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Research article

Field edge rainwater harvesting and inorganic fertilizers for improved sorghum (*Sorghum bicolor L.*) yields in semi-arid farming regions of Marange, Zimbabwe

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ABSTRACT

Sorghum (*Sorghum bicolor L.*) is mainly cultivated in marginal areas of Zimbabwe, where soil fertility is poor and 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, 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 region from 2016/17 to 2018/19. 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 much more sorghum grain than standard contour (SC). Sorghum grain production 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 each variety of sorghum.

1. Introduction

Sorghum (*Sorghum bicolor L.*) is a key food crop in Southern Africa, accounting for 22% of total cereal land after maize (Macauley and 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 reduce food insecurity in semi-arid areas in the present and future (Chanza, 2018; Nhemachena et al., 2014). The grain yields have steadily declined because cultivation is being pushed into more remote areas with inferior soils and drought-prone (Nciizah et al., 2020). Because of the harsh environmental circumstances in which the crop is grown, it has been unable to keep up with rising demand.

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 and V is entirely dependent on rain (Mukarumbwa and 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 meager yields (0.5 t/ha) which are below subsistence

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level (Musara et al., 2019) resulting in high yield gaps compared to output at commercial farms (3 t/ha) (Macauley and Ramadjita, 2015).

Rainfall in the semi-arid areas is relatively low, often poorly distributed, and highly variable (Mhizha and Ndiritu, 2013). There is a high coefficient of variability concerning the quantity, onset, and cessation of rainfall and in addition, long dry spells can occur throughout 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., 2012). This makes crop production in dry-land locations is highly risky due to the high value of potential evapotranspiration, and lack of nutrients (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., 2012).

Field edge and in-contour rainwater harvesting 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 field edge and channeled through a modified graded contour (standard contour) tied at intervals to form miniature ponds (tied contour) have received little research under sorghum production. Most of the studies on rainwater harvesting (RWH) focused on tied ridges (Mandumbu et al., 2020), planting basins (Mupangwa et al., 2019), dead level contours, and in-field infiltration pits (Mhizha and Ndiritu, 2013; Mupangwa et al., 2012). 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 hypothesized that i) the RWH methods (TC, IP, SC) 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, SC) at varying inorganic nitrogen application rates and distance from RWH methods.

2. Materials and methods

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 (19^{o} 11` 30`` S; 32$^{o}$ 03` 28`` E 835 m above sea level) (Figure 1). The experiment was run for three seasons from 2016/17 to 2018/19. The ecological region is composed of 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, poor in Nitrogen and Phosphorus (Table 1). The trial field was on a general slope of 3 %. Farming enterprises consist of a crop-livestock farming system and the predominant crops grown include crops like maize (*Zea mays*), sorghum (*Sorghum bicolor L. Moench*), millets (*Pennisetum glaucum (L.) R. Br.*). and *(Eleusine coracana (L.) Gaertn*) and cotton (*Gossypium hirsutum L.*).

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 × 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 analyzed following the Kjeldahl procedure (Cottenie, 1980), the soil pH following the $CaCl_2$ method (Henderson and Bui, 2002), organic C following the wet digestion method (Walkley and Black, 1934), available P_2O_5 following the Olsen method (Olsen, 1954), and soil texture following Bouyoucons Hydrometer method (Bouyoucos, 1962). Table 1 shows the physical and chemical parameters of the soil at the research site.

2.3. Experimental layout

Three successive standard contours measuring 90 m and spaced 15 m apart were identified on the farmer's field. The standard contours were graded contour ridges that were made to properly discharge runoff water from the field to prevent soil erosion (Mhizha and Ndiritu, 2013). The standard contours were made of a trench (contour channel) 1 m (width) × 0.4 m (depth) with dug soil placed down the slope (Mhizha and Ndiritu, 2013). The contour lengths were split into 3 × 30 m lengths of RWH methods namely tied contour (TC), infiltration pits (IP), and standard contour (SC). A factorial experiment was established in a split-split plot configuration. The RWH methods were the main plot factor. 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 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 2). The dimensions of TC and IP were partly based on Mhizha and Ndiritu (2013), Mupangwa et al. (2012), 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 2).

The two varieties of sorghum were subplot factors 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 variables in each variety of sorghum measuring 2 m (length) × 4.5 m (width) (Figure 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 center of the RWH method.

2.4. Experimental procedure

The field was prepared using the conventional tillage method with an ox-drawn moldboard plow in July every year. Planting furrows were made by an ox-drawn moldboard plow 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) in 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. The amount of N topdressing fertilizer used for each treatment was determined by the difference between N treatments (50, 70, 100, 130, and 170 kg N/ha) and N applied as basal (14 kg N/ha). In all the subplot factors, no-top-dressing treatments were 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. Qualia birds were controlled at the booting stage by scaring the birds during the day to prevent grain loss until harvesting maturity.

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 general

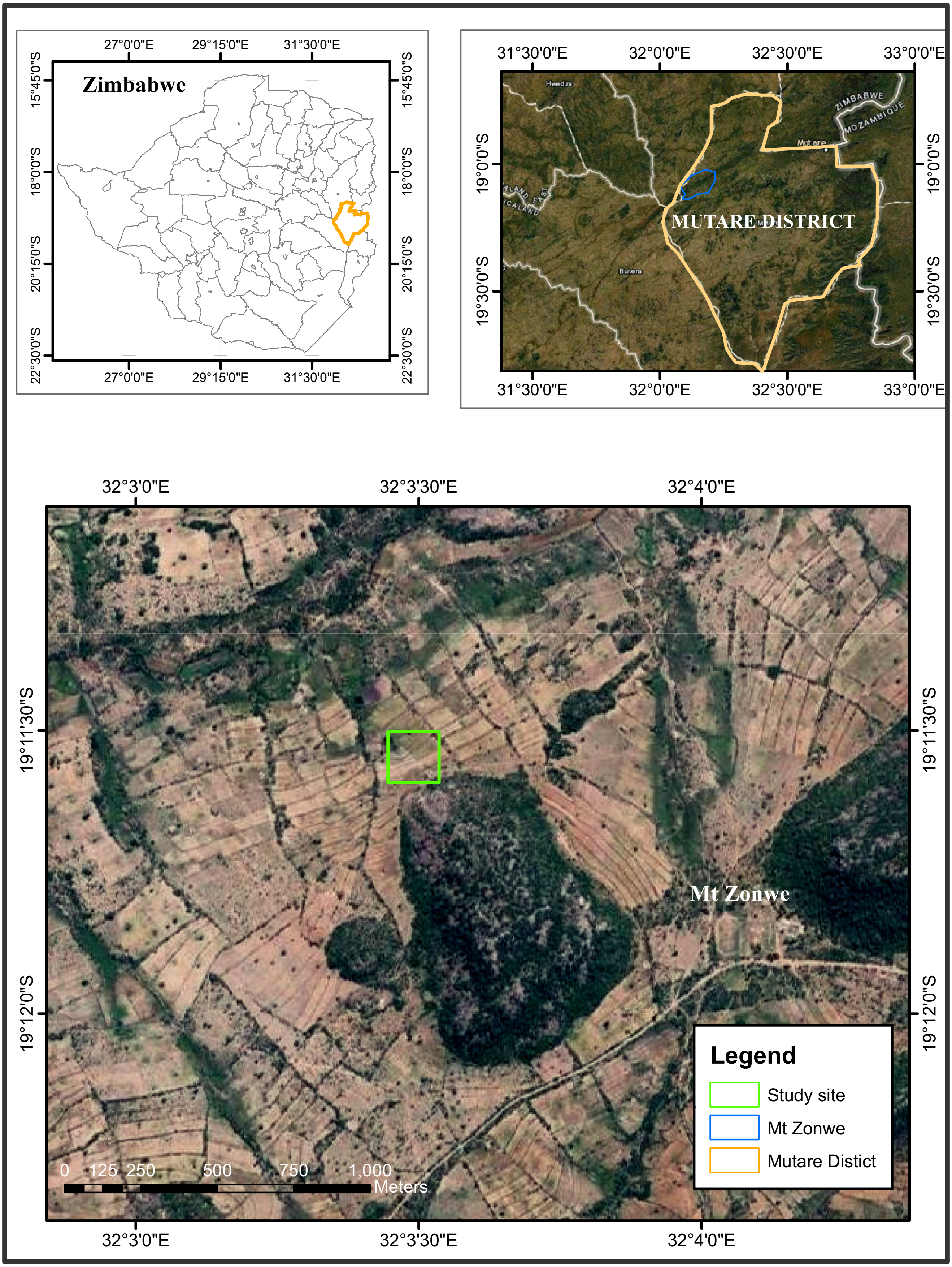

Figure 1. Experimental study site.

Table 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

yield stability. 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 yield 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).

2.6. *Data collection*

2.6.1. *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. Soil samples were collected 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 h at 105 °C. The procedure outlined by (Ingram and Anderson, 1993) was used to calculate the gwc. Soil bulky density was not measured hence the volumetric water content was not calculated. The soil moisture content for the treatments was calculated by averaging the gravimetric moisture content for each season.

2.6.2. *Yield*

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

$$\text{Grain yield after moisture correction} = \text{Grain yield before moisture correction} \times (100\text{-}P)/(100\text{-}Q)$$

where P, was the moisture content of grain measured and Q was the specified grain moisture content (12.5%) (Mulvaney and Devkota, 2020).

2.7. *Statistical analysis*

Normality and homoscedasticity tests were done using Kolmogorov-Smirnov and Bartlett test 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. Results

3.1. *Seasonal rainfall*

According to the Zimbabwe agro-ecological region classification, the growing period in each year received more rainfall than the amount

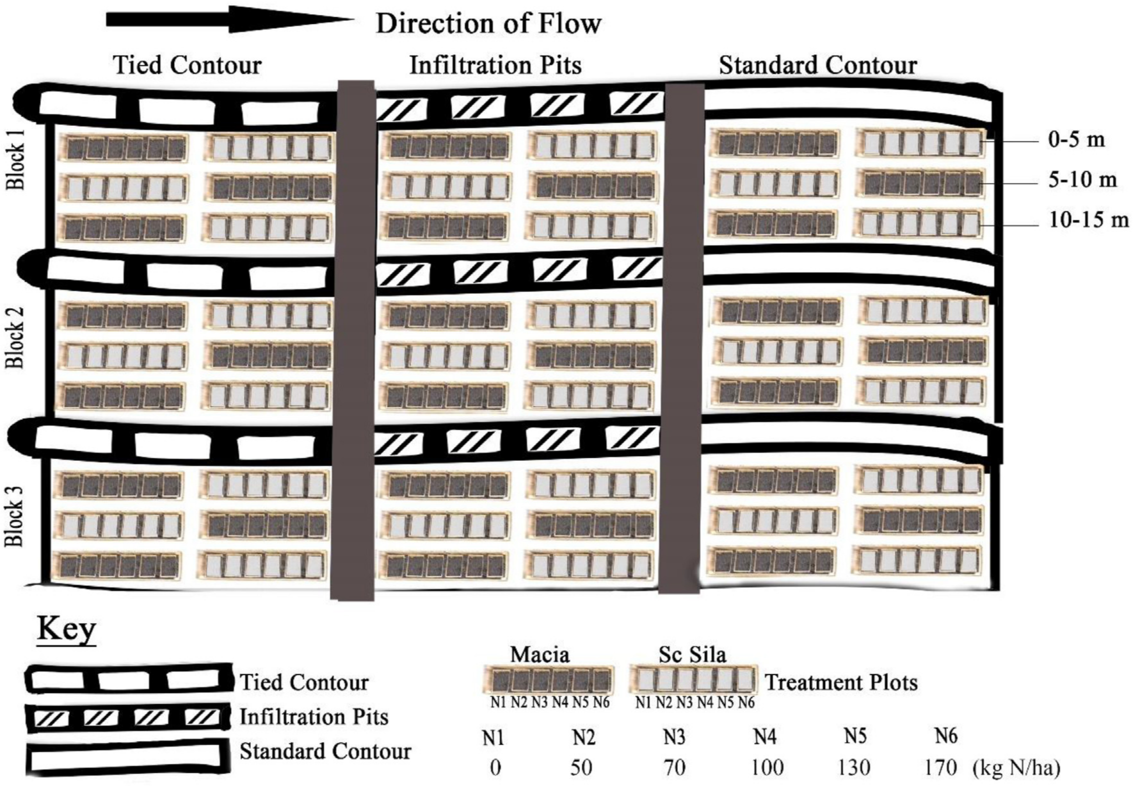

Figure 2. Experimental layout.

prescribed for the region (450–650 mm) (Figure 3). The 2016/17 season was the wettest and received 35% more rainfall normal for agricultural region IV. Rainfall was low at the beginning and towards the end of the season with the moderate mid-season dry spell being experienced over the seasons.

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 2). TC and IP had a comparable gravimetric water content 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 2). The distance 0–5 m from the RWH method had the highest gravimetric content (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 2).

3.3. Sorghum grain yield

The table below summarizes the analysis of 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, 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).

The interaction effect of the RWH method and season significantly influenced ($p < 0.05$) grain yield of sorghum (Table 3). In all the seasons, the RWH methods - TC and IP had considerably higher ($p < 0.05$) sorghum grain yield than the SC (Figure 4). TC and IP had comparable grain yields across all seasons (Figure 4).

A significant interaction effect ($p < 0.05$) between nitrogen application and season influenced sorghum grain yield (Table 3). 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. In all seasons, the treatments with 0 kg N/ha had considerably lower sorghum grain production than the nitrogen-applied treatments (Figure 5). However, 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 the 2017/18 and 2018/19 seasons.

The effect of distance from the RWH method on grain yield of sorghum significantly varied ($p < 0.05$) with the season (Table 3). 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 6). 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, a gradual decline in yield was noted as the distance from the RWH method increased.

RWH method and nitrogen application had a significant interaction effect ($p < 0.05$) on grain yield (Table 3). 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 (Figure 7). 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, sorghum grain yield was considerably lower ($p < 0.05$) at 0 kg N/ha compared to nitrogen-applied treatments. Nitrogen application increased sorghum grain yield in the TC and IP (Figure 7), but not in the SC. Sorghum grain yield increased considerably up to 50 kg N/ha in the SC, beyond which there was no significant improvement.

The interaction effect of sorghum variety and nitrogen application on sorghum grain yield was significant ($p < 0.05$) (Table 3). At all the nitrogen application rates, the sorghum variety Macia had a significantly greater yield than the sorghum variety Sc Sila, except at 130 kg N/ha, where yield was not statistically different (Figure 8). At 0 kg N/ha, there was no substantial difference in yield amongst the sorghum cultivars. None nitrogen applied treatments yielded significantly lower grain yields ($p < 0.05$) than nitrogen applied treatments in each sorghum variety. The grain yield did not differ significantly in all the varieties when nitrogen addition was greater than 50 kg N/ha.

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). Treatments with no nitrogen applied (0 kg N/ha) had considerably lower grain production than treatments with nitrogen applied at rates more than 50 kg N/ha, and this trend was consistent at all distances from the RWH method (Figure 9). 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.

The interaction between RWH, sorghum variety, and distance from RWH influenced sorghum grain yield considerably ($p < 0.05$) (Table 3). 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 10). 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 5–10 m distance from RWH method in the sorghum variety Sc Sila (Figure 10).

4. Discussion

4.1. Soil moisture

The RWH methods TC and IP improved the gwc of the soil (Table 2). This was due to their capacity to collect more runoff water from the catchment area creating a large 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. The standard contour had the least gravimetric water content due to water lost through runoff. The results concur with the findings by Nyamadzawo et al. (2013) who found that about 50 % of water is lost as

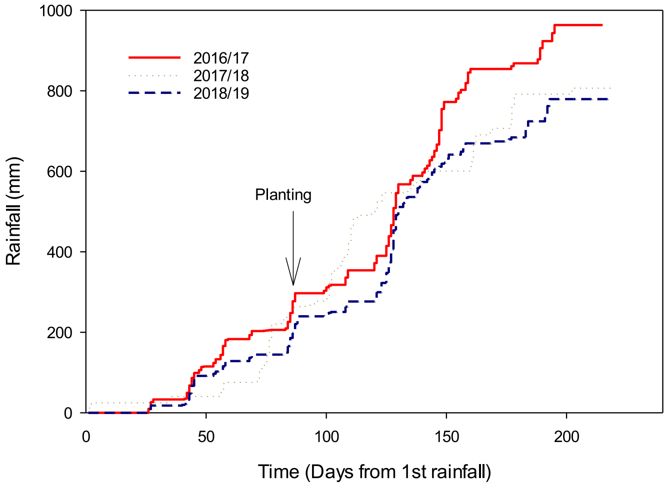

Figure 3. Monthly rainfall pattern throughout the trial.

Table 2. Effects of RWH method, plant distance from RWH 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 preceded by an identical letter are not significantly different at $p < 0.05$. LSD – least significant difference (5 % level), ns – not significantly different at $p < 0.05$. RWH – rainwater harvesting method.

Table 3. 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 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.

runoff from standard contours. Gravimetric water content decreased with an increase in distance from RWH practice (Table 2). Lateral flow of moisture from the rainwater harvesting practices was affected by distance from discharge point resulting in low gravimetric water content with an increase in distance. The 2016/17 season characterized by high rainfall (Figure 3) had the highest gravimetric water content (Table 2). Despite high rainfall total in 2016/17, the season was characterized by well-distributed rainfall 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 with a small period. This could have resulted in water loss due to runoff, as rainfall intensity may have exceeded the soil's infiltration capacity.

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 4) 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 high gravimetric moisture content in the rainwater harvesting practices (Table 2). The soil moisture is later used by the crops evading dry spell conditions during the vegetative period and grain filling. 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. (2012) also revealed that RWH techniques tied ridges, infiltration pits, and dead level contours with and without infiltration pits improve the soil moisture and crop yields. Water retention by TC and IP prolongs soil moisture improving water use 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 attained by the standard contour (Table 2). 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. The availability of assimilates, which is influenced by soil water availability, is critical for effective grain filling (Mahinda et al., 2018; Mupangwa et al., 2018). Thus, rainwater harvesting structures can sustain crop production during dry spells

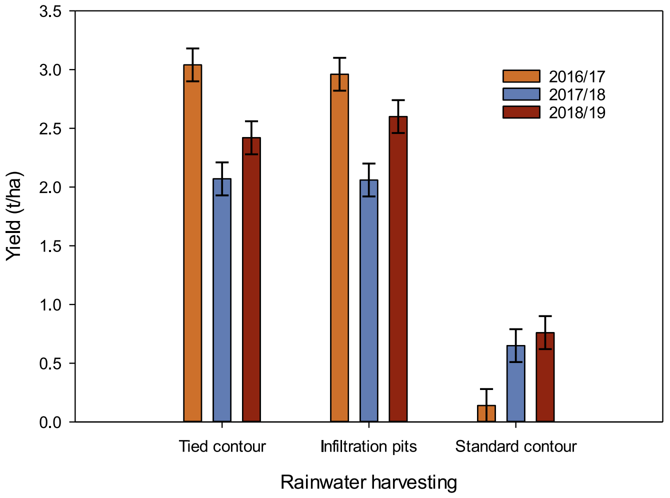

Figure 4. The interaction effect of RWH method × season on grain yield of sorghum. Vertical bars represent standard error.

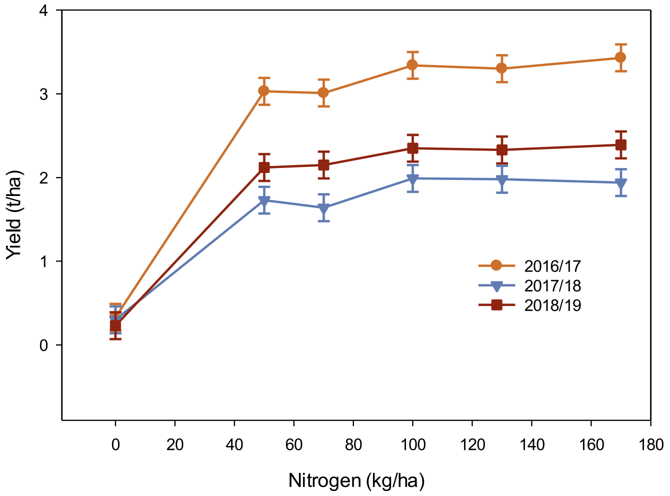

Figure 5. The interaction effect of nitrogen application × season on grain yield of sorghum. Vertical bars represent standard error.

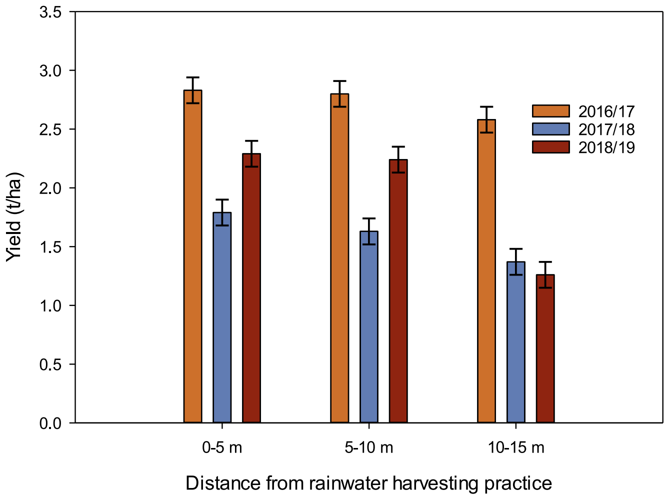

Figure 6. Interactive effects of plant distance from RWH method × season on grain yield of sorghum. Vertical bars represent standard error.

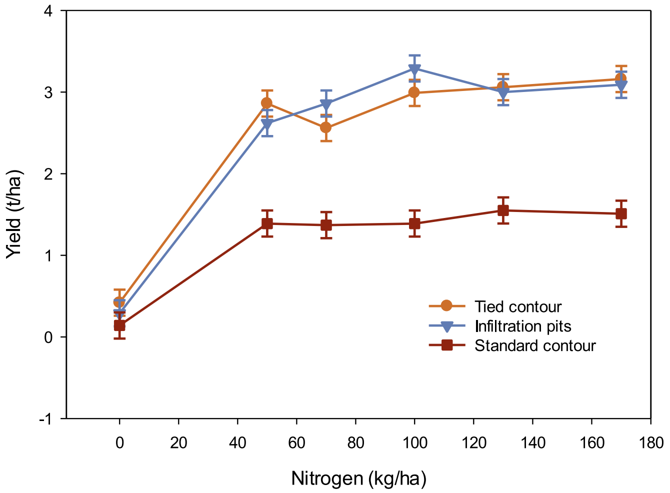

Figure 7. Interactive effects of RWH method × nitrogen application on grain yield of sorghum. Vertical bars represent standard error.

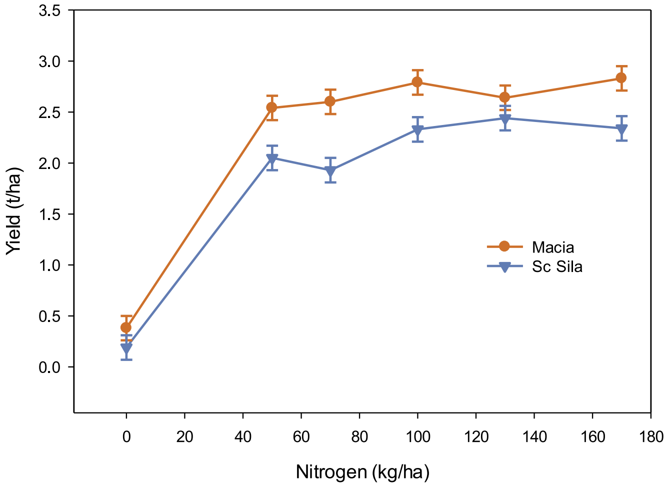

Figure 8. The interaction effect of sorghum variety × nitrogen application on grain yield of sorghum. Vertical bars represent standard error.

improving water use efficiency 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 5). This was attributed to differences in seasonal rainfall characteristics. The season 2016/17 was characterized by above-average rainfall (900 mm) (Figure 3) and evenly distributed rainfall which improved groundwater recharge resulting in more soil moisture (Table 2), 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 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 and Bali, 2017). Thus, the season's rainfall characteristics play a vital role in the effect of nitrogen on crop productivity.

The effect of distance from the RWH technique on grain yield gave maximum benefits at all plant distances in the year 2016/17 in comparison to 2017/18 and 2018/19 seasons (Figure 6). The season 2016/17 was characterized by evenly distributed high rainfall (900 mm) (Figure 3) which resulted in more moisture content evidenced by higher gravimetric water content in the season (Table 2) which probably resulted in higher grain yield at each distance. The greater moisture sphere of influence resulted in no grain yield difference at each distance in the 2016/17 season. In seasons with above-average rainfall, Mupangwa et al. (2012) found comparable 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) but poorly distributed across the seasons. In all the seasons, a gradual drop in yield was observed as plant distance increased from the RWH method (Figure 6). This could be because of a considerable drop in gravimetric water content as plant distance increased from the RWH method (Table 2). Results corroborate with findings by Mupangwa et al. (2012) and (Nyakudya et al. (2014) 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 and Ndiritu, 2013; Mupangwa et al., 2012).

Grain yields were greater in TC and IP than SC at all nitrogen applications greater than 50 kg N/ha (Figure 7). The RWH methods showed

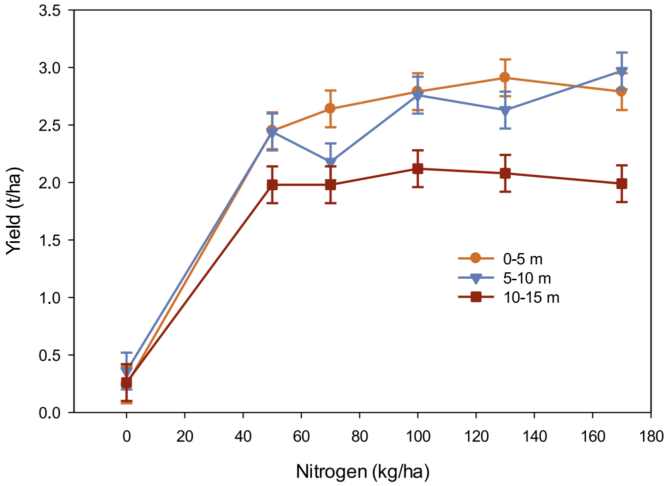

Figure 9. Interactive effects of plant distance from RWH method × nitrogen application on sorghum grain yield. Vertical bars represent standard error.

higher gravimetric water content which may have a bearing on better grain yield response to nitrogen addition. Studies by Mishra and Patil (2015), Shamme et al. (2016), and Sharma and 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 improves crop productivity. The low grain yield response to nitrogen addition in the SC was due to low moisture content evidenced by the low gravimetric water content (Table 2). Higher sorghum grain yield in nitrogen applied treatment compared with no nitrogen applied treatments in the RWH methods (Figure 7) explains the importance of nitrogen in crop growth. Water and nitrogen availability are important in the production of photoassimilates 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 8). 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, 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 than Sc Sila a hybrid sorghum variety. Hadebe et al. (2017) found yield advantage of open-pollinated varieties over hybrids. Higher sorghum grain yield in nitrogen applied treatment compared with no nitrogen applied treatments in each sorghum variety (Figure 7) 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 9). 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 gravimetric water content 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 2). Hence, the reduced grain yield at 10–15 m distance from the RWH method was related to lower water availability which resulted in low grain yield. According to 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, the largest sectorial region for ion and mass movement of water, and the optimum soil environment for root growth.

However, 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 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 10) may be attributed to the higher capacity of tied contours and infiltration pits 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 tied contours and infiltration pits while the SC had the least water content (Table 2). 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.

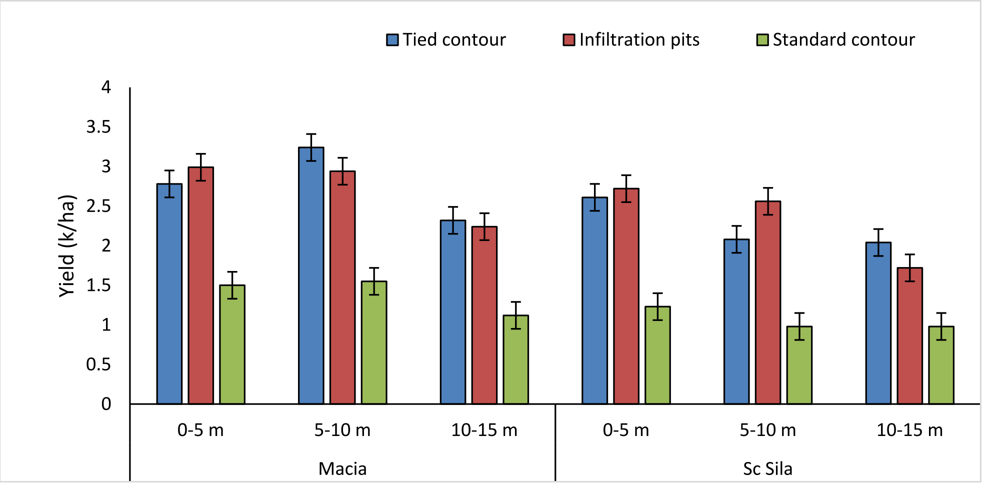

Figure 10. Interactive effects of RWH method × variety × plant distance from RWH method on grain yield. Vertical bars represent standard error.

5. Conclusion

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 standard contour had low crop productivity, evidenced by low moisture 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 under the RWH methods, sorghum varieties, distance from RWH methods, and in all seasons. 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. This may be improved by incorporating porous subsurface plastic membranes in the water harvesting methods and investigating their efficiency in improving the moisture conditions of the cropped land. 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.

Declarations

Author contribution statement

F. N. M. Kubiku: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

G. Nyamadzawo; J. Nyamangara; R. Mandumbu: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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