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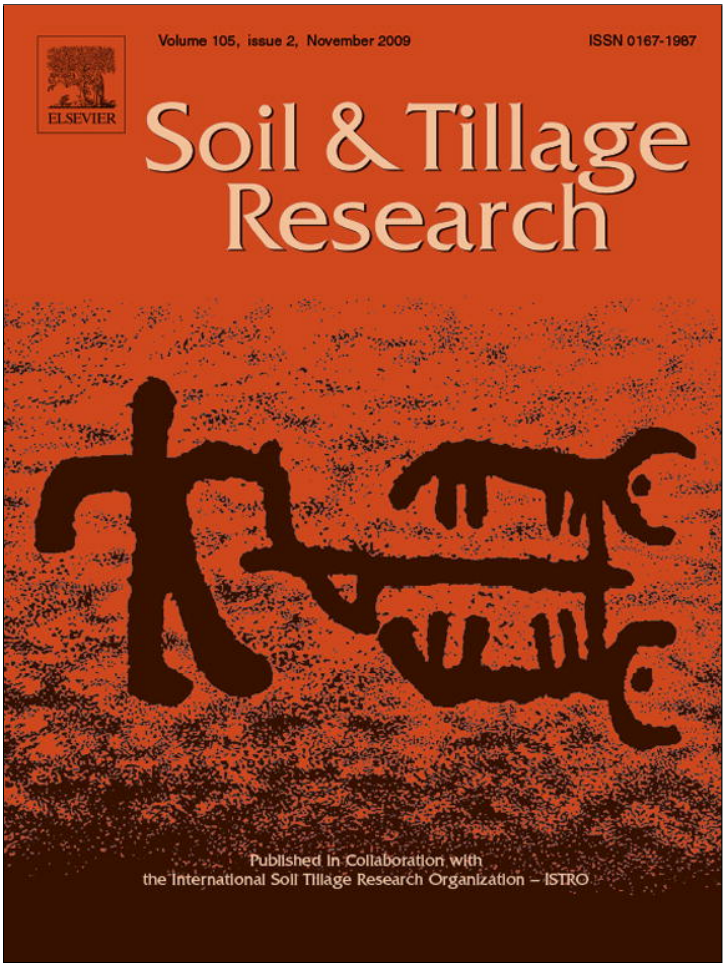

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Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe

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ABSTRACT

The adoption of conservation agriculture (CA), based on minimal soil movement, permanent soil cover with crop residues or growing plants and crop rotation has advanced rapidly in the Americas and Australia over the last three decades. One of the immediate benefits of CA in dryland agriculture is improved rainfall-use efficiency through increased water infiltration and decreased evaporation from the soil surface, with associated decreases in runoff and soil erosion. This paper focuses on the effect of CA techniques on soil moisture relations in two researcher-managed trials in Zambia and Zimbabwe. In 2005/2006 and 2006/2007, we found significantly higher water infiltration on both sites on CA fields compared to conventionally ploughed fields. At Henderson Research Station, Zimbabwe, on a sandy soil, a direct seeded CA treatments had a 49% and 45% greater infiltration rate than the conventionally tilled plots after a simulated rainfall in both seasons. At Monze Farmer Training Centre, Zambia, on a finer-textured soil, the same treatment had 57% and 87% greater infiltration rate than the conventionally tilled control treatment in both seasons. Treatments that included reduced tillage and surface residue retention had less water runoff and erosion on runoff plots at Henderson Research Station, Zimbabwe. On average, soil moisture was higher throughout the season in most CA treatments than in the conventionally tilled plots. However, the full potential of CA in mitigating drought was not evident as there was no significant drought period in either season. Results suggest that CA has the potential to increase the productivity of rainfall water and therefore reduce the risk of crop failure, as was apparent at the Monze Farmer Training Centre, Zambia, in 2005/2006 when a period of moisture stress at tasseling affected CA treatments less than the conventionally tilled treatment.

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1. Introduction

Infertile soils, unreliable rainfall and inadequate management of the natural resource base have led to declining yields and increased risk of crop failure in much of the smallholder dryland farming sector of southern Africa. Tillage in the predominantly maize-based cropping systems on small farms in the region is typically manual using a hand hoe or a single-furrow, animal-drawn mouldboard plough. The plough was introduced from Europe in the early 20th century, but the negative effects were soon apparent and contour bunds were enforced on sloping lands to control soil erosion and runoff (Alvord, 1936). Tillage-based conventional agriculture is assumed to have led to soil organic matter decline, water runoff and soil erosion (Derpsch et al., 1991), and other manifestations of physical, chemical and biological soil degradation (Benites, 2008; Kertész et al., 2008).

Frequently occurring seasonal droughts, nutrient mining and overgrazing add to the crop production risks for smallholder farmers in Southern Africa. Over the last 30 years there has been a constant decline in average maize yield in Zimbabwe (Fig. 1). As a consequence, there is high pressure on the livelihoods and food security of Africa's most vulnerable (CIMMYT, 2004) (Fig. 2).

Conservation agriculture (CA) is based on three principles: (a) minimal soil movement, (b) permanent soil cover with crop residues or growing plants and (c) crop rotations. Successful application of these principles require many changes to the production system, including equipment, residue management practices, weed control and fertilization strategies (FAO, 2002). Thus CA is a complex technology, comprising multiple components and, if introduced to smallholder farmers, needs intensive community-based extension approaches to overcome the problems of a shift from traditional tillage-based agriculture system to CA (Wall, 2007). The adoption of CA has advanced rapidly in the Americas and Australia over the last three decades, mainly on large, mechanized, commercial farms (Derpsch, 2005; Ekboir et al., 2002). Adoption of CA in Africa, especially on smallholder farms, has been slower and considerable areas under CA are only found in

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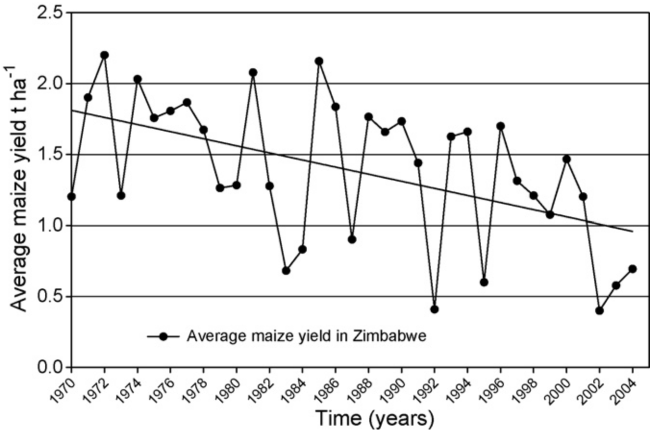

Fig. 1. Average maize yield in Zimbabwe (in t ha^{-1}) from 1970 to 2004 (CSO, 1987; CSO, 1984–1989; FAOSTAT, 2004).

Ghana (Ekboir et al., 2002), Zambia (Haggblade and Tembo, 2003) and Tanzania (Shetto and Owenya, 2007) and to a lesser extent in Zimbabwe (FAO, 2007).

The benefits and challenges of CA systems have been widely published (see recent reviews by Bolliger et al., 2006; Derpsch, 2008; Hobbs, 2007; Reicosky and Saxton, 2007; Wall, 2007). CA has been shown to markedly reduce, halt or revert many components of soil degradation, including soil organic matter decline and soil structural degradation (Derpsch et al., 1986). Some of the benefits of CA may be apparent almost immediately (e.g. increased water infiltration, reduced water runoff, evaporation and soil erosion) while others build up over the longer-term (e.g. increases in soil organic matter, improved soil structure, reduced weed problems and increased soil biological activity) (Derpsch, 1999; Hamblin, 1987; Sayre, 1998). The increase in soil organic matter (SOM) is one of the key indicators of increased sustainability of the system. SOM maintenance and increase are more pronounced in CA systems due to the retention of organic material as crop residues on the soil surface. Higher biological activity on CA fields lead to increased SOM stabilization through fungal hyphae, bacterial exudates and earthworm or termite casts (Six et al., 2002).

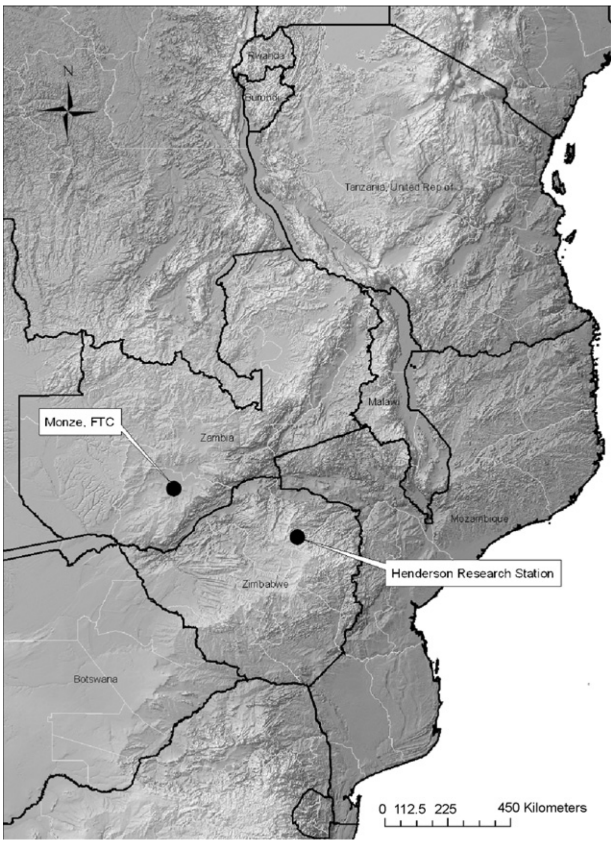

Fig. 2. Geographical location of experimental sites at Henderson Research Station Research Station, Zimbabwe (−17.57 S; 30.99 E) and Monze FTC, Zambia (−16.24 S; 27.44 E).

Increased microbial activity, higher soil organic matter and reduced soil disturbance lead to a more stable soil pore system with improved aggregate development and root exploration of the soil profile (Kladviko et al., 1986; Six et al., 2002). An improved soil structure and continuous soil pores enable higher infiltration and ultimately increased available water for crop production (Roth et al., 1988; Shaxson, 2003; Thierfelder et al., 2005).

Mulch also impedes the evaporation of water from the soil surface by protecting it from direct solar radiation and by greater resistance to air flow across the soil surface, resulting in lower losses of moisture to evaporation in untilled soils covered with mulch compared to tilled soils (Dardanelli et al., 1994).

Bescansa et al. (2006), working in semi-arid Spain, found higher available soil water content due to greater soil organic matter and changes in pore-size distribution as a consequence of reduction in tillage, while Shaxson and Barber (2003) reviewed the influence of soil porosity on water infiltration and moisture retention and concluded that CA, through increased soil biological activity and physical aggregation, improved water infiltration and reduced surface runoff increases plant-available moisture in the soil.

Water runoff in agriculture systems, and the resulting soil erosion, is a consequence of limitations in water infiltration, compacted subsoils, hardpans and/or reduced macropores (Callebaut et al., 1985; Lal, 1990). Higher infiltration rates, which may be apparent in CA fields, prevent losses of surface water and soil. Results from Colombia show that between 10 and 22% of rain water may be lost from an uncovered, ploughed soil surface (Thierfelder, 2003). Rockström et al. (2001) reported from Eastern and Southern Africa that 10–25% of rainwater is lost to runoff, and another 30–50% lost through evaporation on unprotected soil surfaces. These findings are supported by other results on water runoff which compare CA systems with conventional ploughed systems (Lal, 1977; Shaxson and Barber, 2003). As a consequence of higher infiltration rates and reduced evaporation, general improvements in soil water status and water-holding capacity in CA systems can be observed (Bescansa et al., 2006; Derpsch et al., 1986).

Numerous studies have shown significant reductions in soil erosion rates with CA or no-tillage (no-tillage was a term commonly used before the term CA was coined and is still used as a synonym for CA in some places). A summary of several published reports from Brazil show an average reduction in soil erosion of 80% by direct seeding compared to conventional mouldboard ploughing (Table 1). In Zimbabwe, an 8-year study on soil erosion found mean annual erosion loads of 5.1 t ha^{-1} year^{-1} in the conventionally ploughed treatment compared to 1.0 t ha^{-1} year^{-1} with mulch ripping—a system with no soil inversion and residue cover (Munyati, 1997).

In this paper we report results from the 2005/2006 and 2006/2007 cropping seasons from two trials, one in Zimbabwe and the other in Zambia, on the effects of tillage practices on water infiltration, runoff erosion and soil water content. The trials were established to monitor the longer-term effects of CA on soil quality and crop productivity as compared to conventionally tilled systems under conditions representative of the major cropping systems of southern Africa. The objective of these studies is to test the hypotheses that (a) higher water infiltration and surface moisture retention through residues on CA fields result in

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Table 1
Soil loss through erosion under rainfed agriculture and different tillage treatments. Information from different authors.

Source	Conventional ploughing (CP)	Direct seeding (DS)	Location
Benatti et al. (1977)	40.14	13.39	Sao Paulo, Brazil
Mondardo et al. (1979)	19.00	5.50	Paraná, Brazil
Sidiras (1984)[a]	68.20	6.90	Paraná, Brazil
Sorrenson and Montoya (1989)	57.70	2.10	Paraná, Brazil
Sorrenson and Montoya (1989)	9.10	5.60	Paraná, Brazil
Santana (1994)[b]	4.80	0.90	Brazil
Venialgo (1996)[c]	23.00	0.53	Southern Paraguay
Gassen and Gassen (1996)	68.00	7.00	Brazil
Merten (1996)[b]	26.40	3.30	Brazil

Notes:
[a] Cited by Derpsch et al. (1991).
[b] Cited by Landers (2001).
[c] Cited by Derpsch (2005), other references; see reference list.

increased soil moisture content and (b) higher soil moisture on CA fields leads to greater crop productivity from rainwater capture.

2. Materials and methods

2.1. Site description

The first site was established in 2004 at Henderson Research Station (HRS) (−17.57 S; 30.98 E; altitude: 1136 m.a.s.l., mean annual rainfall 884 mm year^{-1}) near Mazowe in Zimbabwe. Predominant soils at the site are *Arensols* and *Luvisols* (FAO, 1998; Table 2). The site was abandoned in 1995 and left under grass fallow until the trial was established in 2004.

The second site at the Farmer Training Centre near Monze (MFTC) in Zambia (−16.24 S; 27.44 E; altitude: 1103 m.a.s.l., mean annual rainfall 748 mm year^{-1}) was established in 2005 on finer-textured soils classified as *Lixisols* (FAO, 1998; Table 3). Prior to establishment, the site in Monze was used for conventional maize production.

Maize (*Zea mays* L.) is the principal crop in both areas, while cotton (*Gossypium hirsutum* L.), soybeans (*Glycine max* (L) *Merr*) and cowpeas (*Vigna unguiculata* L. Walp.) are also important crops.

2.2. Experimental design

2.2.1. Henderson Research Station (HRS)

The experiment at HRS consisted of five treatments in a randomized complete block design with four replications. The conventional farmers practice (CP) at HRS was compared with four CA treatments, seeded in untilled land with surface crop residue retention. The CP in this area consists of ploughing at shallow depth (10–15 cm) using an animal traction mouldboard plough. Residues are burned, grazed or removed and the remaining stubble incorporated with the plough. Maize is planted as a continuous sole crop.

The CA treatments are:

- Ripping and handseeding of maize into a furrow opened by an animal traction subsoiler (the Palabana subsoiler) (SS), which was pulled by a pair of oxen and operates at 20–25 cm depth. The soil surface is disturbed by approximately 20 percent with the subsoiler.
- Direct seeding (DS) of sole maize, seeded with an animal traction direct seeder (2005) or a manual jabplanter (2006). Both implements allow direct seed and fertilizer placement through the mulch in moist soil.
- Handseeding of sole maize in manually dug small basins (BA)—a system being disseminated by many organizations in Zimbabwe and Zambia and termed Conservation Farming. The basins, approximately 15 cm × 15 cm × 15 cm, are dug during the winter period to spread labour.
- Hand seed-seeding of maize into furrows opened by an animal traction ripper (the Magoye Ripper) (MR + leg). The Magoye ripper operates at approximately 10 cm depth and has a lateral soil disturbance of approximately 20 cm. Additionally, the MR treatment is relay cropped with legumes (velvet beans (*Mucuna pruriens* (L.) DC.) in 2005/2006 seeded 6 weeks after the maize and pigeon peas (*Cajanus cajan* L.) in 2006/2007 seeded at the same time as the maize).

Commercial hybrid maize varieties (SC627 in 2005/06 and SC635 in 2006/2007) were seeded on Nov 24 and 27 in 2005 and 2006 respectively and harvested on April 21, 2006, and April 20, 2007. Basal fertilizer at a rate of 165 kg ha^{-1} Compound D (7:14:7, $N:P_2O_5:K_2O$) was applied to all treatments at seeding and placed next to the plant station except when seeded with the animal traction direct seeder, where fertilizer was dribbled in the row by

Table 2
Some soil properties of reference profile C, *endostagnic dystric Luvisol*; Henderson Research Station, Zimbabwe.

Horizons	Depth [cm]	Bulk density [g cm^3]	Color [Munsell]	Mottling [vol.%]	pH [KCl]	CECpot [cmol kg^{-1}]	BS [%]	Corg [%]	Particle size [%]		
									Sand	Silt	Clay
Ahp	0–28	1.29	10 YR 3/2	–	4.5	3.7	39	0.44	77	16	7
Ah2	–35	1.48	10 YR 3/1	–	4.5	2.0	55	0.22	73	20	7
E	–70	1.45	10 YR 3/3	5	4.2	1.6	37	0.06	83	13	4
Bs	–105	1.67	7.5 YR 5/8	20–30	4.5	1.7	44	n.n.	84	14	2
Bt	>115	1.73	7.5 YR 6/0	20–30	4.3	7.0	38	n.n.	66	15	19

Notes: CECpot = potential cation exchange capacity; BS = base saturation; Corg = organic carbon.

Table 3
Some soil properties of reference profile D, *ferric Lixisol*; Monze FTC, Zambia.

Horizons	Depth [cm]	Bulk density [g cm^3]	Color [Munsell]	Mottling [vol.%]	pH [CaCl]	CECpot [cmol kg^{-1}]	BS [%]	Corg [%]	Particle size [%]		
									Sand	Silt	Clay
Ap	0–21	1.58	10 YR 3/4	–	4.8	2.8	57	0.60	82	6	12
AB	–52	1.69	7.5 YR 3/4	2	4.8	5.2	62	0.52	55	8	37
Btg	–100	1.76	7.5 YR 3/4	15	5.2	5.1	52	0.40	53	8	39
BCcg	>105	1.81	5 YR 5/8	>40	5.8	5.5	57	0.17	71	6	23

Notes: CECpot = potential cation exchange capacity; BS = base saturation; Corg = organic carbon.

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the seeder. Top-dressing with 200 kg ha^{-1} ammonium nitrate (34.5% N) was applied to all treatments as a split application on December 23, 2005 and January 06, 2006 and on December 27, 2006 and January 10, 2007.

2.2.2. Monze Farmer Training Centre (MFTC)

At the MFTC, the experiment consisted of eight treatments of which five are reported in this paper. The trial was in a randomized complete block design with four replications. Similar to the trial at HRS, all crop residues are removed from the conventional farmers practice (CP), which is ploughed with the mouldboard plough and seeded with sole maize. On the CA treatments all residues from the previous maize crop were retained on the soil surface. The CA treatments consist of:

- Direct seeding (DS) of maize with an animal traction direct seeder/fertilizer application unit.
- Handseeding of maize in manually dug basins (BA).
- Direct seeding of a maize–cotton rotation with an animal traction direct seeder/fertilizer application unit. Both phases of the rotation (A1M-A1C and A2C-A2M) are established each season but yield results are only presented from the maize phase of the rotation.

The commercial hybrid maize variety SC513 was seeded on December 1, 2005, and November 23, 2006 and harvested on April 4, 2006, and March 29, 2007. Basal fertilization was carried out using the same methodology as at HRS, with 165 kg ha^{-1} of Compound D[1] (10:20:10, N:P_2O_5:K_2O) at seeding and 200 kg ha^{-1} urea (46% N) as top-dressing applied as a split application on January 06 and January 20, 2006 and on December 21, 2006 and January, 04, 2007, respectively.

At both sites maize was seeded in rows spaced 90 cm apart. In all manually seeded treatments seed was placed in these rows with two seeds per station and 50 cm between planting stations (44,000 seeds ha^{-1}). The direct seeder was calibrated to give the same population with seeds approximately every 25 cm in the row. Velvet beans and pigeon peas in the MR treatment at HRS were seeded between the maize rows in rows 90 cm apart. Velvet beans were seeded with 25 cm between plant stations and one seed per station, while pigeon peas were seeded 50 cm apart in the row with two seeds per station.

Weed control was achieved by a pre-emergence application of glyphosate (N-(phosphonomethyl) glycine, 41% active ingredient) at a rate of 3 l ha^{-1} followed by regular hand-weeding as necessary. At harvest, cobs were removed from the plots and the remaining crop residues (stover) retained on the CA treatments and removed from the CP treatment. Stover yields ranged from 3.2 to 5.2 t ha^{-1}.

2.3. Field methods

2.3.1. Water infiltration

In the 2005/2006 and 2006/2007 seasons, measurements of infiltration were carried out with a small rainfall simulator described by Amézquita et al. (1999). Simulated rainfall of a known rate of approximately 95 mm h^{-1} was applied to an area of 36 cm × 44 cm for 60 min and runoff measured from an area of 32.5 cm × 40 cm (0.13 m^{-2}). The difference between water applied and runoff was recorded as infiltration. Infiltration measurements were made at both sites in January of each year when the maize crop was at, or just before, the tassling stage. Infiltration was measured on three sites in each plot, mainly in the inter-row space, when the soil was at or close to field capacity. The construction of the simulator did not allow for measurements within the basins and between the basins, hence water infiltration was only measured in the inter-row space. Horton's infiltration model (Eq. (1)) was used to fit the data and to describe the exponential decay of infiltration rate during the experiment (Kutilek and Nielsen, 1994):

$$f_{cap} = (f_0 - f_c)e^{-bt} + f_c \quad (1)$$

where f_{cap} = maximum infiltration capacity of the soil (mm h^{-1}), f_0 = initial infiltration capacity (mm h^{-1}), f_c = final infiltration capacity (mm h^{-1}), b = Horton's constant, t = elapsed time (h).

2.3.2. Soil moisture

Access tubes were installed in five treatments at HRS and MFTC (3 access tubes per plot in 3 replicates) and moisture content measured to 1 m depth with a capacitance probe (PR-2 probes, Delta-T Devices Ltd., UK) twice per week during the cropping season. Data from the 0–10, 10–20, 20–30, 30–40 and 40–60 cm horizons are reported in this paper. Mean soil moisture in vol.% for each soil depth layer over the cropping season was determined and mean soil moisture content (in mm) in the top 60 cm calculated. Texture samples form each tube were used to calculate field capacity (FC), 50% available soil moisture and permanent wilting percentage (PWP). PWP could not be based on a water-retention curve due to lack of functional soil physical laboratories in the region. Soil moisture content in the 0–60 cm horizon at PWP in the whole horizon would be approximately 47 mm for HRS and 96 mm for MFTC.

2.3.3. Soil erosion and runoff

Erosion and runoff plots were only established at HRS as this site has a 5–7% slope whereas the MFTC is essentially flat. Plots, 9 m long by 4.5 m wide (total area 40.5 m^2), and delineated with strips of metal buried to 10 cm depth to restrict water flowing onto the plots from the adjacent areas, were established on three replicates of three of the treatments: the conventional practice (CP), the direct seeding treatment (DS) and the ripped treatment with the legume intercrop (MR + leg). Water erosion and runoff were measured during the two rainy seasons starting from the 29th November 2005 until the 30th March 2006 and from 7th December 2006 until 17th April 2007, respectively. Water and eroded soil were collected in settling tanks at the base of each plot, and a percentage (8%) of water flowing out of the settling tanks collected and measured. After each rainfall event, eroded soil was collected from the drains and settling tanks, weighed and moisture content calculated. Results of soil mass eroded are reported on a dry-weight basis.

2.3.4. Harvest data

At both sites the maize crop was harvested at physiological maturity and total above-ground biomass and grain yield determined on each plot. The green manure cover crops in HRS were left growing until killed by frost, and the cotton crop at MFTC was routinely harvested but not included in comparisons in this paper.

2.4. Statistical methods

Statistical analyses were carried out using STATISTIX for personal computers (Statistix, 2008). Final infiltration, erosion, runoff, soil moisture and yield data were tested for normality. Analyses of variances (ANOVA) were conducted following the General Linear Model (GLM) procedure at a probability level of $P \leq 0.05$ unless stated differently. Where significance was detected, means were compared using an LSD- or Tukey-test.

[1] Although they have the same name, Compound D in Zambia and Zimbabwe have different nutrient contents as indicated in the text.

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Table 4
Total water infiltration and infiltration rate with a simulated rainfall of 95 mm in 60 min in a conventionally ploughed and four conservation agriculture treatments in two seasons at Henderson Research Station, Zimbabwe.

Treatment	January 2006		January 2007	
	Total infiltration (mm)	Final infiltration rate (mm h^{-1})	Total infiltration (mm)	Final infiltration rate (mm h^{-1})
Conventional ploughing (CP), maize	38	32 b[a]	58 c	52 c
Subsoiling (SS), maize	41	37 ab	71 ab	70 ab
Direct seeding (DS), maize	50	47 a	76 ab	75 ab
Basin planting (BA), maize	37	33 b	68 bc	63 bc
Ripping (MR + leg), maize + legume intercrop	45	42 ab	81 a	78 a
LSD		11.4	11.3	12.9
Probability level (PF)	NS	5%	5%	5%

Notes:
[a] Means followed by the same letter in column are not significantly different at the specified probability level.

3. Results

3.1. Total infiltration

There were no significant differences between treatments in total water infiltration during the simulated rainfall at HRS in 2006, the second season after trial establishment (Table 4). However, in 2007 significantly higher total infiltration ($P \leq 0.05$) was recorded in the intercropped rip-line seeded treatment (MR + leg, 81.4 mm) compared to the CP and BA treatments. Infiltration in DS and SS was not significantly different from MR + leg but it was higher compared to the CP. BA was not significantly different from CP. In the measurements in 2007, about 40% more water entered the soil profile in MR + leg than in CP and on average 27% more water infiltrated in all CA treatments than in CP.

At MFTC in 2006, the first year of trial establishment, water infiltration was significantly higher only at ($P \leq 0.10$) in the BA (63.4 mm) and DS (60.1 mm) treatments than in the conventionally control treatment (CP, 45.9 mm) (Table 5). Surprisingly low total infiltration was recorded in the direct seeded cotton treatment (A2C) (44.7 mm) in 2006. However, in 2007 all of the CA treatments had significantly greater water infiltration ($P \leq 0.01$) than the CP. During the simulated rainfall in 2006, on average 24% more water entered the soil on all CA treatments and in 2007, 66% higher infiltration was recorded on all CA treatments compared to the conventionally tilled control treatment.

3.2. Infiltration rate

Final infiltration rate into the soil was generally higher in CA than in the control treatment in both seasons and at both sites. At HRS, significant differences occurred in 2006 between DS (47.2 mm h^{-1}) and CP (31.6 mm h^{-1}) as well as BA (32.6 mm h^{-1}) 1) (Table 4). The DS treatment had nearly a 50% higher steady state infiltration rate than CP. The high rainfall in this season (1096 mm) led to a higher water table and consequently an overall lower infiltration rate. In the following season (2006/2007) the highest steady state infiltration rate was recorded in MR + leg (78.4 mm h^{-1}) and lowest in CP (51.5 mm h^{-1}), while the SS, DS and BA treatments were intermediate (74.8, 69.7 and 63.2 mm h^{-1}, respectively). Overall, average infiltration rate of all CA treatments was 25% and 39% higher than the control treatment in 2006 and 2007 respectively, although the infiltration rate in the BA treatment was not significantly higher than the CP treatment in either season.

At MFTC in Zambia (Table 5) in the 2006 season, the final infiltration rates of DS (52.8 mm h^{-1}) and BA (52.2 mm h^{-1}) were significantly higher than for CP (33.6 mm h^{-1}). The lowest final infiltration rate (32.2 mm h^{-1}) was recorded in the direct seeded cotton treatment (A2C). In 2007, the differences were more pronounced and all CA treatments had significantly higher ($P \leq 0.05$) final infiltration rates than CP. Average infiltration rate of the CA treatments was 42% and 100% higher than CP in 2006 and 2007, respectively.

3.3. Soil erosion and runoff

Soil erosion and runoff at HRS were relatively high (Table 6) and supported the data from the rainfall simulator. In the 2005/2006 season the greatest erosion (12.0 t ha^{-1}) and runoff (545.1 mm) were observed in the conventional practice (CP) and lowest erosion and runoff were measured in the CA treatments (DS and MR). Total

Table 5
Total water infiltration and infiltration rate with a simulated rainfall of 95 mm in 60 min in one conventionally ploughed and two conservation agriculture treatments in two seasons at FTC Monze, Zambia.

Treatment	January 2006		January 2007	
	Total infiltration (mm)	Final infiltration rate (mm h^{-1})	Total infiltration (mm)	Final infiltration rate (mm h^{-1})
Conventional ploughing (CP), maize	46 b[a]	34 b	36 b	25 b
Direct seeding (DS), maize	60 a	53 a	56 a	47 a
Basin planting (BA), maize	63 a	52 a	65 a	56 a
Direct seeding, cotton (A2C)	45 b	32 b		
Direct seeding, cotton after maize (A1C)[b]			61 a	52 a
Direct seeding, maize after cotton (A2M)			58 a	48 a
LSD	13.2	15.2	18.3	17.6
Probability level (PF)	10%	5%	1%	5%

Notes:
[a] Means followed by the same letter in column are not significantly different at the specified probability level.
[b] A1 and A2 are phases of a direct seeded maize–cotton rotation.

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Table 6
Average soil erosion amounts (Mg ha^{-1}) in two conservation agriculture and one conventionally ploughed treatment, Henderson Research Station, 2005/2006 and 2006/2007.

Treatment	Season 2005/2006		Season 2006/2007	
	Erosion (Mg ha^{-1})	Runoff (mm)	Erosion (Mg ha^{-1})	Runoff (mm)
Conventional ploughing (CP)	12.0 a[a]	545 a	2.4 a	361 a
Direct seeding (DS)	8.0 ab	383 b	0.9 b	165 b
Ripping + legume intercrop (MR + leg)	6.9 b	314 b	1.3 b	221 b
LSD	4.5	125.5	1.1	61.8
Probability level (PF)	5%	1%	1%	1%

Notes:
[a] Means followed by the same letter in column are not significantly different at the specified probability level.

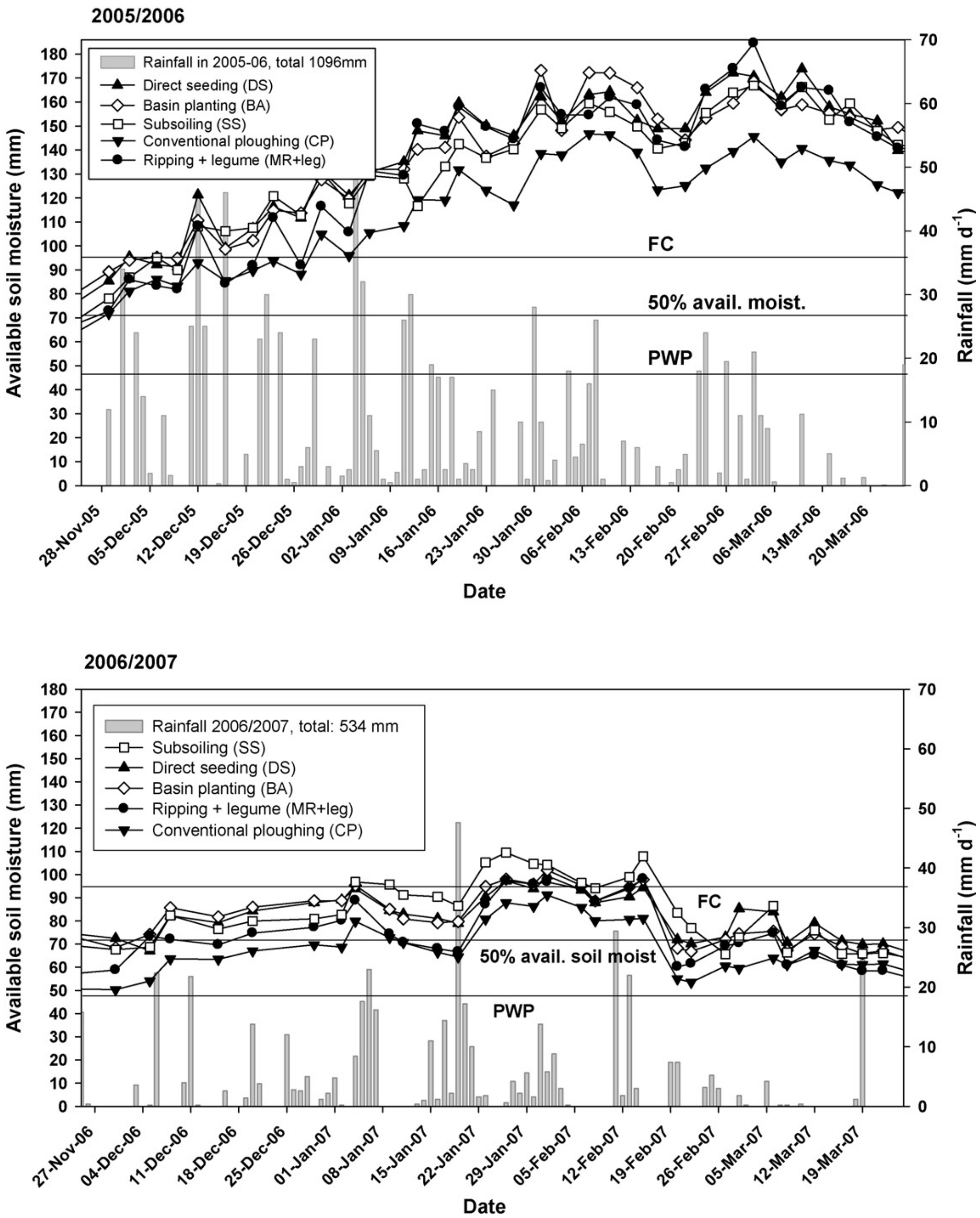

Fig. 3. Available soil moisture (in mm) in the first 60 cm in one conventionally ploughed and four conservation agriculture, Henderson Research Station, Zimbabwe, 2005/2006 and 2006/2007. FC = field capacity; PWP = permanent wilting percentage.

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rainfall recorded during the period of runoff measurements (from October 22, 2005 to May 09, 2006) was 1096 mm and therefore approximately 50% of the rain was lost as runoff from the plots with conventional tillage compared to a little less than 30% loss in the best CA practice—the rip-line seeded maize/velvet bean intercrop (MR + leg).

Overall rainfall was much lower in the 2006/2007 cropping season and total erosion and runoff were consequently lower (Table 6). The highest erosion and runoff was again measured in CP (2.4 t ha^{-1} and 326 mm) and the lowest in DS (0.9 t ha^{-1} and 165 mm).

3.4. Soil moisture measurements

Moisture content of the soil profile closely followed the seasonal rainfall pattern at both sites (Figs. 3 and 4). Available soil moisture (in mm) above the permanent wilting percentage in the conventional farmers practice in the first 60 cm was almost constantly below those of the CA treatments at both sites and both years. Available soil moisture was, however, lower at MFTC in the direct seeded cotton treatment (A2C) at the end of each cropping season starting from mid-March 2006 and 2007 and in DS in February 2006.

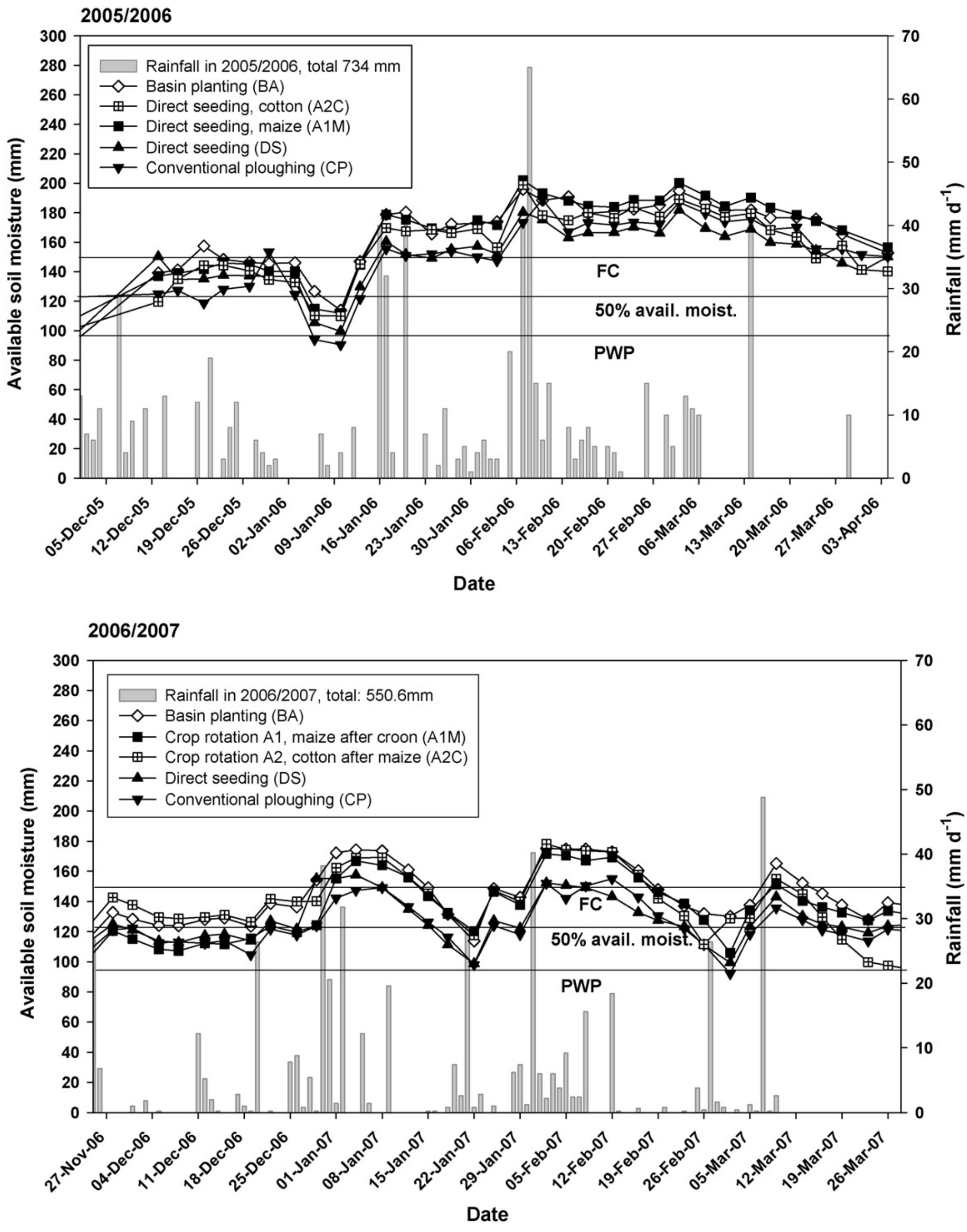

Fig. 4. Available soil moisture (in mm) in the first 60 cm in one conventionally ploughed and four conservation agriculture treatments, Monze Farmer Training Centre, 2005/2006 and 2006/2007. FC = field capacity; PWP = permanent wilting percentage.

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Table 7
Mean integrated soil moisture content (in mm) measured in one conventionally ploughed and four conservation agriculture treatments at Henderson Research Station, Zimbabwe November 1, 2005–March 27, 2006 and November 14, 2006–April 16, 2007.

	Soil horizon					
	0–10 cm	10–20 cm	20–30 cm	30–40 cm	40–60 cm	Total 0–60 cm
2005/2006 season						
Conventional ploughing (CP)	16.7 b[a]	17.9 b	16.0 d	14.4 b	39.8 b	104.8 b
Subsoiling (SS)	17.1 b	19.2 ab	18.5 c	16.8 a	48.2 a	119.7 ab
Direct seeding (DS)	16.8 b	20.5 a	21.9 a	18.4 a	47.6 a	125.2 a
Basin planting (BA)	18.8 a	19.5 ab	21.0 ab	18.5 a	46.8 a	124.7 a
Ripping + intercrop (MR + leg)	17.6 ab	20 a	19.4 bc	17.9 a	45.0 a	119.9 a
2006/2007 season						
Conventional ploughing (CP)	10.9 b	13.1 ab	10.3 c	9.3 b	22.4 b	66.0 a
Subsoiling (SS)	11.6 ab	14.4 ab	12.2 abc	11.6 ab	30.9 a	80.7 a
Direct seeding (DS)	13.8 a	14.9 ab	12.9 ab	11.6 ab	27.2 ab	80.3 a
Basin planting (BA)	12.5 ab	15.5 a	14.8 a	13.9 a	23.1 b	79.7 a
Ripping + intercrop (MR + leg)	12.0 ab	12.4 b	11.4 bc	11.7 ab	23.7 b	71.2 a

[a] Means within the same season followed by the same letter in column are not significantly different at $P \leq 0.05$ probability level, LSD-test.

Differences between treatments in the mean integrated soil moisture content were recorded at HRS in 2005/2006 at all depths (Table 7). In the 0–10 cm layer only BA had a higher soil moisture content than the control treatment, at 10–20 cm only DS and MR + leg were higher than CP. At all other depths the CA treatments had higher integrated soil moisture content than the control treatment. In 2006/2007 the mean integrated soil moisture content showed significant differences ($P \leq .05$) between DS and CP in 0–10 cm depth and between BA and MR + leg in 10–20 cm. At depths below 20 cm CP was always lowest but only significantly different from BA and DS in the 20–30 cm, BA in 30–40 cm and SS in 40–60 cm (Table 7). Average soil moisture in the top 60 cm of soil was significantly different only in 2005/2006 where all CA treatments except of SS exceeded the conventionally ploughed control treatment (CP). CA treatments had on average 17% and 18% higher integrated soil moisture in the first 60 cm than the control treatment at HRS in 2005/2006 and 2006/2007.

At MFTC, Zambia, differences in mean integrated soil moisture content in the surface soil layer 0–10 cm were not significantly different in 2005/2006 (Table 8). Significant differences ($P \leq 0.05$) between CA treatments and CP were only detected in 20–30 cm depth (BA was higher than CP) and 30–40 cm depth (BA was higher than CP and DS).

In 2006/2007, the BA and DS treatments consistently exceeded the conventionally ploughed control treatment (CP) except in the 40–60 cm depth layer (Table 8). In the first four horizons, BA had the highest soil moisture content. Average soil moisture in the top 60 cm of soil was highest in BA and the direct seeded cotton after maize (A1C) compared to the conventionally ploughed CP. CA treatments had on average 3% and 10% higher soil moisture than the control treatment at MFTC in 2005/2006 and 2006/2007.

3.5. Maize grain yield and rainfall-use efficiency

There were no significant difference between treatments in maize grain yields at HRS in 2005/2006 (Table 9). In 2006/2007 the highest grain yields were recorded in DS and BA (5234 and 5273 kg ha^{-1})—significantly greater than in the MR + leg (3658 kg ha^{-1}) treatment. CP and SS were intermediate and not significantly different from the other treatments.

At MFTC all CA treatments significantly out-yielded CP (Table 9) in 2005/2006, with BA having the highest yield (5501 kg ha^{-1}). There were no significant yield differences between treatments in 2006/2007.

The 2005/2006 cropping season at HRS was characterized by very high rainfall amounts (1096 mm) and low rainfall-use efficiency (RUE). There were no significant differences between treatments at this site in this season (Table 9). In 2006/2007 the rainfall-use efficiency (RUE) of DS and BA was greater (9.8 and 9.9 kg grain mm^{-1} rainfall) than the other treatments, although differences were not significantly higher than the RUE of CP and SS. The RUE of the MR + leg treatment was considerably lower than the other treatments because of the very low grain yield achieved in this treatment (6.8 kg mm^{-1}). At MFTC, all CA treatments produced more grain (6.7–7.5 kg grain mm^{-1}) from the rainfall

Table 8
Mean integrated soil moisture content (in mm) measured in one conventionally ploughed and four conservation agriculture treatments at FTC Monze, Zambia, November 2, 2005–April 4, 2006 and November 21, 2006–April 2, 2007.

	Soil horizon					
	0–10 cm	10–20 cm	20–30 cm	30–40 cm	40–60 cm	Total 0–60 cm
2005/2006 season						
Conventional ploughing (CP)	18.4 a[a]	21.4 ab	20.9 b	22.7 b	51.4 a	134.7 a
Direct seeding (DS)	19.9 a	21.3 ab	22.9 ab	22.5 b	45.8 b	132.5 a
Basin planting (BA)	19.4 a	23.9 a	24.2 a	25.9 a	49.6 ab	143.1 a
Direct seeded cotton (A2C)	18.4 a	21.1 b	22.2 ab	24.9 ab	52.0 a	138.6 a
2006/2007 season						
Conventional ploughing (CP)	14.1 c	18.0 b	18.6 c	21.7 d	51.7 a	124.1 c
Direct seeding (DS)	16.2 b	18.7 b	21.6 ab	23.9 c	46.7 b	127.2 bc
Basin planting (BA)	18.2 a	23.1 a	23.2 a	27.2 a	52.3 a	143.9 a
Direct seeded cotton after maize (A1C)[b]	17.2 ab	21.4 a	21.8 ab	26.3 ab	51.5 a	138.3 ab
Direct seeded maize after cotton (A2M)	15.8 b	19.5 b	21.1 b	25.3 bc	53.6 a	135.2 abc

[a] Means within the same season followed by the same letter in column are not significantly different at $P \leq 0.05$ probability level, LSD-test.
[b] A1 and A2 are phases of a direct seeded maize–cotton rotation.

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Table 9
Effects of conservation agriculture on maize grain yield (kg ha^{-1}) and rainfall-use efficiency (in kg mm^{-1} of rain captured) at HRS and MFTC in 2005/2006 and 2006/2007.

Treatments and sites	Season 2005/2006		Season 2006/2007	
	Total rainfall (mm) 1096		Total rainfall (mm) 534	
	Maize grain yield (kg ha^{-1})	Rainfall-use efficiency (kg mm^{-1})	Maize grain yield (kg ha^{-1})	Rainfall-use efficiency (kg mm^{-1})
Henderson Research Station				
Conventional ploughing (CP)	3254 a	3.0 a[a]	4358 ab	8.2 ab
Subsoiling (SS)	3250 a	3.0 a	4344 ab	8.1 ab
Direct seeding (DS)	2456 a	2.2 a	5234 a	9.8 a
Basin planting (BA)	2663 a	2.4 a	5273 a	9.9 a
Ripping + legume intercrop (MR + Leg)	2407 a	2.2 a	3658 b	6.8 b
Mean	2806	2.6	4573	8.6
	Total rainfall (mm) 734		Total rainfall (mm) 551	
	Maize grain yield (kg ha^{-1})	Rainfall-use efficiency (kg mm^{-1})	Maize grain yield (kg ha^{-1})	Rainfall-use efficiency (kg mm^{-1})
Monze Farmer Training Centre				
Conventional ploughing (CP)	3620 b	4.9 b	4877 a	8.9 a
Direct seeding (DS)	4894 a	6.7 a	5141 a	9.3 a
Basin planting (BA)	5501 a	7.5 a	5240 a	9.5 a
Direct seeded rotation[b]	5136 a	7.0 a	6220 a	11.3 a
Mean	4788	6.5	5370	9.8

[a] Means within the same season followed by the same letter in column are not significantly different at $P \leq 0.05$ probability level, LSD-test.
[b] *Note*: Crops in the maize cotton rotation consisted of maize after maize in 2005/2006 and maize after cotton in 2006/2007.

captured in 2005/2006 than the conventionally ploughed treatment (4.9 kg mm^{-1}), whereas in 2006/2007 there were no significant differences although all CA treatments together had a 13% higher RUE than the control treatment. In summary, the crops planted under CA at MFTC on average could make more use of the rainfall compared to the ploughed control treatment in both cropping seasons, which was not as obvious at HRS.

4. Discussion

Infiltration rates were generally high at both sites due to the light textured sandy soils at HRS and a sandy topsoil and well-structured subsoil at MFTC, which contributed to better drainage. In general infiltration was greater on residue protected undisturbed soils than on conventionally tilled and unprotected soils. However, some of the CA treatments did not follow this trend in the first season, e.g. the basin treatment (BA) at HRS and the direct seeded cotton treatment (A2C) at MFTC in 2005/2006. In the 2006/2007 season significantly highest infiltration was measured on direct seeded and rip-line seeded treatments at both sites, suggesting the development of more favourable soil structure on CA fields. There were problems of excess water accumulating in the basin treatment on the sandy soils at HRS, which resulted in lower yields especially in the first cropping season. At MFTC, this was not apparent: high infiltration rates were recorded in the basin treatment, which also resulted in high crop yields.

Results coincide with those from elsewhere showing that higher infiltration rates and soil moisture contents result from the absence of tillage (Derpsch et al., 1986), with surface mulch (Roth et al., 1988; Roth, 1992), and without a surface crust (Shaxson and Barber, 2003). Ehlers (1975) previously discussed the importance of macropores and biopores under CA systems. He concluded that disturbance of a continuous pore systems by tillage will reduce water infiltration. Higher earthworm numbers on CA plots found in MFTC in a different study suggest that the higher water infiltration measured on CA fields in 2006 and 2007 are closely linked to increased biological activity and pore continuity (Thierfelder and Wall, 2007).

On average higher soil moisture content was recorded on CA treatments than on conventionally ploughed control plots on both sites and both seasons. Higher available water for plant production should reduces the risk of crop failure, especially in periodically occurring mid-season droughts and result into higher crop yields. This was particularly true for MFTC, which resulted in significantly higher yields at MFTC in 2005/2006 but not in 2006/2007 as water was not limiting during critical cropping stages. Yield results at HRS showed however contradicting results in 2005/2006—infiltration and soil moisture were higher on CA treatments than the control treatment but some yield results showed the opposite. High rainfall amounts and reduced water runoff led to greater soil moisture content in the soil profile during the cropping season as more rainfall water was captured in the systems. This resulted into waterlogged conditions in this particular season, which negatively affected crop yields. There was however less waterlogging in the CP treatment because of the greater water runoff and the SS treatment, which could perhaps “drain” better than the other CA treatments.

Nevertheless, for plant growth, water access from 20 to 30 cm and below is of paramount importance (Shaxson and Barber, 2003) as most of the roots will be in the surface horizons, especially in the early stages of plant development. Vogel (1995), working on soils in Zimbabwe, found that although some maize root penetration was observed to about 750 mm, most of the soil water was accessed within the first 30 cm. Higher soil moisture in CP at MFTC in the deepest layer are likely to be a result of the inability of maize plants to grow up to a depth of 60 cm and make use of this water.

Results from the available moisture curves from HRS in 2005/2006 (Fig. 3) show that there was no seasonal drought during most of the season and soil moisture was almost always above field capacity. However, in the drier 2006/2007 season at HRS (534 mm rainfall) both the DS and BA treatments were not affected by very high soil moisture, could make better use of the rainwater and had overall higher grain yields. The low yield and lower RUE of the rip-line seeded treatment with the velvet bean intercrop at HRS in 2006/2007 was largely due to higher competition for water between the main crop and the legume during the dryer season.

In the 2005/2006 season at MFTC there was a period of marked reduction in soil water from the end of December 2005 until the second week of January 2006 (Fig. 4). The maize crop was planted on the December 1, 2005, and therefore the period of reduced soil

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moisture occurred 2–3 weeks before tasslingâa period commonly regarded as most critical for the formation of the maize cob. Available moisture was lowest in the control treatment, with soil moisture well below 50% available moisture and sometimes below PWP. It appears that this period of stress resulted in significantly lower grain yields in this treatment. A similar scenario happened in 2006/2007 but reductions were not as marked as in 2005/2006, were after the critical pre-flowering period and therefore had smaller effects on final grain yield.

In the treatment seeded to cotton at MFTC water infiltration rates and soil moisture content were lower than the other treatments towards the end of each cropping season. The lower infiltration rates were probably due to more surface soil disturbance because of more frequent and intensive hand-weeding of the cotton crop in which the canopy was slower to cover than in the maize crop. Higher water consumption in cotton is expected at the end of the season when cotton develops its full canopy and maize is at senescence. However, this also has an effect on the subsequent maize crop as more rain is needed to fill up the soil profile again. This can clearly be seen in Fig. 4 where the direct seeded maize crop after cotton (A2M) had the lowest available soil moisture at the end of 2006 until the soil profile slowly filled up again at the beginning of January 2007 and towards the end of the season was one of the treatments with highest soil moisture.

The relatively high erosion rates (7–8 t ha^{-1} in 2005/2006) and runoff amounts (315–384 mm in 2005/2006; 165–221 mm in 2006/2007) on the CA treatments at HRS are due to the sandy soil texture and hand-weeding, which was necessary because of high weed pressure on-site. However, erosion and runoff rates on the CA plots were still considerably lower than on conventionally ploughed plots. Judicious use of herbicides would help to overcome the problem of surface soil disturbance and would no doubt reduce the amount of soil erosion on CA plots.

5. Conclusion

Results from the on-station trials in Zimbabwe and Zambia, comparing conventionally ploughed and conservation agriculture systems, showed generally higher infiltration and soil moisture on CA plots with residue retention. Higher available soil moisture on CA fields especially during critical crop development stages resulted in higher maize grain yield at MFTC in 2005/2006 thus showing higher rainfall-use efficiency. Some CA treatments especially at HRS, Zimbabwe in 2005/2006 were negatively affected by too much water accumulation in this particular season, leading to water-logging and reduced yield. Higher infiltration on CA fields and reduced runoff changed the water balance, also increasing the components of crop transpiration, evaporation and/or deep drainage, which should, if rainfall is not excessive, reduce the risk of crop failure in the region. The locally generated data are consistent with results from Brazil, Argentina, Colombia and Paraguay (Roth et al., 1988; Shaxson, 2003; Sidiras et al., 1983; Thierfelder, 2003) and can be used for further recommendations in the region.

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