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RESEARCH

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The effects of contour-based rainwater harvesting and integrated nutrient management on maize yields in semi-arid regions of Zimbabwe

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Abstract

In the smallholder farming areas located in semi-arid regions of Zimbabwe, low and unreliable rainfall distribution and poor soil fertility are the major factors limiting crop production. The negative effects of these biophysical factors have been worsened by climate change. However, the major challenges have been the lack of sustainable, low-cost water and nutrient management technologies for these semi-arid regions. The objectives of this study were to evaluate the effects of contour-based rainwater harvesting (RWH) namely tied contours (TC), infiltration pits (IP) which were compared with the standard contour (STDC), and intergrated nutrient management (INM) where cattle manure was used as basal fertiliser and Ammonium Nitrate (AN) as top dressing, on maize yields. Results showed that fields with RWH had higher yields compared to STDC. Average maize yields were 2210 and 1792 kg ha^{-1} for TC and IP which were 88% and 52% above STDC (1176 kg ha^{-1}) respectively. Increasing nitrogen (N) levels resulted in a further increase in maize yields. Return on investment was negative during drier years and was significantly higher in RWH systems compared with STDC during wet seasons. Farmers need to reduce mineral fertiliser application during dry seasons since little rainwater is captured. We conclude that contour based RWH and INM can be used as sustainable low cost methods of crop production. Higher fertiliser application rates when rainfall is limiting, do not result in increased return on investiment.

Keywords Integrated nutrient management, Rainwater harvesting, Semi-arid, Maize, Sandy soils, Climate change

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Introduction

Crop production in smallholder (communal) farming systems in most semi-arid regions of Zimbabwe is rain-fed. Low, erratic and unreliable rainfall (< 450 mm annum) in semi-arid regions of Zimbabwe (Zimbabwe Department of Meteorological 2002), added to frequent droughts due to climate change have resulted in total crop failures and low economic returns. Many smallholder farmers in semi-arid regions of Zimbabwe are located in areas dominated by sandy soils with low water holding capacity and are infertile (Nkurunziza et al. 2019; Kugedera et al. 2023a). Though most of these semi-arid areas were previously used for livestock or wildlife ranching, there has been accelerated land-use change to crop-livestock production systems due increased population pressure and resettlement of new communities (Bado et al. 2022; Chiturike et al. 2023).

Soils in the semi-arid regions of Zimbabwe are generally fragile, sandy and coarse-textured with low concentrations of nitrogen and exchangeable cations (Nyamangara et al. 2000; Ncube et al. 2007; Nkurunziza et al. 2019). The continuous cultivation of these soils exposes to continuous nutrient harvesting by crops and this increase further loss of soil organic carbon (Chivenge et al. 2007; Vanlauwe et al. 2015). In addition, nutrient exports from the arable lands through crop harvesting and the removal of crop residues for livestock feeding accelerates soil degradation and further deplete soil fertility (Sanchez et al. 1997). As a result of very low soil fertility, farmers harvest very little grain which in most cases is not sufficient to take them through half the year.

Soil conditions in smallholder farming areas of semi-arid regions, makes the application of inorganic or organic fertilizers of paramount importance to obtain a meaning full yield (Soropa et al. 2019). However, there are also challenges associated with the use of these fertilisers. In many semi-arid areas, there are challenges of insufficient manure for use as a soil amendment. This has been caused by low livestock numbers due to drought and animal diseases (Svotwa et al. 2008; Zimbabwe Land 2023). On the other hand, the high costs of inorganic fertilizers have resulted in most smallholder farmers failing to access them, resulting in minimal use of inorganic fertilizers (Soropa et al. 2019). However, compared with inorganic fertilizers, animal manures are suitable for use as soil amendments as they are more accessible and available to the smallholder farmers. Therefore, this study is assessing for the promotion of combining organic and inorganic fertilisers, where inorganic N-fertilizer is combined with cattle manure (Dunjana et al. 2012), as a sustainable cropping option for maintaining crop productivity in the semi-arid smallholder farming sector.

Water is essential in driving soil processes and crop growth. However, unreliable rains and low economic status of smallholder farmers make it imperative to explore low-cost water conservation approaches that can extend the availability of water for crop production (Nyamadzawo et al. 2013). Contour-based rainwater harvesting (RWH) represents one such innovation that can be used by smallholder farmers. Examples of simple technological innovations include tied contours (TC) and infiltration pits (IP), (Nyamadzawo et al. 2013; Nyagumbo et al. 2009; Gumbo et al. 2012; Nyagumbo et al. 2019a, b; Kugedera et al. 2022b). Tied-contours are a modification of the standard contours, and the modification involves the placement of cross ties along the contour channels at 5 m intervals to create small dams. Infiltration pits are trenches dug along the channel of the contour ridge to trap water and reduce flow out of the field. These innovations are sustainable because they are semi-permanent, low-cost, and are improved RWH that can increase crop yields in the semi-arid regions (Nyagumbo et al. 2019a, b; Kugedera et al. 2022a). Farmers in semi-arid areas have tended to show more interest in large, semi-permanent to permanent RWH mechanical structures (Hagmann and Murwira 1996; Kugedera et al. 2023b) than in structures that are constructed on a yearly basis, because of labour constraints.

Tied contours and infiltration pits have been reported to increase maize yields in semi-arid regions (Nyamadzawo et al. 2013; Gumbo et al. 2012; Nyagumbo et al. 2019a, b; Chiturike et al. 2023). However, the use of tied contours and infiltration pits alone cannot result in the attainment of the optimum yield potential of crops in sandy soils as issues of soil fertility should be addresed (Ncube et al. 2007; Kugedera et al. 2022a). Contour-based RWH structures combined with improved soil fertility management practices may increase the yields, water use efficiency and water productivity in rain-fed agricultural systems (Hagmann and Murwira 1996), and are a climate change adaptation strategy. While the yield benefits of TC and IP have been scientifically evaluated and quantified in semi-arid areas of Zimbabwe (Gumbo et al. 2012; Nyagumbo et al. 2019a, b; Kugedera et al. 2023a), there is still a gap with regards to crop yield performance under contour-based RWH combined with organic and inorganic fertilisers in semi-arid areas. The objective of the study was to evaluate the effects of contour-based RWH and different rates of nitrogen fertiliser on maize grain yields, net return investment and water use efficiency in smallholder farming area of Zimbabwe. The specific hypothesis being tested was that the combined use of contour-based RWH techniques (TC and IP) improve maize grain yields, water use efficiency, and return on investment in rainfed smallholder farming system in a semi-arid area of Zimbabwe. The specific hypothesis being tested was that the combined use of N fertiliser + cattle manure and RWH techniques (TC and IP) improve maize grain yields, rainwater use efficiency and net return on investment in rainfed smallholder farming systems in semi-arid area of Zimbabwe.

Material and methods

Study sites

This study was carried out at Mt Zonwe in Marange smallholder farming area (17° 43′25″ S; and 31° 1′22″ E, 620 masl) in Zimbabwe during the 2015/16 through to

2017/18cropping seasons (Fig. 1). Growing season started in mid-November to end of April each cropping season. The area is located in agro-ecological region IV according to the Zimbabwe land classification, and is characterised by low, erratic and poorly distributed rainfall (Kubiku et al. 2022a). The rainfall pattern in the area is unimodal mostly falling between October and March, and the long-term seasonal average rainfall < 450 mm per annum (Manatsa et al. 2020). The mean annual temperature is 27 °C and the region is characterised by very high rates of evapotranspiration and mid-season dry spells, and as a result crop failure is a common phenomenon (Chiturike et al. 2023). The predominant cropping system is mainly monoculture sorghum, millets, or cotton, and most farmers have abandoned growing maize due to perennial crop failures caused by inadequate rainfall (Chiturike et al. 2023).

Rainfall characteristics of Mt Zonwe in Marange District

The 2015/16 cropping season received very low rainfall (391 mm), as the country was affected by the El Nino phenomenon. Low rainfall was received in the 1st and the 2nd half of the season, resulting in a total crop failure. The average maize yields in Mutare District during the 2015/16 cropping season was 0.1 t ha^{-1}. However, though the 2016/17 growing season received 680 mm, which was 35% more rainfall than the long-term seasonal average (383 mm), with and good distribution, and the highest amounts of rainfall were received in January during the critical growth stages (tasselling, flowering and grain filling) (Fig. 2). During the 2017/18 season, the 1st half of the season received 386 mm (41%) of the seasons' rainfall; a mid-season dry spell (< 5 mm) experienced in January 2018 coincided with the critical growth stages of the crop. Approximately 59% of the total rains were received in February and March the crops had already wilted.

Site characterization

At the onset of the experiment in 2015, soil samples were randomly collected from the whole field measuring 95 × 50 m. Soil samples were collected from the 0–10, 10–20, 20–40 and 40–60 cm depths using an auger. Fifteen sub-samples were collected per each depth form from fifteen marked points and mixed thoroughly

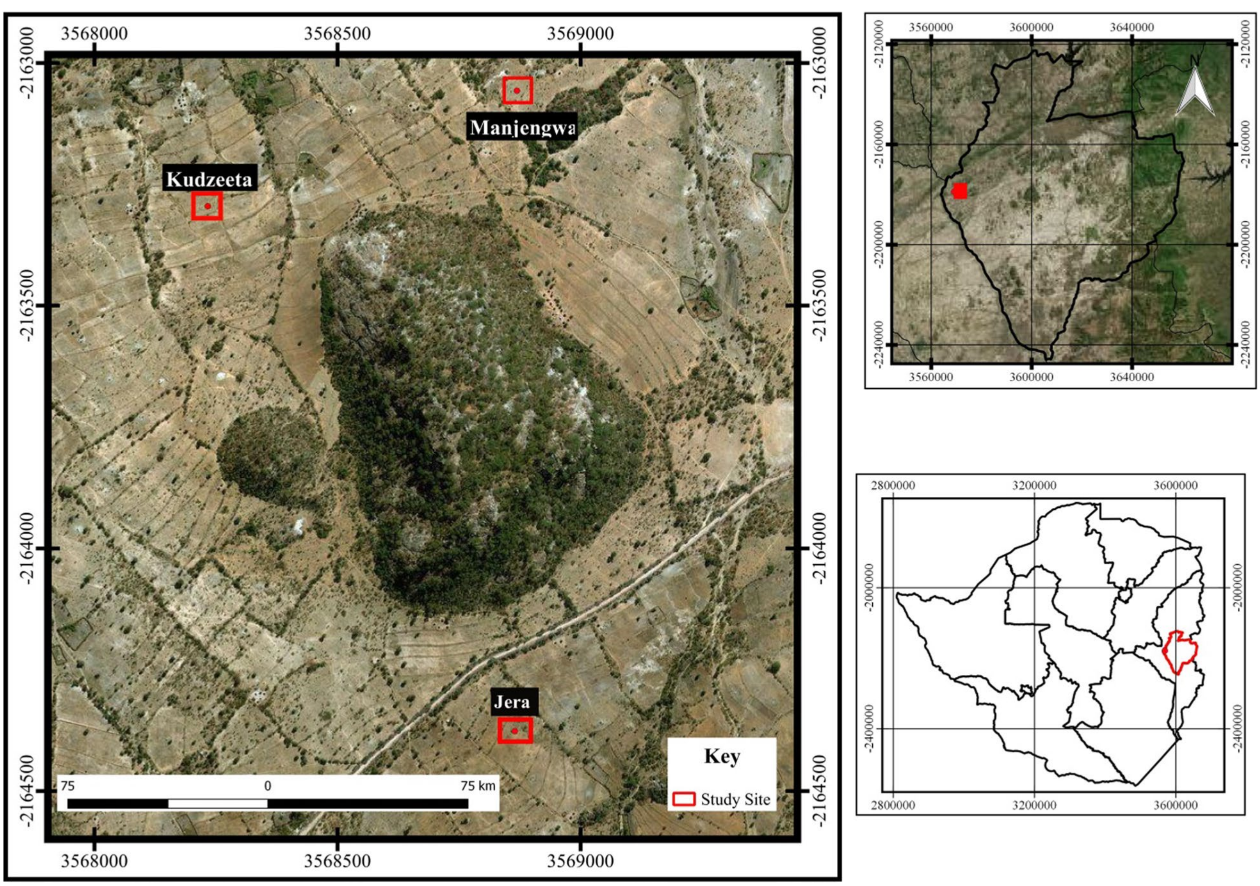

Fig. 1 Map showing three experimental sites (Jera, Kudzeeta and Manjengwa) in Mt Zonwe, Manicaland

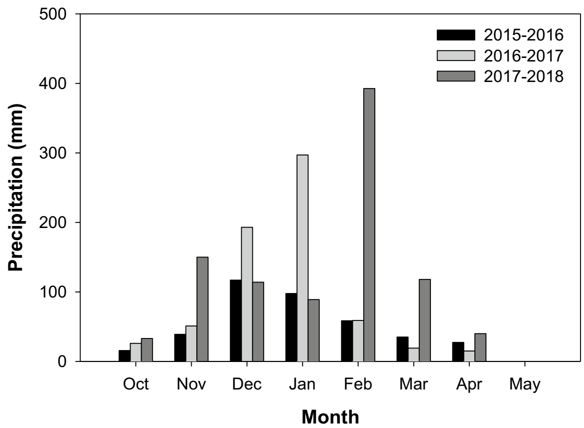

Fig. 2 Monthly rainfall received at the experimental site during the study period

in a plastic bucket and 2 kg was weighed to make a composite sample. The composite soil samples were air-dried, ground and sieved to pass through a 2 mm sieve mesh and 1 kg per soil layer was produced and send for analysis. The soil samples were analysed for total organic carbon (TOC), total nitrogen (N), phosphorus (P), and potassium (K).

Soil organic carbon was determined using the modified Walkley–Black procedure (Nelson and Sommers 1982), which involved wet combustion of organic matter with a mixture of potassium dichromate and sulphuric acid at 125 °C. The residual dichromate was titrated against ferrous sulphate. Bulk density was determined using the clod method, where clods were oven-dried and their mass determined. The clods were then covered with wax to prevent absorption of water before they were dipped in a measuring cylinder with a known amount of water. The amount of displacement water was equal to the volume of the clod (Anderson and Ingram 1989). Soil organic carbon stocks were calculated by multiplying SOC by bulk density and also by depth (Anderson and Ingram 1989). Total nitrogen was determined using Kjeldahl procedure (Anderson and Ingram 1989). The soil pH was determined in a 1:1 (soil:water suspension) using a digital pH meter (Thomas 1996). Available phosphorous was determined using the Olsen method (Nelson and Sommers 1982). Soil texture was determined using the Bouyoucos Hydrometer method (Bouyoucos 1962).

Experimental layout

The experiment was carried out on a field that was 95 m long × 50 m width. The experiment was laid in randomised complete block design (RCBD) with three RWH techniques as main plot factor, and seven nitrogen fertiliser rates as subplot factor under integrated nutrient management where 8 t ha^{-1} cattle manure was applied in all plots. The main factor was RWH techniques at three levels (tied contours (TC), infiltration pits (IP) and standard contour (STDC) as a control) replicated three times. Each RWH treatment occupied 30 m across the slope, with a distance of 2 m between treatments as a buffer. Nitrogen fertiliser was used as sub-plot factor at seven levels (0, 60, 90, 120, 200, 250 and 300 kg N ha^{-1}) on plot sizes measuring 5 m × 4 m. Distance from RWH which were at the field edge as shown in Figs. 3, 4 and 5 was three levels (0–5 m, 5–10 m and 10–15 m). The distances were recorded to enable an analysis of the potential effect of distance from the RWH on maize yields. The study was

Fig. 3 The standard contour ridge, a channel which is meant to dispose excess water from the field

Fig. 4 The tied contour, a modification of the STDC ridge which is used to trap runoff from the field. Photo by George Nyamadzawo

Fig. 5 STDC ridges reinforced with variants of infiltration pits in Marange with dimensions of 5 × 0.5 × 0.5 m for Length x Width x Height. (Photos by George Nyamadzawo)

Table 1 Labour requirement for construction of contour based RWH methods, based on labour require to re-open old contour ridges that were constructed in the 1950s'

RWH method	2015/16 Average man days ha^{-1}	Average man hours ha^{-1}	Average cost ha^{-1}(US$)
New STDC	30	240	150
TC	21	168	105
IP	21	168	105
STDC	21	168	105
Ploughing, seeds, sacks and chemicals			450
60 kg N ha^{-1}			105
90 kg N ha^{-1}			153
120 kg N ha^{-1}			210
200 kg N ha^{-1}			348
250 kg N ha^{-1}			435
300 kg N ha^{-1}			522

1 man day = 8 h; 1 man day cost US$5; TC = Tied contour; IP = Infiltration pit; STDC = Standard contour. 1 tonne was sold at US$370.69

repeated on same study plots to confirm the findings. In each plot, basal fertilizer was applied in the form of cattle manure from the farm at a rate of 500 g of manure per planting station, and this translated to 8 t ha^{-1}.The application rate of cattle manure used was within the range (3–10 t ha^{-1}) of application rates commonly used by the farmers in the smallholder sector. Ammonium Nitrate (34.5% N) was applied as top-dressing when maize was at 8 leaf stage. Early maturing maize seed (SC 403) recommended for semi-arid regions was planted and used as test crops. The maize was harvested after 127 days. During harvesting, plants wereharvested from an area of 4 m^2, and cobs and biomass data were recorded. After shelling, the maize cobs and grains were air-dried to 12.5% moisture content, weighed the and used to calculate maize yields. Water productivity was computed by dividing grain yield with amount of rainfall received during the season. Nitrogen use efficiency (NUE) was calculated as = [Grain yield of fertilized treatment (kg ha^{-1})—Grain yield of unfertilized plot (kg ha^{-1})]/[Fertilizer applied (kg ha^{-1})] (Cassman et al. 1996). Total cost was computed by summing all costs involved which include input costs (seed, fertiliser, transport, storage sacks, pesticides) and labour costs which invloved ploughing, preparation of contours (TC, IP nad STDC), planting, weeding, harvesting and threshing maize. Return on investment was calculated by subtracting total costs from total benefits. Labour requirements for preparation of TC, IP and STDC is indicated in Table 1.

Description of rainwater harvesting techniques used in the experiment

During this study, the effects of tied contours (TC), infiltration pits (IP) and the standard contour (STDC) which was the control and the normal practice used by the smallholder farmers in Zimbabwe, all under integrated nutrient management, were evaluated.

Standard contour

Standard contour (STDC) ridges are found throughout Zimbabwe's smallholder farming areas (Fig. 3). The STDC ridges were promoted as part of conservation measures to reduce land degradation caused by soil erosion as part of the 'The Native Land Husbandry Act of 1951 (Stockings 1978). This act made it mandatory to STDC ridges the smallholder farming areas in high rainfall areas, and enforced conservation and acceptable farming practices with severe penalties for offenders. However, as a result of massive soil erosion, the construction of STDC ridges was made compulsory even in low rainfall areas, where it is more ideal to keep water in the fields than dispose it. The STDC ridges were constructed at a grade of 1:250, for a purpose of disposing 'excess' runoff water as a way of preventing soil erosion. Spacing between contour ridges varies depending on slope and soil type. The standard dimensions for a STDC ridges are 1.7 m for the channel and 1.7 m for the ridge (Nyagumbo et al. 2019a, b; Kugedera et al. 2022a). The STDC takes away about 15% of the total arable area out of production and this was not popular with smallholder farmers (Nyagumbo et al. 2019a, b). It takes about 30-man days to manually construct STDC ridges on 1 hectare of land with an average slope of 2–4%. However, if the land is steep contour ridges will be closer to each other, and it may take even more time to construct the STDC ridges. In Zimbabwe, because STDC ridges were constructed in the 1950s', what is currently required is to repair them, thus reducing the labour needs by between 50 and 70% (Nyagumbo et al. 2019a, b). The disadvantage of the STDC ridge is that it disposes off water from the field especially in low rainfall areas where rain water should be conserved.

Tied contours (TC)

Tied contours are a modification of the STDC ridge that was enforced in the 1950s' (Nyagumbo et al. 2019a, b). The modified TC systems holds water as a result of cross ties, 0.5 m wide × 0.5 m deep, which are placed every 5 m along the channels to create small dams (Fig. 4). Cross-ties are placed in the channel to reduce water flow velocity and reduce runoff, and to improve moisture conservation and infiltration (Nyagumbo et al. 2019a, b). Cross ties create a damming effect, thus converting the STDC ridge from being water disposing structures, to water holding structures. It is relatively less costly to create cross tied on already existing contour structures. Labour requirements are lower, hence they could a cheaper semi-permanent option to improve water retention in semi-arid regions.

Infiltration pits

Infiltration pits are trenches dug along the STDC ridge to trap run-off and increase infiltration and to hold water as it flows (Fig. 4). This technique originated in Zimbabwe from a farmer called Mr. Zephenia Maseko Phiri, in Zvishavane (Maseko 1995). They are suitable for semi-arid regions and can be applied easily on land already with standard contours (Nyagumbo et al. 2009). Infiltration pits had dimensions of 0.5 m × 2 m × 0.5 m (W × L × D). The infiltration pits were placed 0.5 m apart along the contour ridge. The infiltration pits substantially reduce runoff, conserve moisture and can also be used for in-situ composting since the pits are placed along the contours and crop residues can accumulate in the pits from the fields above the contour (Critchley and Siegert 1991). They also act as silt traps for soil that is eroded upslope. They are less costly to construct on already existing contour ridges. There are variations in the dimension of infiltration pits, as no quantitative research data is available on the performance of the structures. Therefore, there are no design specifications based on available research. The most common infiltration pits are 1 × 1 × 1 m in dimension and are placed after every 10 m along the contour channel (Nyagumbo et al. 2019a, b). However, in Marange, farmers preferred the 0.5 × 0.5 × 5 m (W × D × L) pits because they retain water for long periods and these were used for this study (Fig. 5).

Maize variety and source

The study used SC403 maize variety which is suitable for agroecological zone IV and low rainfall areas. It is a drought tolerant variety with yield estimation of 8 tonnes ha^{-1}. The variety has an average physiological maturity time of 75–90 days and harvested after 127 days when grain moisture content of 12.5% is attained. This maize variety was obtained from Farm and City Agricultural Shop in Mutare and is produced by SeedCo Africa in Zimbabwe.

Statistical analysis

Data on maize grain and stover yields data, water productivity and agronomic N use efficiency were tested for normality and subjected to analysis of variance (ANOVA) using GenStat Statistical package 2003 version. The main factor was RWH with N fertiliser rates as sub-plot factor and distance from RWH as blocking factor. Where there were significant differences the treatment means were separated using least significant differences (LSD) at 0.05 probability level. A cost benefit analysis was also done to compare cost of production at different N application rates to returns.

Results

Soil characterisation

The soils are classified as loamy sand (Table 1). Soil has low water-holding capacities, with a permanent wilting point of 6% and a field capacity of only 22% (on-site measurements using Meter, ZL6 cloud data loggers), low soil organic carbon (SOC) and nutrient contents (i.e., low nitrogen and phosphorus content) and the soil pH is acidic. Soil from the experimental plots was classified as sandy, 94% sand, 3% silt and 3% clay. The soil was acidic (pH = 5.3) (Table 2).

Maize grain yield, biomass yield and return on investment

Table 3 summarises the analysis of variance (ANOVA) of maize grain yield, biomass yield and return on investment of two rainwater harvesting techniques, seven varying nitrogen fertiliser application rates and distance from RWH technique over three cropping seasons (2015/16 to 2017/18). Maize grain and biomass yield were significantly influenced ($p < 0.05$) by main treatment factors (Table 3). Return on investment was significant

Table 2 Primary soil characterisation at Mt Zonwe in Marange

Sand	82%
Silt	14%
Clay	4%
Textural class	Loamy sand
pH (water)	5.3
Organic carbon (%)	1.4
Total nitrogen (%)	0.1
Available phosphorus (mg/kg)	4.2

on all other main factors except distance from RWH techniques which was insignificant ($p > 0.05$). However, significant interaction ($p < 0.05$) between the treatments, on the other hand, explains the grain yield discrepancies (Table 3).

Interactions of RWH and N fertiliser application

Increasing N fertiliser rates and RWH resulted in increased maize yields compared to increasing the STDC practice at same fertiliser application rates (Fig. 6). Grain yield was not significant ($p > 0.05$) in 2015/16 cropping season and even effects of RWH and N alone were not significant during this season. Grain yield increased significantly ($p < 0.05$) as influenced by interaction of RWH and N fertiliser during 2016/17 and 2017/18 cropping seasons (Fig. 6). At N rates of 300 kg N ha^{-1}, water harvesting resulted in yield increase of 27–30% above the yields of STDC during the 2015/16 season, 82 and 121% above those observed in the STDC, during the 2016/2017 cropping season.

Effects of season and RWH on maize yield increment compared to STDC

Rainwater harvesting consistently resulted in higher maize yields compared to STDC ridges across seasons. In the 2017/2018 cropping season, RWH resulted in yield increases of between 42 and 97% compared to the STDC (Table 4). TC resulted in a yield increase of between 32 and 100% (23% for 2015/2016, 100% for 2016/2017 and 65% for 2017/2018) when compared to the STDC. Under IP, yields increased maize yields were 23%, 69% and 38% higher compared to STDC for the 2015/2016, 2016/2017 and 2017/2018 seasons respectively.

Effects of RWH practices and distance from RWH structures on maize yields

There were significant interactions ($p < 0.05$) for RWH and distance from the RWH structure on maize grain yields during 2016/17 cropping season except for STDC. During the 2015/16 and 2017/18 season, there were no significant yield differences in maize yields as distance increased under RWH practices and the STDC (Fig. 7). The effects of distances from RWH on maize grain yields varied from season to season. However, significant effects ($p < 0.05$) of RWH and distance from RWH structures were noted (Table 5). At 0–5 m and 10–15 m, TC and IP did not show significant differences on maize grain

Table 3 Summary of ANOVA of maize grain yield under RWH methods and nitrogen application rates across three seasons (2015/16 to 2017/18)

Source of variation	Grain yield	Biomass yield	Return on investment	NUE	WUE
RWH method	*	*	*	*	*
N application rate	*	*	*	*	ns
Season	*	*	*	ns	*
Distance from RWH method	*	*	ns	ns	ns
RWH method × N	*	*	*	*	ns
RWH method × season	*	*	*	ns	*
N × season	*	*	*	ns	ns
RWH method × distance from RWH method	*	*	ns	ns	ns
N × distance from the RWH method	*	ns	ns	ns	ns
Distance from RWH method × season	*	ns	ns	ns	ns
RWH method × N × season	*	ns	*	ns	ns
RWH method × N × distance from RWH method	ns	ns	ns	ns	ns
RWH method × season × distance from RWH method	*	*	ns	ns	ns
N × season × distance from RWH method	ns	ns	ns	ns	ns
RWH method × N × season × distance from RWH method	ns	ns	ns	ns	ns

ns, not significant; RWH, rainwater harvesting method; N, nitrogen, NUE, nutrient use efficiency; WUE, water use efficiency

* Significant at $p \leq 0.05$

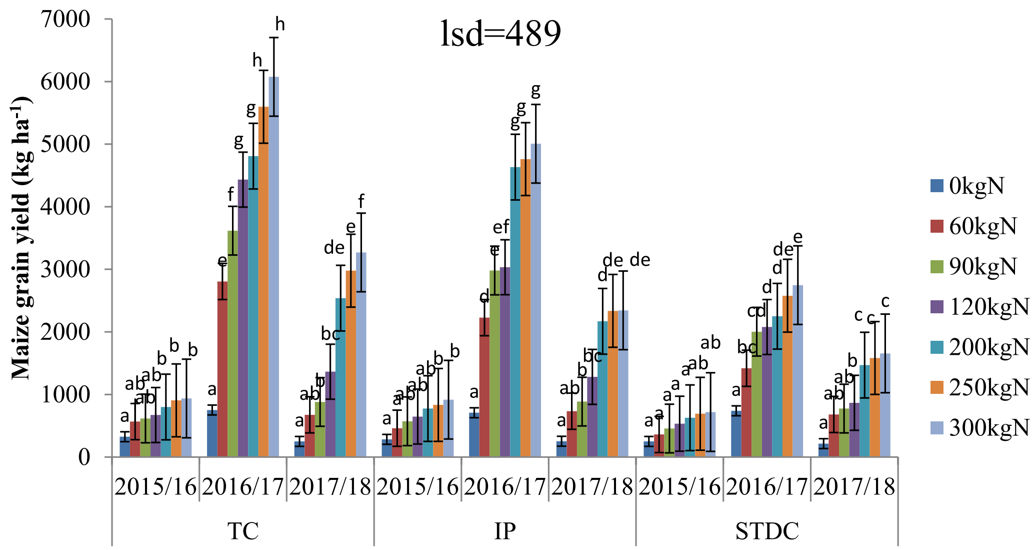

Fig. 6 Interaction effects of RWH and N fertiliser on grain yields. Vertical bars represent standard error (SE). Bars with different superscripts (a–g) show significant different at p ≤ 0.05

Table 4 Yield increment due to TC and IP above STDC

	2015/2016	% increase above STDC	2016/2017	% increase above STDC	2017/2018	% increase above STDC
TC	936	30%	6057	121%	3269	97%
IP	916	27%	5006	82%	2344	42%
STDC	719		2747		1656	

TC, Tied contour; IP, infiltration pits; STDC, standard contour

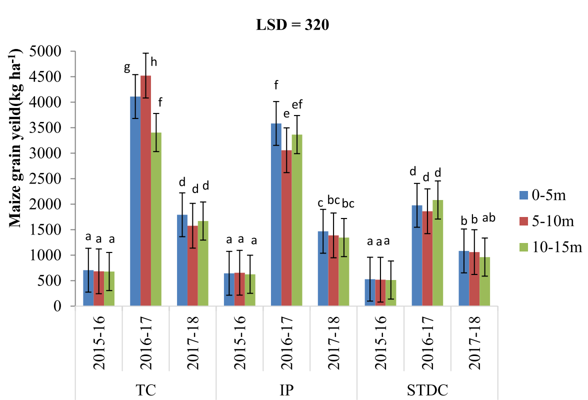

Fig. 7 Effects of RWH technology, season and distance from the RWH structure on maize yields. TC, Tied contour, IP, infiltration pits; STDC, standard contour. Vertical bars represent standard error (SE). Bars with different superscripts (a–h) show significant different at p ≤ 0.05

yields although higher yields were obtained from TC treatments. Three-year mean shows significant effects on maize grain yields with lowest yields obtained from STDC treatments.

Table 5 Effects of distance from contour on maize grain yields

RWH methods	0–5 m	5–10 m	10–15 m	Three-year mean
Maize grain yields (kg ha^{-1})				
TC	2202^a	2261^a	1917^a	2126.67^a
IP	1898^a	1700^b	1779^a	1792.33^b
STDC	1196^b	1147^c	1185^b	1176^c
LSD (0.05)	320	320	320	320
P value	< 0.05	< 0.05	< 0.05	< 0.05

Means in the same column followed by the same superscript are not significantly different at P ≤ 0.05

Nitrogen use efficiency (NUE)

Rainwater harvesting resulted in increased NUE, when compred to STDC. TC had a higher NUE compared to IP and the STDC (Table 6). At 60 kg of N, the NUE values obtained were significantly better than any other application rates. There was no nutrient use efficiency benefit for using ≥ 200 kg N ha^{-1} in combination with TC and IP because the results show no significant

Table 6 Nitrogen use efficiency for the tied contour (TC), infiltration pits (IP) and standard contour (STDC)

N applied (kg ha^{-1})	60	90	120	200	250	300
TC	16.22[a]	14.77[a]	14.83[a]	11.70[a]	11.14[a]	10.17[a]
IP	13.22[b]	12.58[b]	10.88[b]	10.89[a]	9.18[a]	8.03[a]
STDC	6.98[c]	7.52[c]	6.32[c]	5.24[b]	4.87[b]	4.35[b]
LSD (0.05)	2.15	2.15	2.15	2.15	2.15	2.15
P value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

Table 7 Effects of RWH on WUE over three cropping seasons

RWH	WUE (kg ha^{-1} mm^{-1}) 2015/16	2016/17	2017/18
TC	1.77[a]	6.08[a]	1.79[a]
IP	1.64[a]	5.05[b]	1.49[b]
STDC	1.33[b]	2.99[c]	1.11[c]
LSD (0.05)	0.14	0.1	0.25
P value	<0.05	<0.05	<0.05

Tied contour = TC), infiltration pits = IP and standard contour = STDC

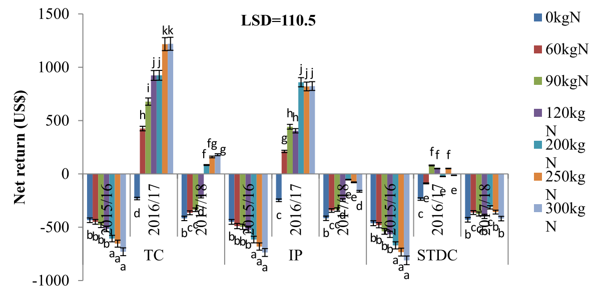

Fig. 8 Effects of RWH, N fertiliser and season on return on investment. Vertical bars represent standard error (SE). Bars with different superscripts (a–g) show significant different at $p \le 0.05$

differences. NUE decreased with increasing N fertiliser application rates (Table 6).

Water use efficiency

Water use efficiency (WUE) varied with season, and 2016/17 season had a higher WUE compared to the other 2 seasons. During the 2015/16 season WUE ranged from 1.0 to 1.8 kg ha^{-1} mm^{-1}, while it was 3.0–6.1 kg ha^{-1} mm^{-1} for the 2016/17 cropping season and 1.1–1.8 kg ha^{-1} mm^{-1} for the 2017/2018 season (Table 7). Water harvesting increased WUE, and there were no significant differences in WUE between TC and IP in 2015/16 cropping season. Water productivity varied significantly lower ($p < 0.05$) from STDC compared with TC and IP (Table 7).

Return on investment

Return on investment was lowest in 2015/16 cropping season compared to other seasons (Fig. 5). Results show that RWH practices and fertilisers use it are not profitable during low rainfall seasons due to little on no rainfall. During low rainfall season (2015/16), return on investment was negative for all practices, meaning that total costs were higher than total benefits with a lowest of US$-810.47 from STDC (Fig. 8). During wet season (2016/17), return on investment increased with increasing N application rates for TC and IP with STDC showing positive values at 90, 120 and 250 kg N ha^{-1} respectively. Net return appears to increase linearly, especially in case of TC. The highest (US$1219.94) was observed from TC + 300 kg N ha^{-1} which was significantly different ($p < 0.05$) from all application rates below 250 kg N ha^{-1} over three cropping seasons (Fig. 8).

Plant biomass

Plant biomass was sampled at harvest time. The plant biomass varied significantly among RWH practices and was higher in TC when compared to IP. However, plant biomass observed in the IP was not significantly different from STDC. The average biomass yields were 2286 (STDC), 2624 (IP) and 3057 kg ha^{-1} (TC). There was a significant variation in biomass among cropping seasons, with the highest amounts of biomass being observed during the 2016/2017 season and least during the 2015/2016 cropping season (Fig. 9).

Biomass production also varied with N application rates. Biomass yield increased with increasing N rates, with the highest amounts of biomass being observed in plots with N application rates of 300 kg N ha^{-1} (Table 8). During lean seasons such as 2015/2016 low biomass productivety also resulted in low maize yields, while in years when there was pleanty of rainfall, both biomass and maize grain yields were high.

Biomass yield varied from distance to distance in combination with RWH techniques. Treatments with TC had the highest biomass yield at a distance of 5–10 m which was 793 kg ha^{-1} and 1998 kg ha^{-1} above IP and STDC respectively (Fig. 10). Distance from RWH techniques did not have any effects on biomass

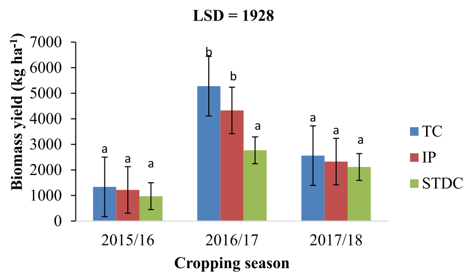

Fig. 9 Effects of RWH and season on biomass yield. Vertical bars represent standard error (SE). Bars with different superscripts (a–b) show significant different at p ≤ 0.05

Table 8 Effects of N fertiliser on biomass yield over three cropping seasons

N fertiliser (kg ha^{-1})	Biomass yield (kg ha^{-1}) 2015/16	2016/17	2017/18
0	519^{a}	1176^{b}	573^{c}
60	911^{a}	2986^{b}	1491^{bc}
90	1053^{a}	3785^{b}	1604^{bc}
120	1185^{a}	4189^{ab}	2025^{abc}
200	1394^{a}	5018^{ab}	3139^{ab}
250	1520^{a}	5625^{ab}	3258^{ab}
300	1651^{a}	6092^{a}	3576^{a}
LSD (0.05)	1928	1928	1928
P value	ns	< 0.05	< 0.05

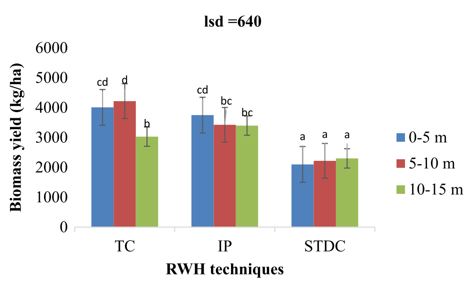

Fig. 10 Effects of RWH and distance on biomass yield. Vertical bars represent standard error (SE). Bars with different superscripts (a–b) show significant different at p ≤ 0.05

yield when using STDC and STDC + all distances had significantly low biomass yield.

Combined effects of RWH, season and distance from RWH techniques significantly affected biomass yield (Fig. 11). Wet seasons are more beneficial when using TC and IP at all distances as compared with STDC. The 2015/16 cropping season had the lowest biomass yield under all RWH techniques and distances from RWH and the results were insignificant between distances. Tied

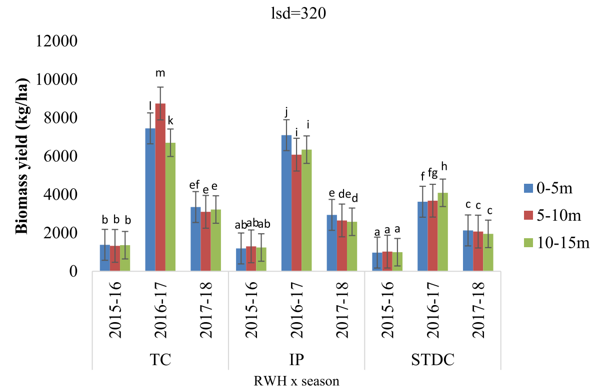

Fig. 11 Effects of RWH, season and distance on biomass yield. Vertical bars represent standard error (SE). Bars with different superscripts (a–b) show significant different at p ≤ 0.05

contour were beneficial at a distance of 5-10 m during wet seasons, with IP having higher biomass yield at 0-5 m and SDTC at 10-15 m during same season (Fig. 11).

Discussions

Effets of RWH structures and N fertiliser on maize grain yields

The use of water harvesting technologies resulted in increased maize yields from 2016/17 season with no significant effects during 2015/16 cropping season. This could be attributed to low rainfall received during 2015/16 cropping season which was associated with frequent dry spells (Kubiku et al. 2022a; Chiturike et al. 2023). Increasing soil water content has the potential of improving nutrient uptake, reduce moisture and drought strees hence boosting maize productivity (Dunjana et al. 2012; Nyagumbo et al. 2009). Resource constrained farmers who cannot afford irrigation can adopt low-cost RWH in semi-arid regions to mitigate climate change and improve crop production (Nyamadzawo et al. 2013; Kugedera and Kokerai 2023). Water captured by TC and IP increase infiltration, reduce surface runoff and make more water available in the plant root zone (Rockstrom et al. 2009; Motsi et al. 2004; Kugedera et al. 2022a, 2023b).

High variability of maize yields between seasons was mainly caused by variation in rainfall received during these seasons, which is a common characteristic in semi-arid regions of Zimbabwe, with distribution varying from 20% in the north to 45% in the south of the country (Nyagumbo et al. 2019a, b). This was also the case in Tanzania where crop production varied between seasons due to amount of rainfall received (Swai et al. 2023). Kugedera and Kokerai (2023) also observed same effects in Zimbabwe with the use of tied ridges and planting pits.

Tied contour and IP are good examples of the promising low-cost approaches of supplementing soil moisture where rainfall is inadequate to meet crop production requirements (Nyagumbo et al. 2019a, b). Furthermore, these are among measures that can be used to reduce the impacts of climate change on crop production in low rainfall areas (Nyagumbo et al. 2009; Gumbo et al. 2012; Kugedera et al. 2022b). Tied contour harvest more water compared IP and STDC, this may be the reason why TC had higher yields than other methods (Kugedera et al. 2023b). Tied contour used during this study holds approximately 2.125 m^3 of water ($5 \times 1.7 \times 0.25$ m), compared to 0.5 m^3 ($2 \times 0.5 \times 0.5$ m) under IP. On a 30 m block for TC, five compartments used hold a maximum of 10.625 m^3 of water compared to 6.0m^3 from 12 IP under same block. The low maize yields observed under the STDC can be attributed to low to no water retention, as this structure disposes of water instead of retaining it. The results showed that water harvesting increased water productivity, compared to STDC Similar findings were reported in Shurugwi by Nyagumbo et al. (2019a, b) with the use of TC and IP.

Application of N fertiliser improved maize grain yields during wet season because availability of water in the soil promotes nutrient absorption and reduce water stress (Kugedera et al. 2022c). Mineral fertiliser quickly releases nutrients which can be immediately used by plants. Increasing N fertiliser up to 300 kg N ha^{-1} had better yields in 2016/17 season due to high rainfall received. This was similar to results by Chiturike et al. (2023) who reported better maize yields in 2016/17 season regardless of nutrient source applied. It becomes more important to use low N content to reduce wastage, increase nutrient efficiencies and crop yields (Desta et al. 2022). In low rainfall areas, it is paramount to combine RWH structures and N fertiliser to improve soil water and nutrient content leading to improved grain yields. However, application of 60 kg N ha^{-1} can be sustainable for smallholder farmers especially during wet seasons since a yield of 3617 kg ha^{-1} was obtained. This can be improved by increasing cattle manure from 8 to 20 t ha^{-1} to improve soil structure, water retention, buffer soil pH and reduce cost of production caused by more quantities of N fertiliser. Kugedera and Kokerai (2023) reported that application of high quantities of cattle manure improve soil fertility and nutrient availability. Increasing quantity of cattle manure applied, depth and with of RWH techniques from 0.5 to 1 m can increase volume of water captured and improve water content in the soil especially dry seasons.

Effect of distance from RWH on maize yield

The distance from the water harvesting structure to the plots affected maize production but depending on season. During the 2015/2016 season, distance did not affect yields, while effects were noted in 2016/2017 and 2017/2018 cropping season due to better amounts of rainfall received in these seasons. Improved yields under rainwater harvesting practices were attributed to a greater moisture sphere of influence down slope (Mugabe 2004). When there is enough rainfall, distances did not affect crop yields due to availability of water across all plots. effects of distances were mainly noted in TC and IP because these harvest a lot of water and more water will be available to plots closer to these structures (Kubiku et al. 2022a). Similar results where greater soil moisture yields closer to the water harvesting structures were also reported by (Nyagumbo et al. 2019a, b). These RWH technologies provide temporal water storage that allows water to infiltrate, while STDC diverts water out of the field. However, as distance increases, the water stored in the soil will diminish due to crop uptake. In semi-arid Gwanda, Gumbo et al. (2012) reported an effective distance of 15 m from the water harvesting structure. More available moisture at distances closer to drainage catchment area has been reported to be higher compared to positions further away due to increased distance of lateral flow (Gumbo et al. 2012; Nyagumbo et al. 2019a, b; Kubiku et al. 2022a). The results are in agreement with earlier findings by Motsi et al. (2004), Mugabe (2004) and Kubiku et al. (2022a) who reported that access tubes at positions close to a rainwater harvesting techniques had more soil moisture than those far away. Reduced yields as distance from rainwater harvesting structure increased may be related to lower water availability and reduced nitrogen uptake compared to positions closer to moisture sources (Soon and Malhi 2005).

Effects of RWH and N fertiliser on return on investment

Benefit cost ratio (BCR) for each treatment increased with increase in N application rates during wet season due to improvements in nutrient availability and absorption by plants. This translated to improved plant growth and development leading to higher yields. Higher yields were transformed to high total benefits. Total benefits surpass total costs when higher yields were obtained and this led to higher BCR (Kimaru-Muchai et al. 2021). Higher BCR were observed from 2016/17 cropping season, this could be attributed to higher water productivity observed during this season. Higher BCR with increasing N fertiliser up to 120 kg N ha^{-1} + RWH practices maybe attributed to better NUE at low application rates (Desta et al. 2022; Kugedera et al. 2023a).

Low return on investment during 2015/16 and 2017/18 was due to low rainfall, low water productivity and low grain yields which gave low total benefits compared to total costs used. Standard contours proved to be non-profitable, that's why farmers have abandoned them. Results from this study were in agreement to observations by Kugedera et al. (2023c) who reported low net return with the use of STDC in Chivi, Zimbabwe. Even during wet season, STDC proved to give negative return on investments due to higher costs needed to construct them and they dispose-off water leading to low yields and total benefits. Only TC proved to be effective during wet season when combined with 90 kg N ha^{-1} which gives return on investment greater than total costs. Return on investment is positively linked to BCR where all treatments with BCR > 1.3 gave positive returns.

Conclusions

Rainwater harvesting increased maize yields compared to the STDC practice. The margin of yield increase varied with season. Among the RWH techniques, TC RWH technology had consistently higher yields than IP. The use of INM, where cattle manure was applied as basal fertilizer and ammonium nitrate was applied as a top-dressing to supply N, resulted in a further increase in maize yield. The application of increasing levels of N fertilizer rates (N intensification) showed that maize yields increased with an increase in N rates. The most significant yield increases were in TC at N rates of 300 kg ha^{-1}. Smallholder farmers are recommended to use TC with 200–300 kg N ha^{-1} due to high grain yields and high net return. These rates can be obtained by combining 15–20 t ha^{-1} cattle manure with 250 kg ha^{-1} of ammonium nitrate. The use of RWH integrated use of cattle manures and increasing N levels all increased water use efficiency and water productivity in rain-fed agriculture systems in the semi-arid regions. This system is sustainable as it lowers cost of production through reducing the amounts of inorganic basal fertiliser inputs which are substituted with organic sources. Benefit cost ratio was highest from TC + 120 kg N ha^{-1}, with STDC having higher BCR at 90 kg N ha^{-1}. This can be a sustainable level for smallholder farmer to apply N fertiliser to maximise food production, low cost of production and increase farm profitability. These systems, therefore, represent sustainable, innovative and easy to use climate-smart farming practices that can increase crop production under smallholder farmer conditions in marginal semi-arid regions.

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Author contributions
GN and PC designed the field experiment. PC collected data from the field. GN and ATK, PC, JG, ATK, GN, IWN, FNMK and NC wrote the paper. SMM, FNMK and RM analysed the. All authors contributed equally on the final manuscript.

Data availability
The data is available on the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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