Effects of tillage on runoff from a bare clayey soil on a semi-arid ecotope in the Limpopo Province of South Africa

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Abstract

Runoff constitutes one of the major water losses from agricultural fields in semi-arid areas. However, by adopting appropriate soil management practices, the runoff can be harnessed for improving crop yields. The main objective of this study was to quantify rainfall-runoff relationships under in-field rainwater harvesting (IRWH) using simulated rainfall, and to compare these results to those obtained with annually tilled conventional tillage (CON) (control). IRWH is a special type of no-till (NT) crop production practice that promotes runoff from a crusted runoff strip into basins where the water infiltrates beyond evaporation but is available for crop use. Runoff was related to time to runoff, total runoff, final runoff rate and runoff coefficient. This experiment demonstrated that by adopting IRWH production technique smallholder farmers could harness an additional 45.54 $m^3 \cdot ha^{-1}$ of water compared to the CON system. The extra water harvested could meet about 1% of maize water requirements.

Keywords: Limpopo Province; no-tillage; runoff; rainfall simulation; rainwater harvesting

Introduction

Water scarcity is a major constraint in semi-arid areas, leading to a natural focus on in-field rainwater conservation (Jensen et al., 2003). Runoff constitutes one of the major water losses in semi-arid areas, causing the loss of valuable water, soil and nutrients (Schiettecatte et al., 2005; Vahabi and Mahdian, 2008). Research results from semi-arid regions have shown that runoff losses can be as high as 50% of the rainfall on bare untilled lands (Stroosnijder, 2003). Excessive runoff not only limits the water available for crop production, but also constitutes an erosion hazard (Rao et al., 1998). However, the goal of water harvesting (WH) is to convert runoff water 'loss' into productive use by storing it in basins where it can infiltrate and become available for crop use (Hensley et al., 2000). Water harvesting, based on the collection of runoff from a prepared catchment surface and its storage in the adjacent crop area, has been used successfully for crop and tree improvement in other parts of the world (Li et al., 2000; Li and Gong, 2002; Schiettecatte et al., 2005). Among the various water harvesting technologies available, in-field rainwater harvesting (IRWH) has been shown to be an efficient water conservation crop production technique especially appropriate for rural poor households (Botha et al., 2003). It was therefore selected for this study.

In-field rainwater harvesting (IRWH) is a relatively new *in-situ* water harvesting technique developed in South Africa (Hensley et al., 2000). The IRWH system is regarded as a special form of water harvesting. It is also known as mini-catchment runoff farming (Oweis et al., 1999). IRWH has been tested in South Africa on clay and duplex soils in semi-arid areas where it has given maize yield increases of between 25% and 50% compared to conventional tillage practices (Hensley et

al., 2000; Botha et al., 2003). The technique is illustrated in Fig. 2. The technique combines the advantages of water harvesting from the no-till, flat, crusted runoff strip, and decreased evaporation from the deeply infiltrating runoff water which accumulates in the basin (Hensley et al., 2000). Thus the IRWH partitions rainfall into runoff (on the no-till runoff strip) and run-on (in the basin).

Runoff is an important water balance component in semi-arid environments (Bennie and Hensley, 2001). Zere et al. (2005) used runoff data to simulate the long-term yields for crops planted on conventional tilled soil and under in-field rainwater harvesting on Glen/Tukulu ecotope. They concluded that the PutuRun Model can be used with reasonable confidence, after calibration, to simulate long-term runoff on conventionally tilled and bare untilled plots on the Glen/Tukulu ecotopes, using daily rainfall data. In Ethiopia, Welderufael et al. (2008) used 2-year runoff data to predict a maize yield increase of between 25% and 35% under IRWH compared with conventional tillage. Some rainfall-runoff relationships from semi-arid ecotopes are summarised in Table 1. The research results presented in Table 1 clearly indicate that the IRWH technique is a promising soil management technology under certain soil conditions, and that it needs to be explored further to promote sustainable crop production in marginal areas.

Results obtained with water harvesting techniques are not always transferable from one set of conditions (i.e. from a particular ecotope) to another, because of the differences in local characteristics (Ojasvi et al., 1999). An ecotope has been described as an area of land on which the climate, topography and soil are reasonably homogenous (McVicar et al., 1974). Considerable IRWH research has been done on specific ecotopes in the Free State Province of South Africa. It is, however, uncertain how the technique will perform on Ferralsols in the Limpopo province.

The agricultural industry in the Limpopo Province is made up of 2 sectors, namely, the large scale commercial and the smallholder farming systems. There were 5 000 commercial farming units and 273 000 small-scale farmers operating in

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					TABLE 1			
					Summarised measured rainfall-runoff relationships from annually tilled and bare crusted soils on semi-arid ecotopes			
Site	Measured period (yr)	Average Rainfall (mm·yr⁻¹)*	Slope (%)	Description of the top soil	Tillage treatment	Runoff as percentage of rainfall	Reference	
Glen (SA)	18	508	5.0	Orthic, red 11% clay	No-till, bare, flat crusted surface	29	Zere et al. (2005)**	
Glen (SA)	18	508	5.0	Orthic, red 11% clay	Annual maize, conventionally tilled	7	Zere et al. (2005)***	
Pretoria (SA)	27	721	3.8	Orthic, red sandy loam	Tilled and left bare	24	Bennie and Hensley (2001)	
Pretoria (SA)	27	721	3.8	Orthic, red sandy loam	Continuous maize	27	Haylett (1960)	
Glen (SA)	6	500	1.0	Melanic, dark brown, 45% clay	No-till, bare flat crusted surface	29.2	Hensley et al. (2000) and Botha et al. (2003)	
Glen (SA)	3	501	1.0	Melanic, dark brown, 45% clay	Conventional-tilled and left bare	3.6	Hensley et al. (2000)	
Glen (SA)	3	538	1.0	Melanic, dark brown, 45% clay	No-till, bare, stone mulch	25	Botha et al. (2003)	
Glen (SA)	3	538	1.0	Melanic, dark brown, 45% clay	No-till, bare, organic mulch	6	Botha et al. (2003	
Glen (SA)	6	500	1.0	Orthic, dark brown, 38% clay	No-till, bare, flat, crusted surface	29.9	Hensley et al. (2000) and Botha et al. (2003)	
Glen (SA)	3	501	1.0	Orthic, dark brown, 38% clay	Conventional tillage and left bare	3.9	Hensley et al. (2000)	
Glen (SA)	3	533	1.0	Orthic, dark brown, 38% clay	No-till, bare, stone mulch	20	Botha et al. (2003)	
Glen (SA)	3	533	1.0	Orthic, dark brown, 38% clay	No-till, bare, organic mulch	4	Botha et al. (2003)	
Dera (Ethiopia)	2				No-till, bare, flat, crusted surface	46	Welderufael et al. (2008)	
Dera (Ethiopia)	2				Conventional tillage and left bare	39	Welderufael et al. (2008)	

*Average rainfall per annum that occurred during the measurement period; ** reporting re-worked original data of du Plessis and Mostert (1965);*** reporting original data of Haylett (1960)*

the Limpopo Province in the year 2000 (Statistics South Africa, 2000). It was estimated that agriculture contributed 4% to the gross geographical product (GGP) of Limpopo Province in 2002 and the smallholder sector provided about 43% of total agriculture income in the province. Smallholder farmers operate from the former homelands. However, it could not be established how many of these farmers cultivate on the Ferralsols. Nevertheless, previous studies indicate that the majority of small-scale farmers in the northern Vhembe District (study area) depend on the Ferralsols for crop and fruit farming (Simalenga and Mantsha, 2003). Vhembe District is largely rural and is one of the 5 districts in the Limpopo Province where a large village population relies on agriculture for their livelihood. The area is marginal for crop production because of relatively low and erratic rainfall. In Vhembe District research results have shown that the average yield of maize was 12 bags per ha, in a good year, and about 5 bags per ha in a bad year. Poverty and food insecurity is therefore a major challenge facing smallholder farmers in the province. One of the recommendations of Simalenga and Manstha's (2003) study was that the farmers need to adopt water management strategies to mitigate the effects of bad weather.

The hypothesis is that the IRWH technique will increase crop yield on the Limpopo Ferralsols, compared to conventional tillage, due to the fact that enhanced runoff on the flat, crusted no-till runoff strip shown in Fig. 2 will result in a large fraction of the rainfall being stored in the basins. The stored water will result in a higher rainfall-use efficiency than with annually tilled conventional tillage (CON), which will have ex-field runoff losses as well as higher water losses due to evaporation.

The main objective of this research was to quantify rainfall-runoff relationships on a clayey soil under IRWH using simulated rainfall of various intensities, and to compare these results to those obtained with CON. The study will improve our understanding of rainfall-runoff processes under 2 tillage practices and thereby provide insight into the constraints and potential of IRWH production technique on this ecotope.

Materials and methods

Site description

The study was conducted at the University of Venda experimental farm (approximate latitude 22°58'S and longitude 30°26' E; altitude 596 m a.m.s.l.) located at about 2 km west of Thohoyandou town in the Limpopo Province of South Africa. Thohoyandou falls under Thulamela Municipality in Vhembe region. A map showing the location of the study area is presented in Fig. 1. The study area falls within the eastern part
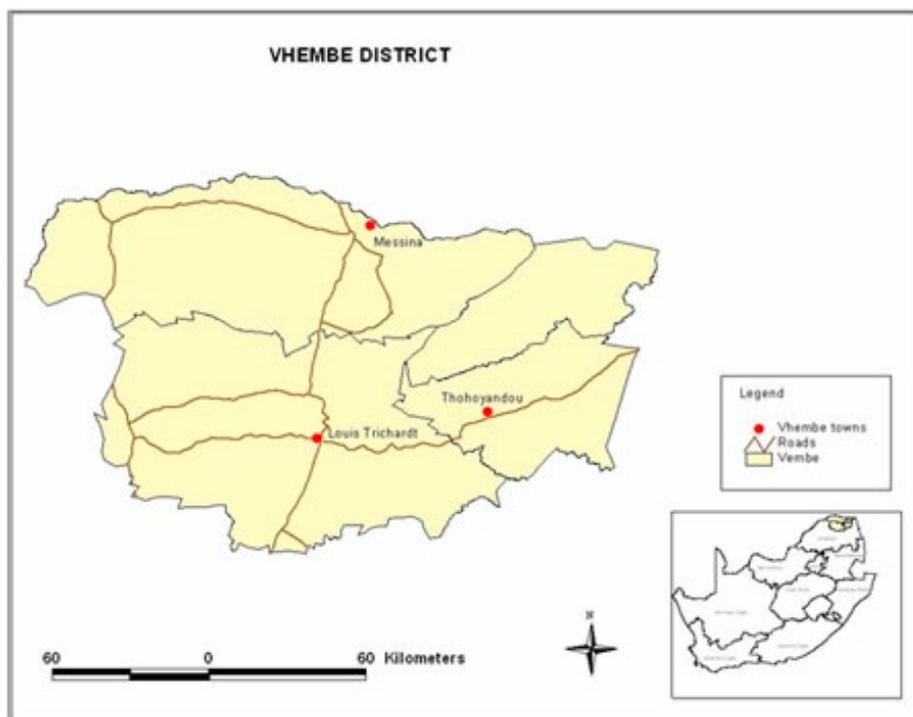
Figure 1
Location of the study area

of the lowveld which forms part of the greater Limpopo River basin. The experimental farm is 14 ha (arable) in extent on 8% gently undulating slopes running in a north-south direction. Rainfall is highly seasonal with 85% occurring between October and March (summer) (Table 2). The mean maximum temperature (T_{max}) is around 30°C while the mean minimum temperature (T_{min}) is about 20°C during the growing period. The highest evaporative demand also occurs from October to March. The mean annual aridity index (AI) is 0.52, causing the area to fall on the borderline between semi-arid and sub-humid according to the UNESCO classification criteria. Average rainfall is about 780 mm (range: 281 - 1 239 mm).

Three soil profiles were dug to depth of 1 500 mm on a research block measuring 100 m x 50 m. Soil profiles were described and classified locally as Hutton form, and belong to Land Type Ab179 (Soil Classification Working Group, 1991).

The approximate equivalent World Reference Base is Rhodic Ferralsol (WRB, 2006). Soil samples were taken from each demarcated horizon and analysed. Average results are reported. The soil profile is uniform and deeply weathered to a depth of >1 500 mm with no depth limiting material. The average clay content in the profile is 60% and is dominated by kaolinite (99%) clay minerals. The soil is also characterised by a relatively high silt content (>30%). Organic carbon is higher (1.7%) in the surface horizons than in the subsoil horizons (0.5%) (Table 3). Exchangeable cations are low and are dominated by Ca followed by Mg, Na and K, in that order. Despite their high clay content, these soils have low bulk density, ranging between 1.1 and 1.2 Mg·m^{-3} (Table 3). The low bulk density could partly be explained by high organic matter in the surface horizons and by the micro-structure typical of Ferralsols (Medina et al., 2002). Water holding capacity is considered high due to the high clay content.

TABLE 2
Long-term (1983-2005) monthly rainfall for Thohoyandou (22° 58' S, 30° 30' E)

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
T_{max} (°C)	30.8	30	29.6	27.6	26.2	23.6	23.7	25.4	27.2	27.5	28.9	30	27.6
T_{min} (°C)	19.9	19.7	18.9	16.4	12.7	9.9	9.8	11.7	14.2	16.3	17.6	19.4	15.5
T_{mean} (°C)	25.3	24.8	24.2	22.0	19.4	16.8	16.8	18.6	20.7	21.9	23.3	24.7	21.5
Rainfall (mm)	135	134	92	40	18	12	8	8	25	64	98	140	781
ETo (mm)	158	157	149	104	96	74	85	111	126	143	127	177	1507
Aridity index	0.85	0.85	0.62	0.38	0.19	0.16	0.10	0.10	0.20	0.44	0.77	0.79	0.52

TABLE 3
Selected physical and chemical soil properties of the experimental site

Horizon depth (mm)	Particle size distribution %							Soil texture	Bulk density (Mg·m^{-3})	pH (H$_2$O)	Organic carbon (%)	Extractable cations <----------(cmol$_c$ (+) kg^{-1})---------->			
	cSand	mSand	fSand	vfSand	cSilt	fSilt	Clay					Na	K	Ca	Mg
0 - 300	1.7	2..3	4.1	4..2	4.0	26.2	57.5	Clay	1.11	5.4	1.71	0.12	0.09	2.12	1.24
300 - 600	1..5	1..5	2..8	3..2	9.4	20.7	60.9	Clay	1.140	5.4	0.72	0.10	0.04	1.48	0.95
600 - 1500	1.8	1..5	3.0	3..2	9..2	21.1	60.2	Clay	1.20	5.5	0.52	0.12	0.03	1.01	0.78

c = coarse; m = medium; f = fine; v = very
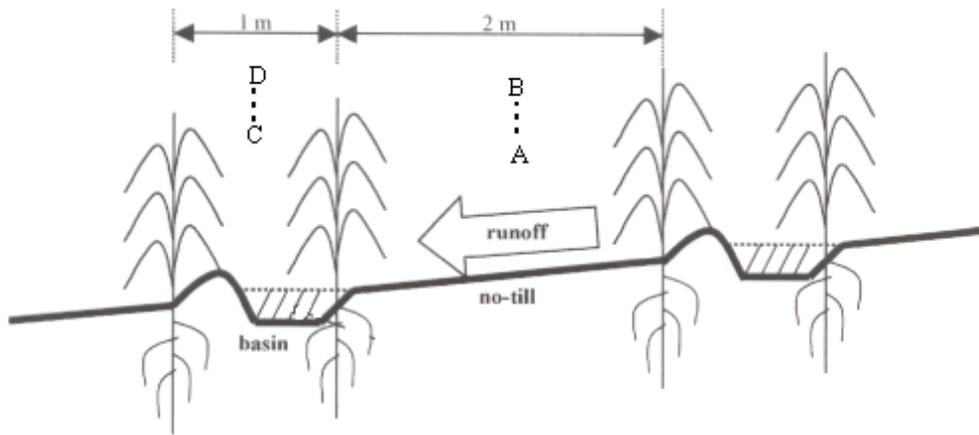
Figure 2
Diagrammatic representation of the in-field rainwater harvesting technique, showing distribution of access tubes (A, B, C, D) for measuring soil water. Row spacing and access tube distribution was similar in CON treatments (after Hensley et al., 2000).

Description of IRWH system

Two distinct areas can be seen from the diagram (Fig. 2): a 2-m catchment area or runoff strip and a 1-m basin or collection area. The runoff area is sloped towards the basins to direct the surface water into them. Runoff created in this way is called in-field, which differs significantly from ex-field runoff that occurs with CON; in-field runoff can be harnessed positively and used to enhance water conservation and therefore sustainability. Raindrop impact on the runoff strip causes surface compaction and therefore contributes to the formation of soil crusts, which stimulates in-field runoff. No-till is practised on the runoff strip to maintain a smooth surface (Hensley et al., 2000). The use of a 2:1 surface area ratio between the runoff and basin area is based on field experience with crops in a semi-arid environment. Crops are planted in tramlines (1 m x 2 m wide) along the basins or collection area. Tramline planting is also based on standard maize practices in the eastern Free State region of South Africa.

The role of the basin area is to: stop ex-field runoff; maximize infiltration; and store the harvested water in the soil surface beneath the basin. The basin acts as surface storage until the infiltration process is completed. The infiltrated water is stored in the rooting zone where it remains available for crop uptake but loss by evaporation is minimised.

Soil surface state characterisation

Surface (0-100 mm) soil water content was determined by gravimetric methods prior to rainfall simulation. The surface roughness index was determined in the 1 m x 1 m runoff plot with a 100 peg-board method (Zobeck and Onstad, 1987). Pegs of length 100 mm (pre-calibrated) with a diameter of 25 mm were evenly spaced on the 800 mm x 800 mm x 20 mm board, i.e. 10 x 10 holes with 60 mm intervals between rows and pegs. The holes in the board are made slightly wider than the pegs so that they can move freely. During measurements the board was placed at randomly selected sites on the soil surface and the vertical distance to the surface was then recorded for each peg. Three measurements were recorded for each plot. The mean value was taken as the roughness index of the surface.

The slope in the selected plots was determined following a simple method described in Bothma (2010). Two broomsticks, each 500 mm long were used for this purpose. One broomstick (A) was placed at the bottom slope with a cord attached 500 mm from the base of the broomstick. Another broomstick (B) was mounted at the top of the 2 m runoff area (Fig. 2). The cord from broomstick (A) was then stretched level to broomstick (B) using a spirit level. The difference in height from the soil surface at A and B was then used to calculate the slope.

Tillage treatments and historical background

The study focused on plots subjected to artificial rainfall. Treatments were:
- In-field rainwater harvesting (IRWH) (No-till)
- Annually tilled conventional tillage (CON)

The experimental site was established in 2005 in order to evaluate the effects of IRWH on sunflower-cowpea cropping systems. The experimental design was split-plot with IRWH and CON as main treatments and cropping systems as subplots. Three cropping systems were tested: sole sunflower (*Helianthus annuus* L.); sole cowpeas (*Vigna unguiculata* L.); sunflower-cowpea intercropping. In order to establish IRWH plots, the land was ploughed initially and then disced to obtain a fairly level surface. Spades and rakes were used to create the basins and runoff area. The runoff area was levelled so as to form a slope of nearly 8% by raking and then left undisturbed so as to develop a surface crust. Weeds were controlled by spraying with glysphosphate at a rate of 360 g·ℓ^{-1}. This was done both during the growing period and off season. The surface soon developed a crust which enhanced runoff into the basin.

On the CON plots conventional ploughing (including mouldboard plough and harrow disc) was done at the beginning of the experiment and was later hand dug to a depth of about 200 mm before planting every season. This was necessary so that the access tubes that were installed to monitor soil water content were not damaged. Weeding during the growing season was done using hand hoes.

The following plot surface characteristics were recorded before the simulation experiment:
- Slope – 8%
- Surface roughness (mm) – IRWH = 10; CON = 29
- Surface soil water content – 4% (by mass) for all plots.

Rainfall simulation experiment

Simulated rainfall allows for complete control of experimental conditions (Truman et al., 2007).

Rainstorms with specified intensities were simulated with the Hofrey rainfall simulator (Fig. 3.1). The design of the simulator was based on the oscillating overhead sprinkler type

Figure 3.1 (left)
Hofrey simulator assembly mounted on trailer

Figure 3.2 (below)
Hofrey simulator setup showing (a) closed compartment, (b) metal runoff frame, and (c) runoff collection

described by Classens and van der Walt (1993). This design produces a reasonable distribution pattern of raindrop sizes under field conditions. The Hofrey simulator has a closed compartment (Fig. 3.2a) with adjustable height of oscillating sprinkler nozzle. This simulator is equipped with pressure gauges and timer control for the oscillation of the sprinkler. In the closed compartment, a metal runoff frame (Fig. 3.2b) of 1 m by 1 m is inserted at 100 mm soil depth. On the downslope side of this frame is a gutter into which a pipe is connected for the purposes of runoff collection (Fig. 3.2c). The rainfall simulator fits on a trailer which can be towed by a vehicle.

The simulation experiment was conducted *in situ* on bare soil in September/October 2009, after crop harvesting in April. Two blocks of IRWH and CON were conveniently chosen from the eastern end of the experimental block because of their proximity to the source of electricity. Plots were randomly selected from IRWH and CON treatments. Gravimetric water content was measured in all plots earmarked for rainfall simulation at the beginning of the experiment. The plots were then covered in plastic sheets. The plastic sheets were removed on the day of the experiment. It was assumed that the plastic sheeting would keep away any rain and maintain soil moisture at the same level in the control and IRWH plots during the experiment. The experiment was completed in the shortest possible time so as to minimise any moisture variation. The 1 m^2 runoff plots were prepared in 3 replicates by forcing the frame to a depth of 100 mm into the soil and then installing both the gutter and container, in which runoff was collected using a measuring cylinder. The sprinkler chamber was then pushed into position before the desired rainstorm intensity was applied. Simulated rainfall was applied at constant intensity. Four rainfall intensities (RI) were applied (23, 33, 52 and 71 mm·h⁻¹) for a duration of 60 min. Although lower rainfall intensities (5, 10 and 15 mm·h⁻¹), close to the natural rainfall of the site, were simulated during the calibration of the equipment (calibration curve not presented), simulation using these rainfall intensities under field conditions consistently gave erratic and inconsistent results. It was therefore decided to use higher rainfall intensities than average intensities of the area. Although natural rainfall intensities at the study site are typically low (less than 20 mm·h⁻¹), the use of higher rainfall intensities were justified because infrequent heavy rains do occur at the study site (Mzezewa et al., 2010). Selection of rainfall intensities so as to
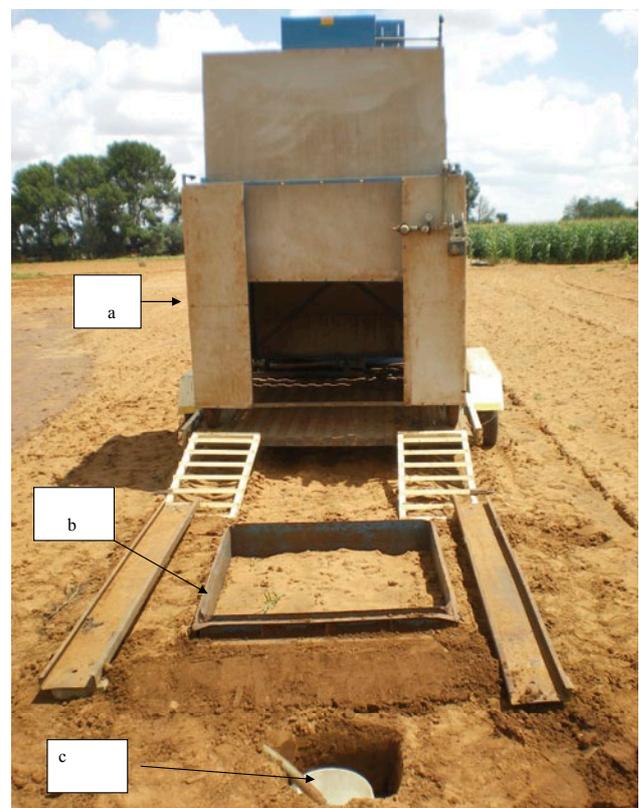
cover the full possible range is especially important in semi-arid areas where rainfall often occurs as short high-intensive storms (Hamed et al., 2002). The time till the first runoff occurred was recorded and samples were taken. Thereafter samples were taken every 5 min. Runoff was measured using measuring cylinders. Each rainfall event was replicated 3 times per plot. A total of 24 rainfall simulations were carried out (2 tillage systems x 4 rain intensities x 3 replicates).

Runoff parameters

Three indicators were used to study the runoff process, viz., time to runoff (min); total runoff (mm) during the simulation

period of 60 min; final runoff rates (mm·h^{-1}). The latter was estimated as the average of nearly constant (steady) 5-min readings with the smallest difference between them. Runoff coefficients were calculated as the ratio (%) of total runoff (mm) to total rainfall (mm) applied during the simulation period.

Statistical analyses

An analysis of variance (ANOVA) was conducted using SPSS version 17.0. (SPSS Inc., 2008). Mean separations were achieved by using Tukey's honestly significant difference (HSD). A probability level of less than 0.05 was designated as significant. If there was a statistically significant interaction between main effects of tillage and rain intensity, then the interaction was presented. Otherwise only the main effects of tillage were reported.

Results and discussion

Tillage effects

Time to runoff was significantly influenced by tillage practice (Table 4). Mean time to runoff in IRWH treatment was less than CON treatment by about 6 min or 48%. Total runoff was 1.7-fold higher in IRWH plots compared to CON plots, but the differences were not significant (Table 4). Short runoff time is beneficial for water harvesting especially on the study site where most of the rainfall comes in light showers (Mzezewa et al., 2010). A shorter hydrological response time from IRWH compared to CON strips was expected. This was attributed to the tillage effects. The formation of surface crust on the runoff strip of IRWH plots would result in early runoff compared to the CON treatment. Surface crust is a major factor in runoff generation (Philippe et al., 2001). No-till promotes surface soil sealing. Jin et al. (2008) reported that long-term application of no-till might lead to soil compaction, thereby increasing the runoff and decreasing infiltration. Higher total runoff under IRWH treatment was also attributed to low surface roughness (10 mm) on IRWH plots compared to CON (29 mm). The generation of runoff has been linked to soil-surface roughness (Carmi and Berliner, 2008). Guzha (2004) attributed higher runoff rates in no-till (NT) compared with other tillage systems due to lack of surface depressional storage. Lack of significant difference in total runoff between the 2 treatments in the current experiment may be attributed to the higher simulated rainfall intensities (23 - 71 mm·h^{-1}) compared to the natural rainfall normally received on the study site. High intensity rainfall could have caused slacking and collapse of clods in CON plots leading to the formation of a surface seal similar to that in IRWH plots, akin to the observation of Welderufael et al. (2008). Our results are in agreement with the findings

of Rao et al. (1998) who reported no significant difference in runoff between no-till with crusted surface and conventional tillage plots on an Alfisol. Lack of difference in runoff from the 2 tillage systems was attributed to structurally unstable crusting soils. In Ethiopia, Welderufael et al. (2008) measured runoff, resulting from natural rain, from flat, crusted no-till plots (similar to IRWH) and conventional tillage plots on a Fluvic Regosol during the 2003 and 2004 seasons. They found no statistical difference between the runoff for the 2 treatments. They attributed this to high rainfall intensity that probably caused the clods on the CON plots to disperse and slake quickly, promoting faster crust formation, and resulting in the soil surface having similar properties to that on the IRWH plots.

Final runoff rate was significantly affected by tillage system (Table 4). By the end of the simulation period IRWH plots were discharging significantly higher runoff (26.2 mm·h^{-1}) than CON plots (20.5 mm·h^{-1}) (Table 4). Runoff from IRWH plots is stored in the basins where it infiltrates for use by crops whilst runoff from CON plots is ex-field and ends up in river systems. Our results indicated that the IRWH technique offers advantages of water harvesting over CON systems, as previously reported (Hensley et al., 2000; Botha et al., 2003).

Tillage system had a significant effect on runoff coefficients (Table 4). The runoff coefficient in IRWH plots was 2.1-fold higher compared to CON treatment, as expected. Runoff coefficients obtained in this study are higher compared to those reported for similar production practices on some South African ecotopes (Table 1). Surface seal is the dominant factor in reducing infiltration in most African soils. The work of Stern et al. (1991) in South African soils demonstrated that kaolinite-dominated soils have the most stable aggregates, but the presence of smectites in small quantities may dramatically affect the degree of dispersion. This observation was corroborated by other researchers (Lado and Ben-Hur, 2004). Contrary to findings reported in the literature, soils at this study site which contain 99% kaolinite clay minerals produced higher runoff than those at Glen (38% and 45% clay) which contain a high proportion of smectite clay mineralogy (Hensley, 2000). The dispersion of soil colloids is also controlled by the nature and distribution of the exchangeable cations, of which sodium is the most dispersive cation. However, exchangeable sodium is low at this site (< 0.12 cmol^{+}·kg^{-1}) and therefore cannot be blamed for exacerbating the collapse of soil aggregates. The differences between runoff generated at this site and Glen could largely be attributed to the poor topsoil structure of Ferralsols at this site. The differences were also largely attributed to steeper slopes on the current experimental site (8%) compared to the flat slopes used in studies such as those reported in Table 1. High rainfall intensities simulated could have resulted in heavy raindrop impact that led to the collapse of soil aggregates and therefore higher runoff than expected. However, our results are

TABLE 4
Mean runoff, time to runoff and runoff coefficients as affected by tillage

Tillage treatment	Parameters				
	Time to runoff (min)	Total simulated rain (mm)†	Total runoff (mm)	Final runoff rate (mm·h^{-1})	Runoff coefficient (%)
CON	13.1a	45	13.5a	20.5a	30a
IRWH	6.8b	45	22.5a	26.2b	50b
SEM	0.9		3.3	0.7	5.7
Tillage x RI	*		n.s.	*	n.s.

SEM =standard error of mean; †Rainfall averaged across all RI's over the simulation period.
[a]Means not followed by the same letter in the same column are statistically different based upon Tukey's HSD means separation test at P < 0.05.
*significant at P < 0.05; n.s. not significant.
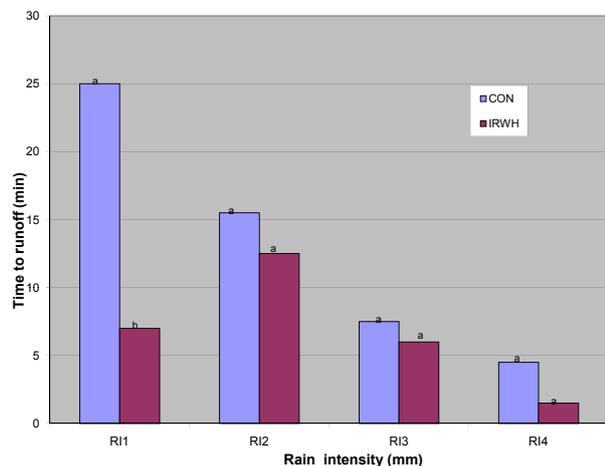
Figure 4
Time to runoff as a function of rain intensity and tillage treatment (RI1=rain intensity 23, RI2=rain intensity 33, RI3=rain intensity 52 and RI4=rain intensity 71 mm·h⁻¹). Means followed by different letters indicate significant difference at P < 0.05.

Figure 5
Final runoff rate as a function of rain intensity and tillage treatment (RI1=rain intensity 23, RI2=rain intensity 33, RI3=rain intensity 52 and RI4=rain intensity 71 mm h⁻¹). Means followed by different letters indicate significant difference at P < 0.05.

comparable to those of Welderufael et al. (2008) who reported that the ratios of runoff to precipitation (R/P) on NT plots and CON plots were 46 and 39%, respectively.

A high runoff coefficient means a high rate of runoff and therefore high potential for in-field water harvesting. Our results therefore indicate that the IRWH production technique is a promising water harvesting practice on this ecotope.

Tillage x rain intensity interaction effects

A significant tillage x rain interaction effect was observed on runoff time (Table 4; Fig. 4).

At rainfall intensity of 23 mm·h⁻¹, time to runoff was significantly shorter in IRWH compared to CON treatment. Runoff started after 7 min in IRWH plots compared to 25 min in CON treatment plots. The difference in runoff time could translate into a huge additional volume of water in the IRWH system compared to CON, on this type of soil. For example, in this case, on 1 ha of IRWH with 2 m runoff strips and 1 m basins (i.e. 66% runoff strips), a difference of 18 min before runoff is initiated (25 less 7) at a rainfall intensity of 23 mm·h⁻¹ would result in an additional 45 540 ℓ·ha⁻¹ or 45.54 m³·ha⁻¹. This would meet about 1% of the irrigation water requirements of maize, assuming maize water consumption of 5 840 m³·ha⁻¹, as determined at nearby Thabina smallholder irrigation scheme (Yokwe, 2009).

However, as the rain intensity increased, the differences between the treatments were not statistically significant. This could suggest that at higher rainfall intensities tillage system had less influence on time to runoff although time to runoff was consistently shorter in IRWH plots compared to CON plots throughout the simulation period (Fig. 4). The results suggested that under the experimental conditions, the time to runoff was always shorter on the IRWH treatment compared to the CON treatment, regardless of the rain intensity applied. This could also suggest that runoff was induced more easily under IRWH compared to CON treatment.

A significant tillage x rain intensity interaction effect on final runoff rate was observed (Table 4 and Fig. 5). Final runoff rate was significantly higher in IRWH compared to CON treatment at rain intensity of 33 and 51 mm·h⁻¹. No significant differences in final runoff rates were observed between tillage
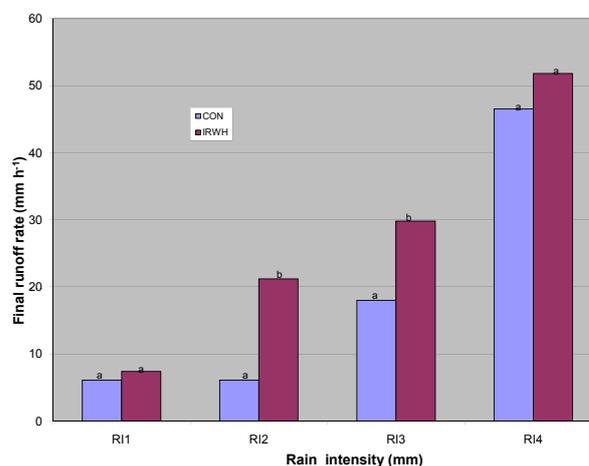
treatments at rain intensities of 23 and 71 mm·h⁻¹ (Fig. 5). A possible explanation for the lack of significant difference between the treatments at high rainfall intensity could be the effect of the high kinetic energy of raindrops, which could have destroyed the soil structure. However, lack of statistical significance at low intensity could not be explained. It is clear from Fig. 5 that the final runoff rate increased as rainfall intensity increased, as expected. Our observations were similar to the findings of Arnaez et al. (2007). It is also clear that the final runoff from IRWH treatment was consistently higher compared to CON treatment across all rain intensities. The results suggested that at any given rain intensity the IRWH technique harnesses more runoff compared to the CON treatment. The tillage x rain intensity results indicated that differences in hydrological response in the 2 tillage systems can be explained, in part, by differences in how the 2 tillage systems react to various rain intensities.

Conclusions

The IRWH production technique outperformed the CON system in harnessing runoff, confirming the findings from literature. We found that an enormous amount of water could be harvested from IRWH systems compared to the CON. This experiment demonstrated that by adopting the IRWH production technique smallholder farmers could harness an additional 45.54 m³·ha⁻¹ of water compared to the CON system. The extra water harvested could meet about 1% of maize water requirements. Based on the results of this study, IRWH could be used to improve crop water availability in disadvantaged rural smallholder farming communities on similar ecotopes.

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