infiltration pits (IP) had higher AE than modified standard contour (SC) across all nitrogen application rates, distance from rainwater harvesting practice, and seasons. Sorghum variety Macia had higher nitrogen use efficiency indices than Sc Sila at 50 and 70 kg N/ha while >100 kg N/ha had no difference in nitrogen use in both varieties. A decreasing trend in nitrogen productivity with an increase in nitrogen application rate was shown in both varieties. Mineral nitrogen fertilizer application increased rainwater productivity up to 100 kg N/ha beyond which there was no significant difference. Regardless of sorghum variety and season, tied contour and infiltration pits had higher rainwater use efficiency than standard contour at each distance from rainwater harvesting practice. This study recommends the use of TC and IP and application of mineral nitrogen fertilizer to sustainably improve nitrogen and rainwater productivity in semi-arid smallholder sorghum farming systems.

Keywords: Sorghum; agronomic efficiency; rain-fed; rainwater harvesting; rainwater use efficiency

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6.1 INTRODUCTION

The global crop demand is estimated to increase by 100 to 110% from 2005 to 2050 to meet global food demand (Hunter et al., 2017; Serraj et al., 2019). Sustainably meeting such demand may be an immense challenge, particularly in the face of declining soil fertility and frequent droughts due to climate change. Sorghum has the potential to meet the food demand but is mainly grown in areas with marginal rainfall and poor soil fertility, resulting in very low yields (Hadebe et al., 2021). Yields will not improve until smallholder farmers apply adequate mineral fertilizer and employ water management practices that conserve soil moisture and increase the water available to the plant in semi-arid regions. Sustainable water and nutrient management must be adopted to achieve the required yield benefits. Economical use of nutrients improves food security and minimizes production costs (Clark & Tilman, 2017; Kopittke et al., 2019). Improving rainwater and nutrient use is among important research issues in sub-Sahara Africa (Hatfield & Dold, 2019), the objective being to increase the productivity of rainwater and nutrients while minimizing water and nutrient losses from the field (Vidican et al., 2020). Therefore, higher profitability can be achieved by placing more emphasis on the high efficiency of nutrient and rainwater use. The use rainwater harvesting practices and adapted high-yielding sorghum cultivars is important to realize increased nutrient and water productivity. Nutrient management principles such as 4R Nutrient Stewardship, aim at the application of the right nutrient source, at the right application rate, at the right place, and at the right time (Bruulsema et al., 2019; Fixen et al., 2015) need to be adopted. It is critical to understand nutrient and rainwater use to improve (*Sorghum bicolor L.)* sorghum yield in arid and farming environments. Rainwater and nutrient use efficiency are crucial principles for assessing crop production systems in rainfed agriculture and can be greatly improved by fertilizer management as well as soil-plant-water relationships.

Nutrient use efficiency (NUE) has been defined as the ratio of nitrogen removed in harvested products to the amount of nitrogen applied (Bijay-Singh, 2017). Partial factor productivity and agronomic efficiency are the most commonly used indices of nitrogen use efficiency. They determine a cropping system's efficiency concerning its nutrient supply (Norton, 2017). Lower levels indicate less sensitive soils or excessive nutrient application, while higher levels indicate that nutrient supply is restricting productivity. Agronomic efficiency is a useful performance indicator, especially when selecting more efficient genotypes for nutrient uptake or evaluating nutrient transfers between soil pools (Norton, 2017). In NUE indices, as nutrient application rates approach their optimum, productivity rises, but at a slower pace, and NUE falls (Singh et al., 2018). Source, time, and place factors, soil, and climatic conditions determine the degree of the decline (Fixen et al., 2015). Nutrient use efficiency can be doubled when nitrogen application methods underpinned by the 4R nutrient stewardship principles and water management practices such as rainwater harvesting are adopted (Ahmad et al., 2018).

Masso et al. (2017) reported low agronomic efficiency and partial factor productivity in smallholder farming systems due to inappropriate agronomic practices such as blanket fertilizer guidelines, too low fertilizer application rates coupled with unbalanced fertilization. Fertilizer recommendations such as 200 kg/ha basal fertilizer of compound D and 150 kg/ha of ammonium nitrate top dress in sorghum production are focused on achieving optimum output on resource-rich farms (Ganyo et al., 2019). This is because mineral fertilizer accounts for a significant portion of production costs, and low profitability appears to influence a farmer's decision to use it or not (Mtangadura et al., 2017; Wortmann et al., 2020). General fertilizer guidelines, even though they are appropriate for a small number of situations (biophysical and socioeconomic), would invariably be ineffective for others (Cedrez et al., 2020). Furthermore, the application rates are undifferentiated by region, soil conditions, or classification. As a consequence, many farmers disregard them; if they use them, will result in wasteful or unprofitable mineral fertilizer usage. Therefore, there is a need to constantly carry out research to determine the site and crop-specific optimum fertilizer application rates for better nutrient use efficiency to reduce costs and environmental pollution due to excess application (Ichami et al., 2019; Rurinda et al., 2020). Nitrogen flows through the system have negative consequences when applied at an inappropriate time, rate, form, and place reducing NUE (Ahmad et al., 2018; Bruulsema et al., 2019; Fixen et al., 2015).

Rainwater use efficiency is another important primary factor in improving sorghum yield under water scarcity in rainfed agriculture (Hadebe et al., 2020). Water use efficiency is the yield output per unit of evapotranspiration (Mabhaudhi et al., 2016) influenced by crop morphological and physiological traits, genotype, plant population, and soil conditions such as soil water holding capacity, metrological conditions, and agronomic practices (Hadebe et al., 2017a). An appropriate sorghum variety should maintain high rainwater use efficiency to improve yield under water limiting conditions (Hadebe et al., 2020). Therefore, crop selection and rainwater harvesting are among agronomic activities for increasing rainwater use efficiency. In this view, the inclusion of suitable drought-tolerant sorghum and rainwater harvesting practices can improve rainwater use efficiency in rainfed and semi-arid environments.

In Zimbabwe, smallholder sorghum production takes place in semi-arid rain-fed farming systems where soils are inherently infertile and subject to unreliable rainfall resulting in variable nutrient and rainwater productivity (Tonitto & Ricker-Gilbert, 2016). Since soils are susceptible to various types of erosion hazards (physical, chemical, and biological), effective management strategies are needed to increase or maintain soil nutrient and rainwater productivity (Masso et al., 2017). The soils in smallholder farmer fields are mostly sandy, ranging from sandy loamy to loamy sands, and are deficient in a variety of nutrients, especially nitrogen (Nezomba, 2016). The soils have also been depleted of meagre nutrients by continuous cereal mono-cropping at sub-optimal fertilization rates, resulting in low productivity. There is little likelihood of increasing nutrient and rainwater productivity unless nutrient levels and rainwater management improve (Tamagnone et al., 2020). Fertilizer application and rainwater harvesting (RWH) can have a major impact on increasing smallholder nutrient and rainwater use efficiency (Ngosong et al., 2019).

However, the use of mineral fertilizer is sub-optimal because of high costs, unavailability, high risk due to uncertain rainfall, and incorrect fertilizer recommendations (Tamagnone et al., 2020). Abunyewa et al. (2017) noted that very limited research has been conducted in semiarid rain-fed farming systems to exploit the possible synergistic effects of rainwater harvesting and nutrient application on crop production. Rainwater and nutrient use efficiency have not received much attention under contour-based rainwater harvesting practices in rain-fed agriculture. Nitrogen use efficiency of crops under dry-land conditions depends largely on available water to the plant that depends on rainfall. The objective of this study was to evaluate the effect of tied contour and in-contour infiltration pits RWH and mineral nitrogen fertilizer use on nutrient and rainwater use efficiency under two sorghum varieties in a rainfed smallholder semi-arid farming system.

6.2 MATERIALS AND METHODS

The description of the study site, experimental design, and procedures has been outlined in Chapter 3 and published by Kubiku et al. (2022a).

6.2.1 Data collection

The nitrogen contained in basal fertilizer and top-dressing fertilizer was used to compute the agronomic efficiency. Soil moisture content, amount of rainfall, and sorghum grain yield were collected and reported in Chapter 3 (Kubiku et al., 2022a).

Nitrogen efficiency (NUE) (kg grain/kg N) was computed using the following formula:

- Agronomic efficiency (AE_N)= [Grain yield of mineral nitrogen fertilizer treatments (kg/ha) - Grain yield of 0 kg N/ha treatment] / [Nitrogen fertilizer applied (kg/ha] (Shamme et al., 2016)

Where N is the total mineral nitrogen fertilizer applied + nitrogen supplied by the soil,

Rainwater use efficiency (RUE) was computed using the following formulae:

- RUE = GY/R (Gwenzi et al., 2008)

Where RUE is the rainwater use efficiency (kg/mm/ ha), GY is sorghum grain yield (kg/ha), R is cumulative rainfall from time of planting to physiological maturity.

6.2.2 Data Analysis

Agronomic efficiency and rainwater use efficiency data were subjected to statistical analysis of variance for a split-split plot in a randomized complete block design (Chapter 3). Genstat statistical software was used to compute statistical analysis and the least significant difference test at 0.05 was performed to separate significant treatment means.

6.3 RESULTS

6.2.3 Rainfall

The growing seasons received more rainfall than the long-term average (650 mm) of the farming region. The wettest season was experienced in 2016/17 with 48 % more rainfall being received than the long-term average of 650 mm for the region (Figure 6.1). Mid-season dry spells were experienced in all years despite high rainfall totals being experienced and coinciding with the booting stage of the crop (Figure 6.1). Cumulative rainfall was the least in the 2018/19 season with a severe mid-season dry spell. Seasons characterized by high rainfall intensities generate more runoff from the catchment area for collection by rainwater harvesting structures.

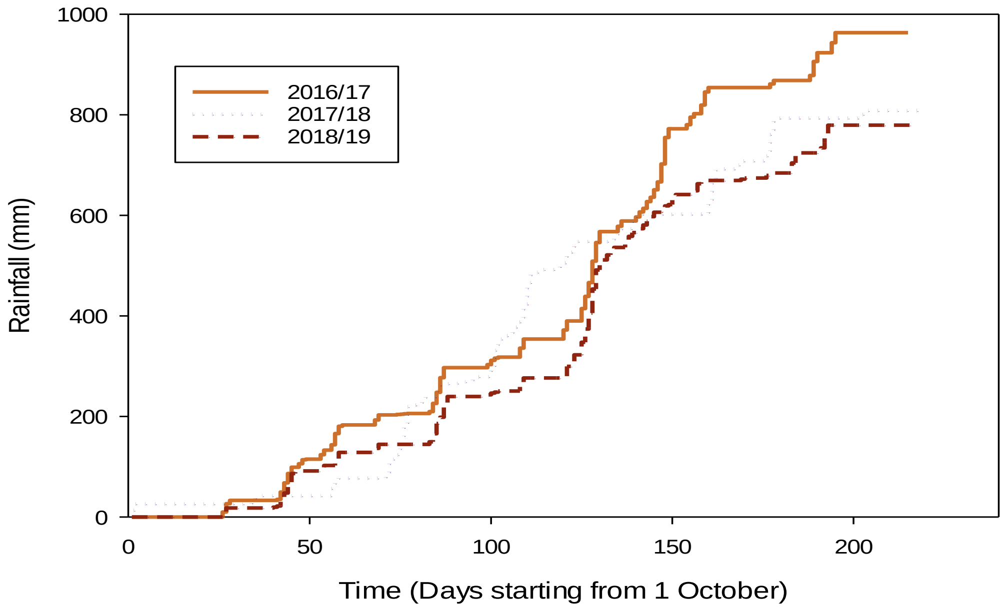

Figure 6. 1: Cumulative rainfall during the experimentation period

6.3.1 Agronomic Efficiency

6.3.1.1 Effect of RWH practice x season on AE_N

The results showed that AE_N was influenced by the interaction effect of RWH practice and season. The RWH practices - TC and IP showed no significant difference in AE_N in all the seasons while the SC had significantly low ($p<0.05$) AE_N across all seasons (Figure 6.2). The mean AE_N of TC and IP were 25.25 and 25.69 kg grain/kg N respectively while the SC had 12.59 kg grain/kg N.

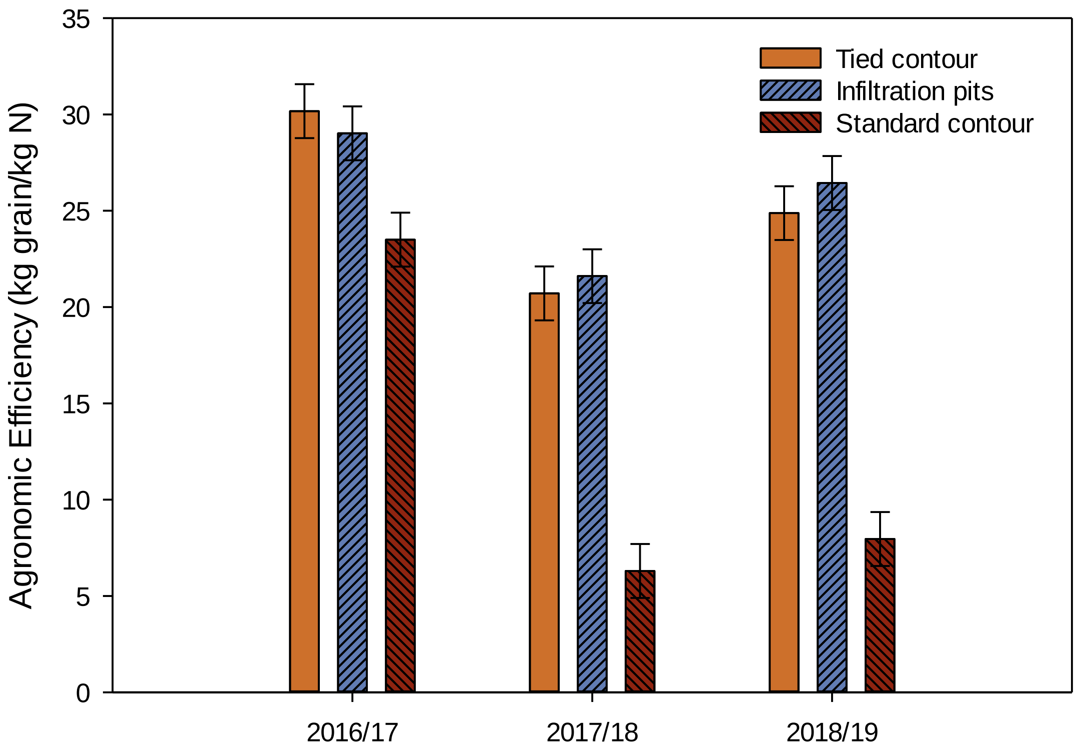

Figure 6. 2: Effect of rainwater harvesting practice x season on agronomic efficiency

6.3.1.2 Effect of RWH practice x nitrogen application on AE_N

The analysis of variance showed significant interaction ($p<0.05$) effect of RWH and nitrogen application on AE_N. The TC and IP had higher AE_N than SC at all nitrogen application rates (Figure 6.3). There was no significant difference in AE_N between TC and IP. A gradual decrease in AE_N was shown in each RWH practice with 50 kg N/ha showing the highest AE_N while nitrogen application rate of 170 kg N/ha had the lowest AE_N.

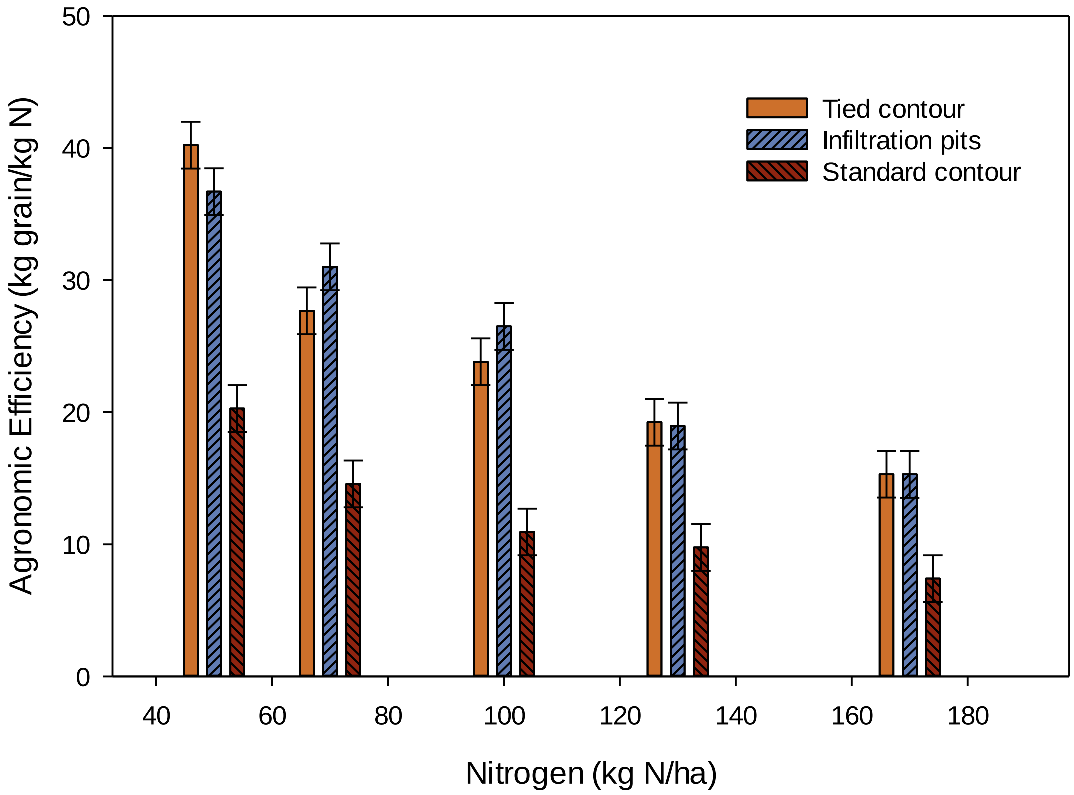

Figure 6. 3: Effect of rainwater harvesting x nitrogen application on agronomic efficiency

6.3.1.3 Effect of RWH x distance from RWH practice on AE_N

Significant interaction effect ($p<0.05$) of RWH and distance from RWH practice influenced AE_N. At each distance from RWH practice, TC and IP showed comparable AE_N, but significantly higher than the SC (Figure 6.4). The AE_N was in the range of 22.3 – 27.2 kg grain/kg N under TC, 19.9 – 29.5 kg grain/kg N under IP, and (11 – 27.2 kg grain kg/N) under SC across the distances from RWH practice.

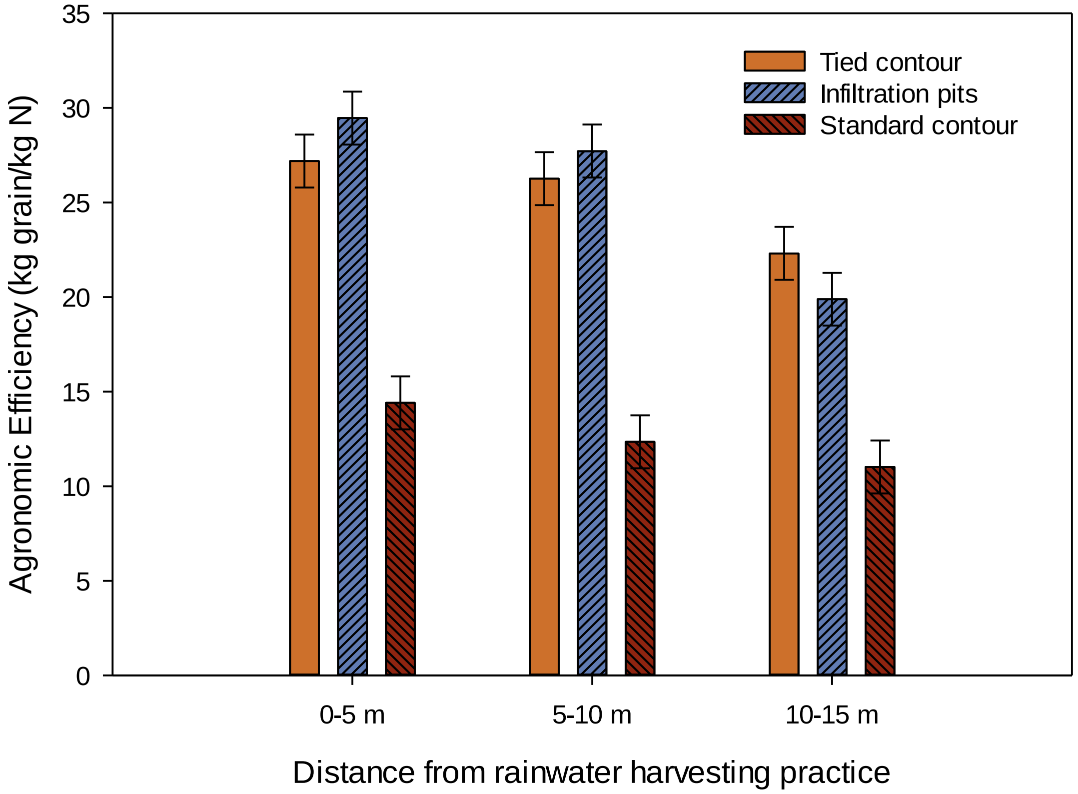

Figure 6. 4: Effect of rainwater harvesting x distance from RWH practice on agronomic efficiency

6.3.1.4 Effect of sorghum variety x nitrogen application on AE_N

The interaction effect of sorghum and nitrogen significantly ($p<0.05$) influenced AE_N with sorghum variety Macia showing higher AE_N than Sc Sila at nitrogen application of 50 and 70 kg N/ha while there was no significant difference in AE_N at >100 kg N/ha in both sorghum varieties (Figure 6.5). A decreasing trend in AE_N with an increase in nitrogen application was shown in both varieties with the highest and least AE_N at 50 kg N/ha and 170 kg N/ha respectively.

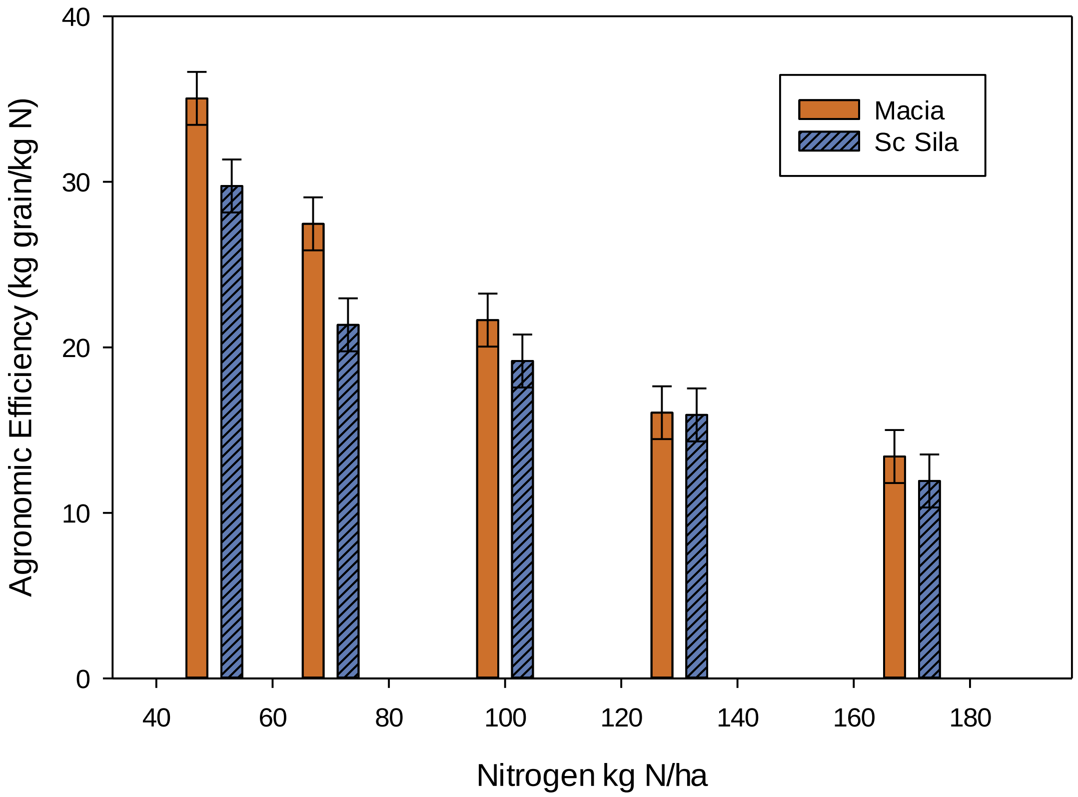

Figure 6. 5: Effect of sorghum variety x nitrogen application on agronomic efficiency

6.3.1.5 Effect of sorghum variety x distance from RWH practice on AE_N

Sorghum variety and the distance from RWH practice had a significant interaction effect ($p<0.05$) on AE_N. The sorghum varieties showed variations in AE_N at each distance from RWH practice. In the sorghum variety Macia, the distance between 0-5 m and 5-10 m showed no significant difference in AE_N, but a significantly higher AE_N at 10-15 m distance from the RWH practice (Figure 6.6). The sorghum variety Sc Sila had greater AE_N at 0-5 m than distances > 5 m from RWH practice. The AE_N was in the range of 18.43-2496 and 17.05-241 kg grain/kg N under the sorghum varieties Macia and Sc Sila respectively.

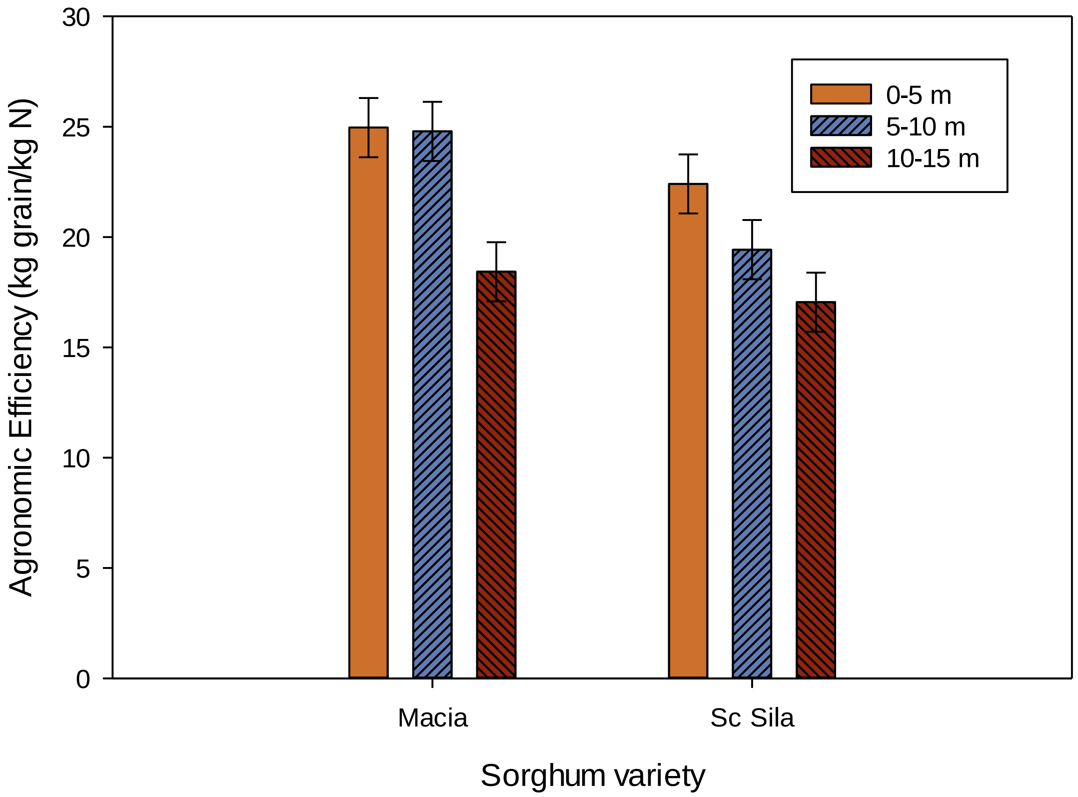

Figure 6. 6: Effect of sorghum variety x distance from RWH practice on agronomic efficiency

6.3.1.6 Effect of nitrogen application x season on AE_N

The interaction effect of sorghum variety and season had a significant effect ($p<0.05$) on AE_N. The season 2017/16 had significantly higher AE_N at each nitrogen application rate compared to the 2017/18 and 2018/19 seasons (Figure 6.7). Nitrogen application of 50 kg N/ha had the highest AE_N in each season while the lowest AE_N was lowest at a nitrogen application rate of 170 kg N/ha in each season. A significant decreasing trend in AE_N was shown with an increase in nitrogen application across seasons (Figure 6.7). The AE_N was in the range of 16.54 - 42.25 kg grain/kg N (2016/17), 9.64 - 24.42 kg grain/kg N (2017/18) and 11.82 - 30.53 kg grain/kg N (2018/19).

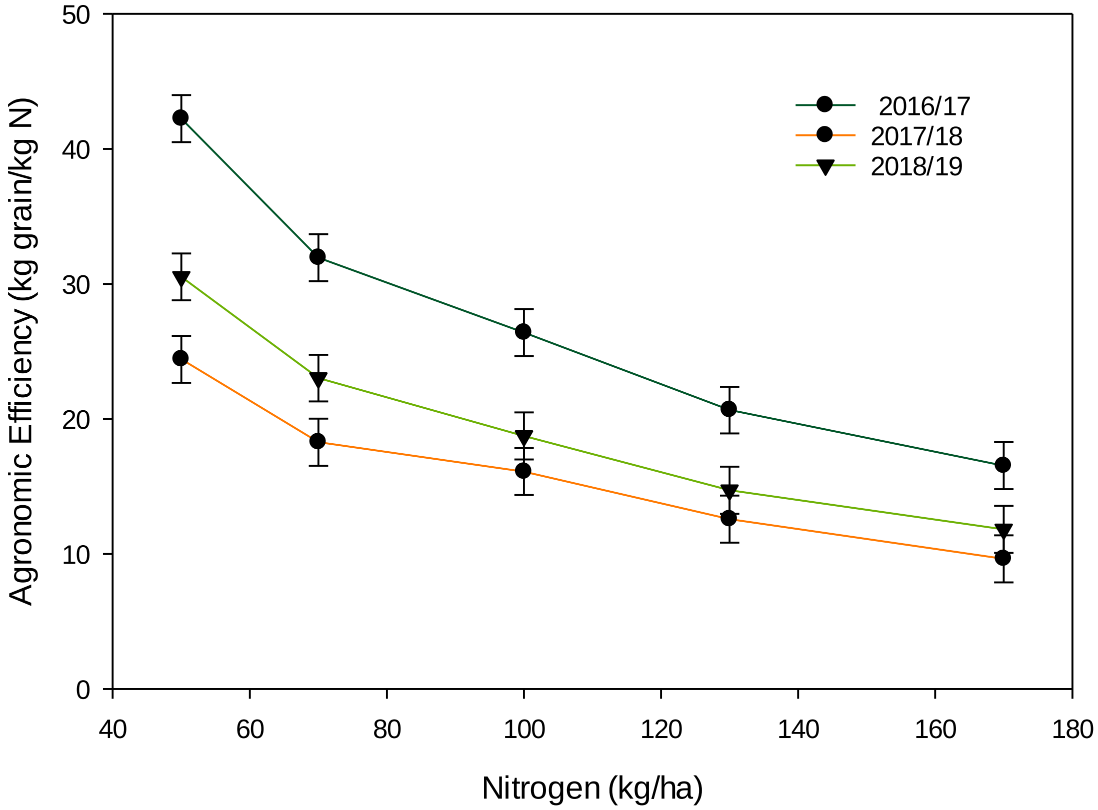

Figure 6. 7: Effect of nitrogen application x season on agronomic efficiency

6.3.1.7 Effect of distance from RWH x season on AE_N

The AE_N significantly varied with distance from RWH practice in each season. The 2016/17 season had no significant difference in AE_N at each distance from RHW practice while in the 2017/18 season the distance 0-5 m had significantly higher AE_N than 10-15 m distance and the 5-10 m distance showed comparable AE_N with the 0-5 m and 10-15 m distance from RWH practice (Figure 6.8). Significant differences in AE_N were more apparent 2018/19 season where 0-5 m and 5-10 m distances showed higher AE_N than the 10-15 m distance from the RWH practice. The AE_N was in the range of 26.13 – 28.86 kg grain/kg N (2016/17), 14.48- 18.21 kg grain/kg N (2017/18), and 12.61-23.99 kg grain/kg N (2018/19). However, a general decrease in AE_N was also observed with an increase in distance from the RWH practice in all seasons (Figure 6.8).

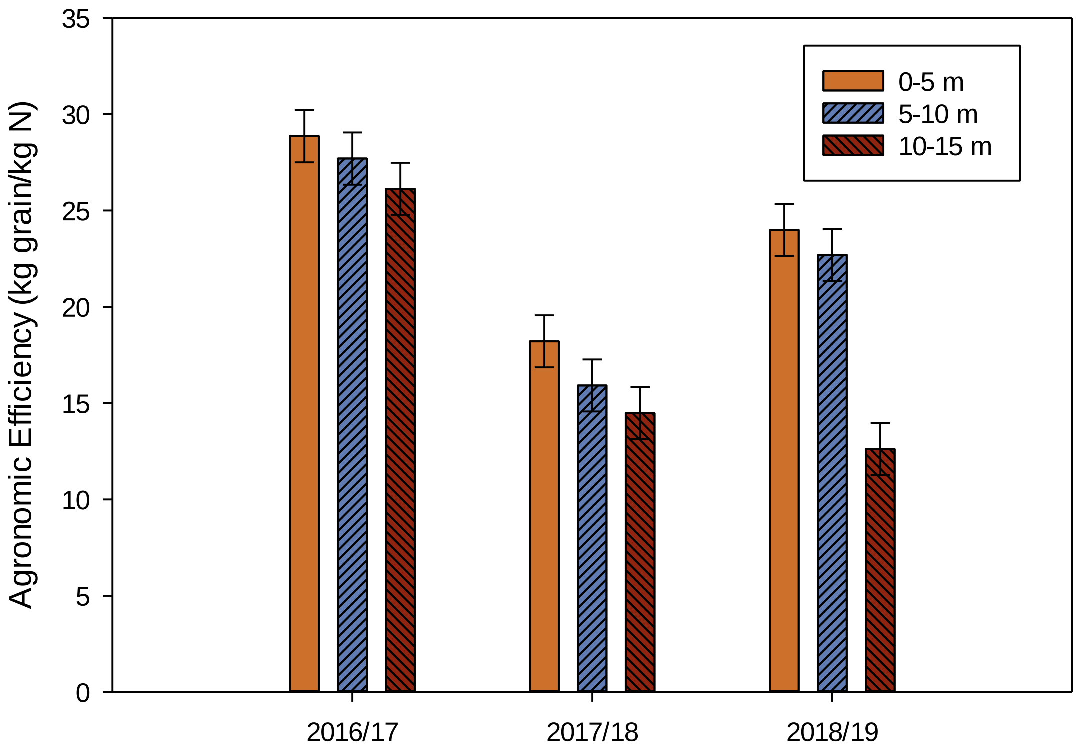

Figure 6. 8: Effect of distance from RWH practice x season on agronomic use efficiency

6.3.2 Rainwater use efficiency

The effect of RWH practice, sorghum variety, and distance from RWH practice are presented in Table 6.1. Significant interaction effects among the treatments except for nitrogen largely explain for variation in rainwater use efficiencies observed. Nitrogen application had a significant effect ($p<0.05$) on rainwater use efficiency. Nitrogen application of 50 and 70 kg N/ha had no significant difference in rainwater use efficiency (2.66; 2.63 kg grain/mm/ha), but lower than >100 kg N/ha (Table 6.1). Nitrogen application rates > 100 kg/ha had no significant difference with rainwater use efficiencies of 2.97; 2.95; 3.00 kg grain/mm/ha at 100; 130 and 170 kg N/ha respectively.

Table 6. 1: Effect of rainwater harvesting practices, sorghum variety, nitrogen application, and distance from rainwater harvesting practice on rainwater use efficiency

RWH Method	**Rainwater use Efficiency (kg/mm/ha)**			
	2016/17	2017/18	2018/19	**Mean**
TC	3.70[a]	3.03[a]	3.53[a]	**3.42**
IP	3.56[a]	3.13[a]	3.78[a]	**3.49**
SC	2.77[b]	0.98[b]	1.10[b]	**1.62**
P value	0.01	0.01	<0.001	
LSD	0.50	0.98	0.70	
Variety				
Macia	3.65[a]	2.59[a]	3.10[a]	**3.11**
Sila	3.03[b]	2.17[a]	2.51[b]	**2.57**
P-value	0.003	0.28	0.001	
LSD	0.32	0.85	0.26	
Nitrogen				
50	3.14[a]	2.22[a]	2.62[a]	**2.66**
70	3.12[a]	2.10[a]	2.66[a]	**2.63**
100	3.46[b]	2.55[a]	2.91[b]	**2.97**
130	3.43[b]	2.54[a]	2.89[b]	**295**
170	3.56[b]	2.49a	2.95[b]	**3.00**
P-value	0.001	0.07	0.02	
LSD	0.24	0.39	0.24	
Distance from RWH				
0-5 m	3.45[a]	2.72[a]	3.34[a]	**3.17**
5-10 m	3.42[a]	2.39[a]	3.26[a]	**3.02**
10-15 m	3.15[b]	2.03[b]	1.82[b]	**2.34**
P value	0.03	0.01	<0.001	
LSD	0.25	0.43	0.24	

Means in the same column followed by the same letter have no significant difference at $p<0.05$.

RHW – Rainwater harvesting, TC – Tied contour, IP – Infiltration pits, SC – Standard contour

The significant interaction effect ($p<0.05$) of RWH practice x sorghum variety x distance from RWH practice influenced rainwater use efficiency. In sorghum variety Macia, TC and IP had comparable rainwater use efficiency, but significantly higher than standard contour at each distance from RWH practice. A similar trend was observed in sorghum variety Sc Sila except for 5-10 m distance which showed significant differences between TC and IP (Figure 6.9).

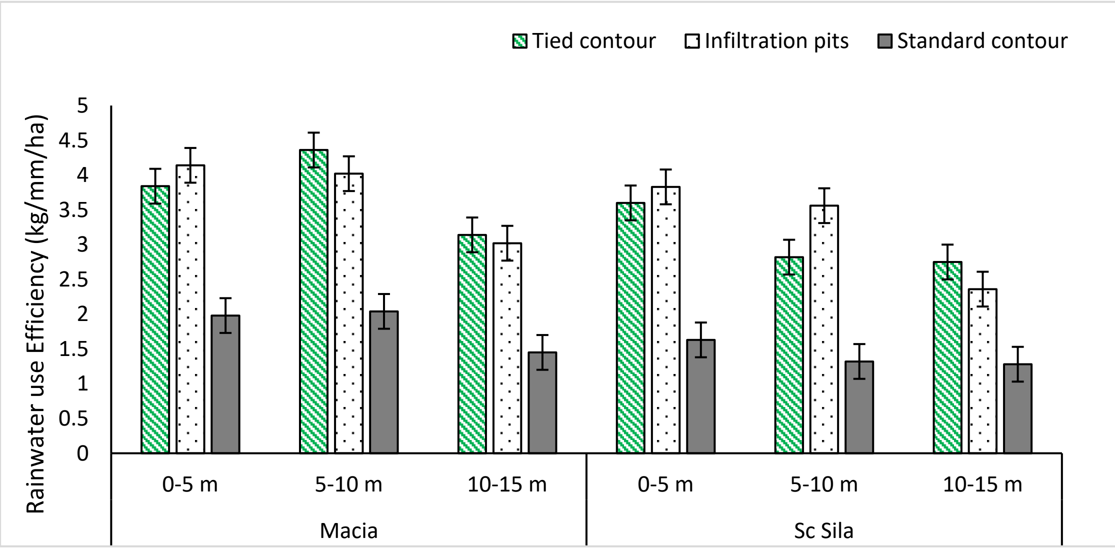

Figure 6. 9: Effect of rainwater harvesting x sorghum variety x distance from RWH on rainwater use efficiency

A significant interaction ($p<0.05$) effect of RWH x distance from RWH practice x season was shown on rainwater use efficiency. In all three cropping seasons, TC and IP had significantly higher rainwater use efficiencies than SC at each distance from RWH practice (Figure 6.10). There was no substantial difference in rainwater use efficiency between TC and IP across all distances from RWH practice in each season.

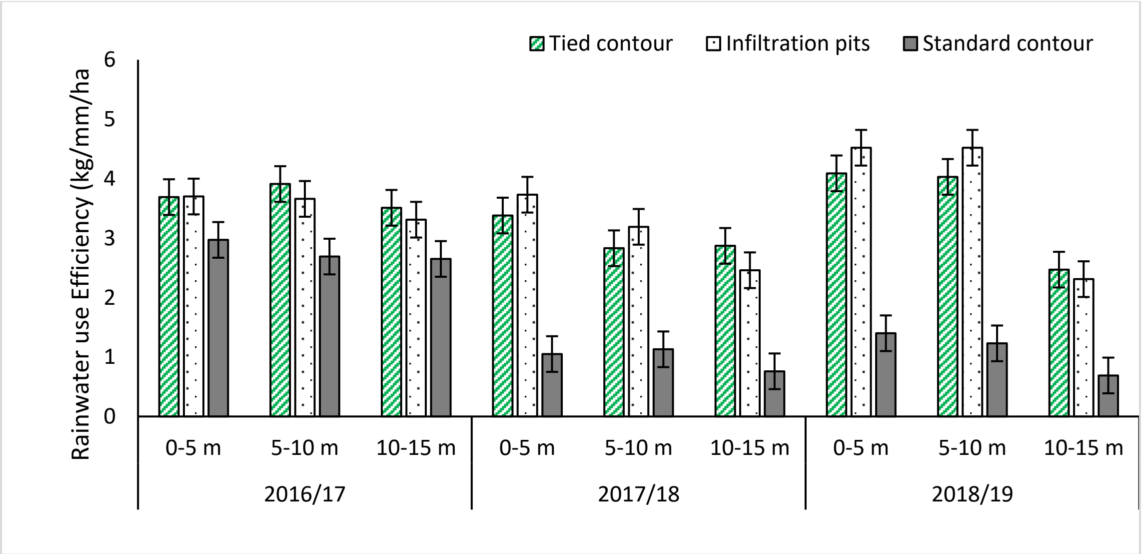

Figure 6. 10: Effect of rainwater harvesting x sorghum variety x distance from RWH on rainwater use efficiency.

6.4 DISCUSSION

6.4.1 Agronomic Efficiency

The higher AE_N observed under TC and IP rainwater harvesting practices than the SC in all the seasons (Figure 6.2) was attributed to their capacity in rainwater capture and subsequently releasing it through lateral flow resulting in higher water content (gwc) (Table 3.2). Moisture influences nitrogen uptake and use (Abunyewa et al., 2017). The low AE_N shown under the SC (Figure 6.2) was attributed to low poor water retention due to greater rainwater runoff resulting in low water content (Table 3.2). Low soil moisture reduced nutrient uptake and nutrient utilization resulting in low yield and hence low agronomic efficiency.

The interactive effects of RWH and nitrogen application rate on AE_N were evident with TC and IP showing comparatively higher AE_N at each level of nitrogen application than the SC (Figure 6.3). Moisture retention by the RWH techniques (Table 3.2) accounts for the differences in AE_N due to greater utilization of nitrogen in a moist soil environment (Abunyewa et al., 2017). The extended moisture availability by RWH techniques reported by Mupangwa et al. (2016) enhances AE_N. Moisture influences nitrogen uptake and utilization at the economic sink (Sharma & Bali, 2017; Abunyewa et al., 2017) resulting in higher AE_N. In the SC, low nitrogen use efficiency was attributed to moisture deficit as most of the rainwater was lost through runoff hence resulting in low soil moisture (Table 3.2), and hence low nitrogen productivity (Abunyewa et al., 2017). Nitrogen use is a function of available soil moisture and nitrogen uptake. Recent findings by Hatfield & Dold (2019) showed that moisture deficit/stress in crop plants reduces nitrogen concentration compared with well-watered plants resulting in a negative effect on nitrogen use efficiency. Thus, integrating TC or IP rainwater harvesting practices and nitrogen application play an important function in improving nitrogen productivity in rain-fed agriculture.

The AE_N was considerably higher under TC and IP at each distance from rainwater harvesting practice compared with SC (Figure 6.4). Higher AE_N was associated with greater rainwater capture resulting in differential soil moisture conditions between the RWH practices and the SC (Table 3.2). Comparable AE_N between TC and IP was due to a similar principle of operation with no difference in soil moisture (Table 3.2). The AE_N moisture in the SC was due to low soil moisture (Table 3.2) caused by more runoff (Nyamadzawo et al., 2013) which adversely affected nutrient utilization (Mupangwa et al., 2012a).

The sorghum variety Macia expressed higher AE_N than Sc Sila at nitrogen application rates of 50 and 70 kg N/ha (Figure 6.5). This was contrary to hybrid varieties which often exhibit higher AE_N responses to nitrogen application (Hadebe et al., 2017a). However, similar observations were reported by Shamme & Raghavaiah (2016) who found that landrace sorghum genotypes had higher nitrogen productivity than hybrid varieties in semi-arid rain-fed farming environments. The incremental addition of mineral nitrogen fertilizer resulted in a general decline in the nitrogen use efficiency index in the varieties (Figure 6.5). However higher nitrogen utilization was at lower nitrogen fertilizer application of 50 kg N/ha shown by higher AE_N in both varieties. Ngosong et al. (2019) and Ajeigbe et al. (2018) reported similar results with a significant reduction in N use efficiency at higher nitrogen application rates, which was supported by a strong negative correlation between the agronomic efficiency and total soil nitrogen.

In each sorghum variety distances closer to the RWH practices had higher AE_N than distances further away (10-15 m) (Table 6.6). This was attributed to differential moisture conditions as distance increases from the RWH practice and the effect is more severe at the furthest point (Table 3.2). The results corroborate with Nyagumbo et al. (2019) who attributed the differential in nitrogen productivity to differences in moisture availability at distances further away.

Nitrogen use efficiency index varied with seasons and nitrogen application rate. The 2016/17 season showed the greatest AE_N at each nitrogen application rate compared to the 2017/18 and 2018/19 seasons (Figure 6.7). The 2016/17 season was characterized by high rainfall amounts and evenly distributed rainfall intensities which influenced nitrogen uptake and use. Mupangwa et al. (2016) attributed this to soil moisture was not a limiting factor to crop growth hence greater nitrogen productivity in seasons with above-average rainfall.

6.4.2 Rainwater use efficiency

The addition of mineral nitrogen fertilizer increased rainwater use efficiency, no matter the rainfall quantity and distribution during the seasons (Table 6.1) confirming the significance of nitrogen in enhancing rainwater productivity. Nitrogen is one of the primary nutrient limiting rainwater use efficiency in semi-arid soils and positive rainwater use efficiency responses to nitrogen in this study is consistent with observations made in previous studies by Lian et al. (2016), Mupangwa et al. (2016), and Ajeigbe et al. (2018). However, above 100 kg N/ha there was no difference in rainwater use efficiency, and the same results were reported by Lian et al. (2016), Ajeigbe et al. (2018), and Mupangwa et al. (2018).

The use of tied contour and infiltration pits had higher rainwater use efficiency than standard contour at all distances from rainwater harvesting practice regardless of sorghum variety (Figure 6.9) and season (Figure 6.10). Rainwater collected by the rainwater harvesting practices improved soil moisture at all distances (Table 3.2) in both sorghum varieties (Macia, Sc Sila), and seasons compared with conventional practice. They enhance the effective utilization of precipitation for crop production by minimizing runoff allowing lateral flow of moisture further away downslope (Table 3.2) and subsequently making it available for use by plants. The soil moisture improved the yielding ability of the sorghum varieties hence rainwater productivity in rain-fed semi-arid farming regions. Similar observations were reported by Mupangwa et al. (2016)) and Lian et al. (2016) where rainwater harvesting techniques improved rainwater productivity. Contrary to the findings, Parihar et al. (2019) found that the use of TC and IP did not improve rainwater use efficiency at any distance from the rainwater harvesting practice. The differences were probably due to differences in climatic condition and soil type. However, TC and IP had no considerable difference in rainwater use efficiency at each distance under both varieties Macia and Sc Sila (Figure 6.9). This was attributed to equal potential in rainwater collection shown by comparable moisture content (Table 3.2) resulting in comparable rainwater productivity. In the standard contour lateral flow of moisture was to a shorter distance because most of the water is lost through runoff resulting in reduced use of precipitation at all distances.

6.5 CONCLUSION

Rainwater harvesting techniques (TC and IP) improved AE_N in all seasons, nitrogen application rates, and distances from RWH practice. The sorghum variety Macia expressed higher agronomic efficiency than Sc Sila at nitrogen application rates of 50 and 70 kg N/ha. In each sorghum variety distances closer to the RWH practices had higher AE_N than distances further away (10-15 m), and the 2016/17 season showed the greatest AE_N at each nitrogen application rate compared to the 2017/18 and 2018/19 seasons. The addition of mineral nitrogen fertilizer increased rainwater use efficiency, no matter the rainfall quantity and distribution during the seasons. Rainwater use efficiency was greatest under TC and IP than SC at each distance from RWH practice regardless of sorghum variety and season. Rainwater harvesting practices (TC and IP) had no considerable difference in rainwater productivity at each distance under both varieties Macia and Sc Sila. It is concluded that upgrading the current existing contours into TC and IP can enhance climate change resilience through improved nitrogen and rainwater productivity in smallholder rainfed farming systems.

CHAPTER 7: SYNTHESIS

7.1 INTRODUCTION

The low and poorly distributed rainfall coupled with insufficient amounts of N fertilizer use in rain-fed smallholder farming systems affected sorghum (*Sorghum bicolor L.*) yields in Zimbabwe. Contour-based rainwater harvesting (RWH) is one of the climate change adaptation strategies that farmers can adopt in the semi-arid regions of Zimbabwe, but has received little recognition as viable adaptation strategy. Rainwater harvesting and nutrient management are probably climate change resilient practices that can be used as strategic entry points for reducing the risk of crop failure due to water scarcity (Nyamadzawo et al., 2013). The research aimed to quantify sorghum grain yield response under *in-situ* water retention techniques (basins, ripper, and tied ridges), and investigate sorghum grain yield response to RWH (Tied contour, Infiltration pits) and nutrient management practices. A meta-analysis was conducted to determine sorghum yield response to *in-situ* rainwater retention techniques. The *in-situ* rainwater retention practices were assessed under different rainfall amounts, soil texture, mulch, and nitrogen fertility using the weighted mean yield difference approach. To determine sorghum grain yield response to RWH, three experiments were set up. Experiment 1 was made up of the two sorghum varieties under RWH practices and inorganic nutrient management practice. Experiment 2 was made up of the two sorghum varieties under inorganic nitrogen + organic fertilizer. Experiment 3 consisted Macia and Sc Sila sorghum varieties under RWH practices and organic nitrogen management. In all the three experiments a randomised completed block design experiment in a split-split plot configuration was conducted in 2016/17 to 2018/19 seasons at Mt Zonwe smallholder farming area in Mutare district, Zimbabwe. Analysis of variance was used to determine the performance of sorghum varieties (Macia, Sc Sila) under contour RWH practices at varying nutrient management practices (inorganic nitrogen fertilizer, inorganic nitrogen fertilizer + organic fertilizer, organic fertilizer). The inorganic fraction consists of varying nitrogen rates while the organic fertilizer component consisted of cattle manure at different rates. Nitrogen and rainwater use efficiencies were evaluated under RWH practices and inorganic N fertilizer experiments. Data was collected on soil moisture contend, sorghum grain yield, nitrogen use efficiency and rainwater use efficiency.

7.2 Meta-Analysis of sorghum yield response to rainwater harvesting

Results of the meta-analysis showed that basins, ripper, and tied ridges had no sorghum grain yield advantage over the conventional practice in all agronomic environments (Chapter 2). Yields were comparable to conventional farming practice while substantial yield depression was seen under tied ridges and ripper planting. Tied ridges showed substantial sorghum grain yield reductions (-0.25 t/ha) under < 600 mm rainfall while ripper planting resulted in considerable grain yield reduction (-0.32 t/ha) under 600 – 1000 mm rainfall (Chapter 2). Sorghum grain yield depression under tied ridges was attributed to localized waterlogging caused by intense short-duration rainfall patterns which often occur in semi-arid regions. Tied ridges are made of ridges up to 20 cm high tied at intervals which allow significant water collection (Masaka et al., 2021). In moderate rainfall areas (600-1000 mm) sorghum grain yield reduction under ripper planting was also attributed to waterlogging due to moisture storage. It implies that rainfall amount is an important factor in determining the effectiveness of the alternative practices. Substantial grain yield reduction (-1.06 t/ha) was also shown by ripper planting under soil textural class of 20 – 35 % clay (Chapter 2). Grain yield depression was attributed to termite activity due to minimum soil disturbance in ripper planting (Mutsamba et al., 2016). The variation in yields with varying rainfall intensities and seasonal rainfall implies that farmers have to pay closer attention in selecting appropriate soil water management practice to avoid waterlogging. Similarly, the challenges caused by clay soils mean that smallholder farmers need better soil management strategies such as raising beds to improve the grain yield of sorghum. Another implication of the findings is that farmers and other stakeholders should carefully consider the potential benefits and limitations of the alternative practices before adopting them. For example, they should consider factors such as soil type, agronomic environment, and cultural practices before deciding whether or not to use the alternative practices as climate resilient strategies.

7.3 Effects of contour-based rainwater harvesting and inorganic fertilizer on sorghum grain yield

Tied contour and IP have the potential to improve soil moisture retention. This is likely due to the fact that both practices promote the infiltration of water into the soil (chapter 3). However, it is important to note that the results may vary depending on the soil type and other environmental factors. Mupangwa et al. (2006) found that the use of TC and IP in semi-arid regions of Zimbabwe can lead to increased soil moisture, and that the effects are long-lasting. The researchers found that the increase in soil moisture was still evident three years after the initial implementation of the conservation practices. It implies that these practices may help to improve crop yields, particularly in areas with limited rainfall. Additionally, by increasing soil gwc, these practices could help to reduce the risk of soil erosion over time. The effect of RWH practices on soil moisture content decreased with increasing distance from the practice. This suggests that the positive effects of RWH practices are localized, and that to maximize their benefits, they should be implemented close to the crops that will benefit from them. In all seasons, TC and IP yielded more sorghum grain than modified standard contour (SC). It implies that TC and IP are consistently more effective than SC at increasing sorghum grain yields because of moist soil environment created by the RWH practices. In contrast Kumar et al. (2017) found that, while there was no significant difference in soil moisture between the different systems, the use of tied ridges and infiltration pits did lead to a significant decrease in plant growth. In other words, the use of these techniques had a negative impact on plant growth.

Sorghum grain yield was significantly greater at all nitrogen application rates and consistently higher at all plant distances from the RWH method in the 2016/17 season with more rainfall. This explains the important role played by nitrogen on plant growth and development. In comparison to TC and IP, the SC had significantly lower grain yield at all nitrogen application rates. The moist microenvironment created by TC and IP improved nitrogen productivity hence more grain yield. At all plant distances from the RWH method, TC and IP had considerably higher grain production than SC in each variety of sorghum. This was attributed to the greater moisture sphere of influence created by TC and IP. The findings show that use of TC, IP, and application of inorganic nitrogen are climate change resilient strategies which can be used by smallholder farmer to improve soil moisture content and sorghum grain yield.

7.4 Interactive effects of contour-based rainwater harvesting and organic fertilizers on grain yield of sorghum

The findings from contour based RWH practice and cattle manure in chapter 4 showed that applying cattle manure from 5 t/ha up to 20 t/ha can increase sorghum grain yield. The TC was the most effective practice for increasing yield while IP is also effective, but to a lesser extent than TC. The SC had the lowest yield among the RWH practices tested. The results imply that that farmer should consider applying cattle manure up to 20 t/ha to maximize grain yield depending on the availability of cattle manure. Another implication is that TC may be the most effective practice for increasing grain yield, followed by IP while SC may not be the best choice for maximizing yield. The moisture harvested under the RWH practice play an important role on mineralization of cattle manure to provide nutrients hence higher grain yield. In a study from Nigeria, Chiroma et al. (2006) found that the combination of TC and IP, along with the application of cattle manure, increased sorghum grain yield by up to 30%. Similarly, Kugedera et al. (2020) conducted a three-year study in South Africa, and found that the use of TC, IP, and cattle manure increased the sorghum yield by up to 50%. In Zimbabwe, Motsi et al. (2004)

also found that the use of RWH techniques, such as TC and IP increased the grain yield by up to 50%, compared to conventional tillage practices. The increase in sorghum grain yield concurs with the findings of this study which were attributed to improved soil fertility and increased water retention. Contrary to the findings, Musyimi et al. (2022) reported that the use of cattle manure actually reduced the yield of sorghum by up to 25%, compared to the control group.

This study found that applying cattle manure can increase sorghum grain yield in both Macia and Sc Sila, with Macia having a higher grain yield than Sc Sila. This indicates that farmers may want to consider the specific variety of sorghum they are growing when making decisions about cattle manure application. It implies that farmers should consider choosing a high-yielding variety like Macia if they are trying to maximize grain yield. In contrast, Dé et al. (2012) found that the use of cattle manure had a neutral effect on sorghum yield, neither increasing nor decreasing it. The use of TC and IP increased grain yield compared to SC, in all distances from RWH (0-5 m, 5-10 m, 10-15 m), variety and, over the three seasons. This implies that farmers may want to use TC or IP to increase their grain yield, especially when growing a variety like Macia. This was attributed to rainwater harvested by the RWH as evidenced by high moisture content (gwc). The results corroborate findings in chapters 3. Kubiku et al. (2022a) found that the use of TC and IP led to a significant increase in sorghum yield at all distances from the RWH practices. They also found that the yield was greatest at a distance of 5 m from the RWH practices. In contrast, Motsi et al (2004) found that the use of tied contour and infiltration pits did not improve sorghum grain yield at all distances from the rainwater harvesting practices, and the yield was greatest at a distance of 2 m from the RWH practices. The results of this study may be due to differences in soil type, climate between the study area, catchment characteristics and slope. It implies that farmers should consider the rainfall conditions and varieties being grown when deciding which practices to use. Contour

RWH, and choosing the appropriate sorghum variety in conjunction with application of manure prove to be ideal climate change resilient crop intensification practices for smallholder farming system.

7.5 Contour-based rainwater harvesting and integrated nutrient management effects on sorghum grain yield

In chapter 5, the results of the RWH and inorganic nitrogen + cattle manure experiment revealed that the grain yield of sorghum was substantially higher under TC and IP compared to SC at all distances from RWH practices and across all seasons. The results are in tandem with findings in chapter 3 and 4. The RWH practices created a moist microenvironment downslope making them climate change resilient practices suitable for semi-arid farming systems. This was evidenced by higher gwc in TC and IP. The conferred moisture benefits by TC and IP significantly improved the grain yield of sorghum varieties Macia and Sc Sila compared to SC. Debdulal et al. (2020) found that TC and IP significantly increased sorghum grain yield by up to 30 % while Milkias et al. (2018), found that the techniques led to an increase in sorghum grain yield of up to 60%. Similarly, a study conducted by Nyagumbo et al. (2019) in Zimbabwe showed that the crops grown with RWH techniques had significantly higher yields, with an average increase of around 20%. Both studies concurred with the finding of this study that the increase in sorghum grain yield was due to improved soil moisture, which allowed the sorghum plants to absorb more nutrients and produce higher grain yield effectively. Contrary, Nyakudya et al. (2014), which found that TC and IP did not lead to an increase in sorghum grain yield. In this study, the authors found that while the techniques did improve the amount of water available in the soil, this did not translate into an increase in crop yield. Masvaya et al. (2017) also found that while the IP were able to capture and retain more water in the soil, the roots of the sorghum plants were not able to reach all of the water stored in the soil. They attributed this to a number of factors, including the timing and amount of rainfall, as well as the fertility of the soil. At each incremental level of nitrogen addition to cattle manure, there was an increase in sorghum grain yield in both varieties, however, Macia had a substantially higher grain yield than Sc Sila. Based on the results, nitrogen addition increases grain yield in both varieties, but Macia had a higher-yielding variety than Sc Sila. Therefore, farmers may want to consider using Macia if they are looking to maximize grain yield. Another implication is that farmers should consider adding nitrogen to cattle manure as a climate change resilient strategy to increase grain yield.

7.6 Effects of RWH and inorganic nitrogen use on nitrogen and rainwater use efficiency

The evaluation of nitrogen and rainwater use efficiency under the RWH practices and inorganic nitrogen fertilizer showed that TC and IP had considerably higher agronomic efficiency (AE) than SC across all nitrogen application rates, distance from RWH practice, and seasons (Chapter 6). It implies that TC and IP are more effective at increasing nitrogen use efficiency than standard contour farming practices. This is likely due increased soil moisture by the RWH practices, which allowed more of the applied nitrogen to be taken up by the crop. The benefits of RWH practices extended beyond the immediate area around the practices. Rainwater collection improved the moisture status of the field increasing nitrogen productivity. It implies that farmers may not need to consider distance from RWH to improve AE. Sorghum variety Macia had higher AE than Sc Sila at 50 and 70 kg N/ha while >100 kg/N ha had no difference in AE in both varieties. This may mean that Macia may be more efficient at using nitrogen fertiliser than Sc Sila. This suggests that there is a point of diminishing returns for nitrogen fertiliser application in sorghum. Once the nitrogen application rates exceeded 100, there is no additional benefit to crop yield, and the added fertiliser may simply be wasted. This could have implications for reducing the economic and environmental cost of sorghum production. A decreasing trend in AE with an increase in nitrogen application was noted in both varieties.

The implication of this finding is that there is a trade-off between nitrogen application rates and nitrogen use efficiency in sorghum. That is, the more nitrogen that is applied, the less efficiently it is used by the crop. This could have implications for optimising fertiliser management to balance crop productivity and economic and environmental costs. Tied contour and IP increased rainwater use efficiency (RUE) compared with SC across all distances and varieties. This was due to the moisture conservation effect resulting in higher rainwater productivity under the RWH practices. This suggests that these practices can help to improve crop yields in areas with limited rainfall, and could be valuable tool for farmers in regions affected by drought. Nitrogen fertilizer application increased rainwater productivity up to 100 kg N/ha beyond which there was no difference. It suggests that there is an optimal level of nitrogen fertilizer application for maximising rainwater productivity, beyond which further fertilizer application does not improve crop yields. This has important implications for efficient use of water and fertilizer resources, and could help to minimize environmental impacts of agriculture. Tied contour and infiltration pits improved rainwater productivity at each distance from RWH practice regardless of sorghum variety and season. This was due to the greater potential exhibited by the RWH practices in rainwater capture. It indicates that the benefits of RWH practices are not limited to the area immediately surrounding the practice. Instead, there is a broader area of influence, in which these practices can increase rainwater productivity. This finding could have implications for designing climate change resilient RWH systems and optimising the layout of farms.

7.8 CONCLUSION AND RECOMMENDATIONS

In a meta-analysis, the use of *in-situ* RWH (tied ridges, basins, and ripper) did not improve sorghum grain yield in all the agronomic conditions (rainfall, soil texture, nitrogen fertility, and mulch). The findings help farmers and farm advisors to choose the most appropriate *in-situ* RWH practices for their specific situation. Tied contour and IP improved soil moisture content and sorghum grain yields in all the nutrient management practices compared with the conventional farming practice (SC). Distances closer to the RWH practice (10 m) had higher soil moisture content and sorghum grain yield compared to distances further away (15 m). Reducing contour spacing can be beneficial, therefore smallholder farmers are recommended to use TC and IP at a spacing of 10 m to improve soil moisture and sorghum grain yield. Application of inorganic nitrogen fertilizer of 50 kg/ha, and the nutrient amendment of 5 kg cattle manure/ha + 50 kg N/ha was beneficial. The application of cattle manure up to 20 t/ha improved sorghum grain yield. Based on the findings, smallholder farmers are encouraged to apply nitrogen fertilizer at a rate of 50 kg N/ha. In integrated nutrient management practice, nutrient amendment of 5 kg cattle manure/ha + 50 kg N/ha may be recommended, and under organic nutrient management, cattle manure application of up to 20 t/ha is recommended depending on availability. Sorghum variety Macia gave higher yields compared to Sc Sila under TC and IP, and nutrient management practice. Implies that Macia can be recommended to smallholder farmers due its better performance in terms of yielding ability in comparison to Sc Sila. The tied contours and IP also considerably improved nitrogen use efficiency (agronomic efficiency) and rainwater use efficiency. The research findings suggest that TC, IP, and nutrient management practices are climate change resilient crop intensification practices which can be used to enhance sorghum grain yield in smallholder farming environments. The study was carried out in Marange area found in agroecological IV of Mutare district over three years hence its generalisation maybe limited. It is, therefore, recommended to work with the government and non-governmental extension agency boards to further explore the effectiveness of the alternative practices in different agronomic environments to provide technical guidelines that farmers can use as reference material for RWH technologies. This will help to fill gaps in the current body of knowledge and contribute to a more comprehensive understanding of the benefits and limitations of alternative practices. Further research needs to be carried out to determine the economic feasibility RWH. Policymakers may need to consider the economic viability of the alternative practices by weighing the costs and benefits of adopting the alternative practices. Finally, the research community needs to continue to investigate the benefits and limitations of the alternative practices to develop policies with a new paradigm shift, which may view TC and IP as potential RWH technologies. This will promote their modification of contours into RWH practices (TC and IP) to enhance the sorghum grain yield in the face of climate change in the semi-arid smallholder farming systems.

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