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A comparative analysis of conservation agriculture systems: Benefits and challenges of rotations and intercropping in Zimbabwe

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ABSTRACT

Increasing soil degradation in southern Africa and the potentially negative effects of climate change demand "greener" solutions to reverse this trend. Conservation agriculture (CA) has been proposed as one of those solutions and field level data show marked benefits of this new cropping system. Nevertheless, the use of rotations and/or associations in CA systems is challenging at both the farm and community level. Intercropped maize (*Zea mays* L.) with grain legumes, cowpea and pigeonpea (*Cajanus cajan* L. (Millsp.)), as well as maize rotated with cowpea (*Vigna unguiculata* L. (Walp)) and sunnhemp (*Crotalaria ochroleuca* L.) was studied for up to eight seasons under CA and conventional agriculture in Zimbabwe. The objective of this study, carried out on-farm and on-station, was to highlight the effects of CA systems on some soil quality indicators and crop productivity. Where possible the specific effects of rotation and intercropping was separated and compared with monocropping. The on-station and on-farm results show: an increase of up to 331% in water infiltration, a 31% greater soil carbon in the top 60 cm than on adjacent conventionally ploughed fields, a 6% lower bulk density in the top 10 cm and 32.5–36 t ha^{-1} less cumulative soil erosion in CA fields after seven cropping seasons compared with the conventional control treatment. The comparative productivity analysis between continuous maize, maize intercropped with cowpea or pigeonpea and maize in rotation with cowpea or sunnhemp, shows marked benefits of rotation especially in CA systems. The benefits of CA especially when rotated with leguminous crops, increase over time, suggesting that there are improvements in soil structure and fertility. However, field level benefits will not increase the overall adoption of rotations and intercropping in CA systems, unless the socio-economic constraints at the farm and community level are addressed.

1. Introduction

Increasing concern about the future of agriculture in sub-Saharan Africa in light of accelerating soil degradation (Oldeman et al., 1990; Kumwenda et al., 1998; Sanginga and Woomer, 2009) and potential threats of climate change (Lobell et al., 2008), have increased the need for new and more adapted cropping systems that increase production, whilst conserving the natural resource base (Wall, 2007; Kassam et al., 2009; Thierfelder and Wall, 2009). Conservation agriculture (CA) is one of the "greener" solutions currently being controversially discussed (Gilbert, 2012) as a potential cropping system that can mitigate the negative effects of declining soil fertility and climate change, under a range of farming systems (Hobbs, 2007; Kassam et al., 2009). CA is a cropping system based on: minimum soil disturbance, the retention of living or dead plant material as surface mulch and rotation of crops of different species in full rotations, as inter-or relay crops (FAO, 2002; Hobbs, 2007).

Rotations with leguminous crops have the potential to increase the level of nitrogen in the soil through biological nitrogen fixation (BNF) (Giller, 2001). Although the use of mineral fertiliser alone will not solve the challenges of soil degradation and declining fertility (Sanchez, 2002; Ngwira et al., 2012), there are strong advocates for such quick solutions (Gilbert, 2012). The use of mineral fertiliser should be in tandem with cropping systems like CA that built up organic carbon (humus) and achieve sustainability in the longer term (Wall, 2007).

Nevertheless there are constraints to the successful implementation of CA systems, especially in the small-scale farming sector; challenges that need to be overcome by adapting CA to the circumstances of the site and the farmer (Wall, 2007; Giller et al., 2011; Baudron et al., 2012; Valbuena et al., 2012).

Conventional farming systems in southern Africa are based on the mouldboard plough, or on small hand hoes locally called "badza" for land preparation and planting. Ploughing is normally done during winter or at the onset of the rainy season in October/November. Crop residues are being grazed, burned or removed and in some instances incorporated by the plough or hand hoe.

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Table 1
Some soil properties of reference profile C, *endostagnic dystric Luvisol*, Henderson Research Station and a field of farmer Mr C. Barwa, Madziwa Communal Area, Zimbabwe.

Horizons	Depth	Bulk density	Mottling	pH	CEC	BS	Ctot	Particle size [%]		
	[cm]	[g cm^3]	[vol%]	[CaCl$_2$]	[cmol kg^{-1}]	[%]	[%]	Sand	Silt	Clay
Henderson										
Ahp	0–28	1.29	–	4.5	3.7	39	0.44	77	16	7
Ah2	–35	1.48	–	4.5	2.0	55	0.22	73	20	7
E	–70	1.45	5	4.2	1.6	37	0.06	83	13	4
Bs	–105	1.67	20–30	4.5	1.7	44	–	84	14	2
Bt	>115	1.73	20–30	4.3	7.0	38	–	66	15	19
Madziwa	0–10	1.33	NA	5.5	5.1	NA	0.45	89	5	6
	10–20	1.25	NA	5.5	5.7	NA	0.26	89	4	7
	20–30	1.28	NA	6.2	6.2	NA	0.26	91	4	5
	30–60	1.40	NA	6.2	6.0	NA	0.17	89	3	8

Notes: CEC, cation exchange capacity; BS, base saturation; Ctot, total carbon.

For CA, new seeding technologies need to be applied. Currently there is a range of planting systems being promoted for small-scale farmers in southern Africa (Johansen et al., 2012). Farmers in Malawi, Mozambique, Zambia and Zimbabwe who traditionally use manual tools (e.g., the hand hoe), have started to experiment with CA and now plant their crops with a pointed dibble stick (Bunderson et al., 2011), a manual jabplanter (*matraca*) (Johansen et al., 2012), a manual hoe planter[1] or into previously made planting basins (Haggblade and Tembo, 2003; ZCATF, 2009).

Where animal traction is available, farmers are hesitant to start manual CA and have developed replacement tools for the mouldboard plough. There are a number of rip-line seeding and sub-soiling tools available (e.g., the Magoye ripper, different designs of knife ripper and the Palabana sub-soiler) that are cheap replacements for the plough. The existing plough can be modified by removing the shear blade and attaching the ripper assembly instead. Currently, a capital investment of only US$25 is required to purchase the ripper attachment. More expensive but also more practical tools are the animal traction direct seeders (i.e., from Fitarelli Máquinas Agrícolas, Brazil or Grownet Investment, Zimbabwe). With the direct seeder, sowing and fertiliser application is done at once, which significantly saves time and labour for farmers (Johansen et al., 2012).

While the principle of minimum soil disturbance is more adopted by farmers, the retention of crop residues as mulch and the introduction of crop rotations and associations is more complex (Thierfelder and Wall, 2010b; Thierfelder et al., 2012). In many cases socio-economic constraints play a significant role in the reduced adoption of those principles (Giller et al., 2009). Farmers cannot retain enough residue in areas with a strong crop-livestock interaction (Zambia and Zimbabwe) compared with other areas where livestock is less common (Malawi and Mozambique). Nevertheless livestock is an important asset in the small-scale farmer setting, e.g., as a source of traction, manure and nutrients, as capital and insurance in times of drought. Strategies need to be developed that allow for both livestock feed and crop residue retention (Thierfelder and Wall, 2012).

Farmers do not practice crop rotation or intercropping because of the lack of availability of seed and dysfunctional markets for produce (Snapp et al., 2002) and the perceived area loss to a rotational crop instead of maize, which is the main food crop in subsistence households of southern Africa (Dowswell et al., 1996). Other obstructions are the lack of knowledge about the benefits of crop rotation and associations such as breaking pests and disease cycles, improvements in soil fertility, reductions in risk of crop failure and additional incomes (Thierfelder and Wall, 2010b), and finally the lack of knowledge on how to grow these crops under CA (Snapp et al., 2010).

Previous work on CA systems in southern Africa has highlighted the cumulative benefits of rotations (Thierfelder and Wall, 2010a,b; Thierfelder et al., 2012) but a comparative analysis of rotation and intercropped maize-based CA systems is still missing.

Long-term data (2005–2012) from on-station and on-farm trials was used to show the importance rotation and intercropping in CA systems on: soil carbon, bulk density, infiltration and soil erosion. The specific objectives of this study were to analyse and quantify the rotational and intercropping benefits on some soil quality indicators and crop yield and to undertake an extensive comparative analysis.

2. Materials and methods

2.1. Soils and experimental sites

The experiment was carried out at Madziwa, Ward 6 in the Shamva District (Madziwa), Zimbabwe (17.00S; 31.43E; altitude, 1169 m a.s.l) and at the Henderson Research Station (Henderson), Mashonaland Central, Zimbabwe (17.58S; 30.99E; altitude: 1136 m a.s.l.).

The trial at Madziwa was located in part of the communal area accessed by livestock. The terrain is gently undulating and the soils are derived from granitic and gneiss substrates and have a predominantly sandy soil texture in the top soil, although in some places the soil improves in the subsoil to a sandy loam (Table 1). Soils are typically characterised as *Arenosols* and in more fertile areas as *Cambisols* and *Luvisols* (WRB, 1998), low in organic matter and fertility (Nyamapfene, 1991). Major crops grown in the area are: maize (*Zea mays* L.), sorghum (*Sorghum bicolor*, L. (Moench)), cowpeas, common beans (*Phaseolus vulgaris* L.), groundnuts (*Arachis hypogaea* L.) and sunflower (*Helianthus annuus*, L.). The area is deforested due to the high population pressure in the communal area.

The Henderson site is characterised by an inclination of 5–6% while the Madziwa plots were on flat land. The soils are derived from granitic and gneiss substrates and are typical of the majority of Zimbabwean soils in communal farming areas (Nyamapfene, 1991). Predominant soil types are *dystric Arenosols* and *endostagnic Luvisols* (WRB, 1998). They are characterised by sand and sandy-loam soil textures (Table 1). The site is heterogeneous and has been affected by previous erosion events. Major crops grown in the area are: maize as the main staple food crop accounting for 50–90% of the caloric intake (Dowswell et al., 1996), soyabeans (*Glycine max*. L.), cotton (*Gossypium hirsutum* L.), tobacco (*Nicotiana tabacum* L.), sorghum and some grain legumes, such as common beans, cowpeas and groundnuts. The potential natural vegetation for both study

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[1] http://www.qybzg.com.

Table 2
Summary of seeding and harvesting dates at Madziwa and Henderson Research Station, 2005–2012.

Site	Cropping season	Seeding date	Harvesting date	Maize variety	Rainfall
Madziwa	2005/06	13.–14.12.2005	02.–03.05.2006	SC513	589
	2006/07	28.–29.11.2006	25.–26.04.2007	SC525	570
	2007/08	19.11–07.12.2007	09.–24.04.2008	ZM423	785
	2008/09	13–18.12.2008	07.05–02.06.2009	ZM521	791
	2009/10	23.11.–05.12.2009	20.04–27.05.2010	ZM521	550
	2010/11	27.11.–09.12.2010	12.04.–12.05.2011	ZM525	693
	2011/12	14–18.12.2011	15.05–06.062012	Pris601	714
Henderson	2004/05	10.12.2004	10.05.2005	SC627	718
	2005/06	24.11.2005	21.04.2006	SC627	1096
	2006/07	27.11.2006	20.04.2007	SC635	534
	2007/08	29.11.2007	16.04.2008	SC635	1060
	2008/09	17.11.2008	30.03.2009	SC635	733
	2009/10	23.11.2009	08.04.2010	ZS261	617
	2010/11	29.11.2010	05.04.2011	ZS261	681
	2011/12	04.11.2011	03.05.2012	Pris601	574

Note: Varieties were changed periodically to make use of genetic improvement over time. Varieties were however kept the same within all replicates in each year; planting and harvesting of on-farm trial replicates was done within time period dictated by soil moisture, maturity and farmer availability.

areas would be dry tropical forest and *miombo* woodland (Anderson et al., 1993).

The climate in the area is a moderately warm, winter dry and humid mid-latitude climate (CWah) according to Köppen's classification (Köppen, 1918). Given the moderate temperature conditions, rainfall amount and variability are the most critical climatic factors for smallholder agricultural production in the region (Vogel, 1994). The rainy season starts in October/November and ends between March and April (Table 2), although crop production is often affected by mid-season dry spells.

2.2. Experimental design

2.2.1. Madziwa

The experiments in Madziwa started in 2005/2006 and the results presented are for the seven years, from 2006 to 2012. The CA experiment at Henderson Research Station started in the 2004/2005 rainy season and results are presented for the period 2005–2012.

Trials at Madziwa were established in farmers' fields in 2005. Each farmer replicate consisted of a plot of 3000 m^2, which was initially subdivided into three equal portions where the main treatments were established.

(1) The conventional control treatment (CP) using an animal traction mouldboard plough at shallow depth (10–15 cm). Tillage was done in one single pass just before seeding. Residues were removed after harvest and the remaining stubble incorporated with the plough.
(2) The first CA treatment was a rip-line seeded (RS) treatment using a Magoye chisel-tine opener to create rip-lines. Seeding and fertilising were done by hand after the rip-lines had been created. Residues, such as thatching grass were used in the initial year to achieve sufficient ground cover and in consecutive years, crop residues from the fields were retained by either fencing the plot area, stacking the residues up near the plots, or by importing residues from an adjacent irrigation scheme. Locally growing grass species (*Hyparrhenia* spp.) were used as supplements if insufficient crop residues were available. The target residue cover at the onset of the rainy season was 2.5–3 t ha^{-1}.
(3) The second CA treatment used an animal traction direct seeder (DS) (Irmãos Fitarelli, Brazil, model #12). As in the first CA treatment, residues were retained from the previous harvest or supplemented with *Hyparrhenia* grass as needed. Seeding and fertilising were done automatically by the direct seeder.

Sole maize was planted in the first cropping season (2005/2006) and maize in rotation with soyabeans in 2006/2007 and cowpeas in 2007/2008. In the cropping season (2007/2008) the number of farmer replicates was increased to eight and the plots were subdivided into six subplots each of 500 m^2. On four sites a maize–cowpea rotation was tested against a maize–cowpea intercropping, whereas on the four other sites a continuous maize monocropping was tested against a full maize–cowpea rotation. The sites selection was based on farmer choice for the different cropping systems. This design was maintained in the subsequent years.

All three main tillage treatments received equal amounts of basal and top-dressing fertilisers and were planted with the same maize varieties in each year (Table 2). In this study "typical" but lower than recommended fertiliser rates were used. Basal dressing in Madziwa was 165 kg ha^{-1} Compound D (11 kg ha^{-1} N:10 kg ha^{-1} P: 10 kg ha^{-1} K) followed by a top-dressing of 69 kg ha^{-1} N as ammonium nitrate. The N top-dressing was applied in two equal splits 4 and 7 weeks after planting. In the legume phase of the full rotation only basal fertiliser was applied to the legume. The used rates are possibly higher than a smallholder farmer would use on his legume crops in Zimbabwe. However, the same P and K level was kept constant to avoid additional bias. The intercropped legume did not receive any additional fertiliser to avoid different fertiliser rates between main treatments.

Maize was seeded at a recommended plant spacing of 90 cm between rows and 50 cm in-row with two seeds per station to achieve a target plant population of 44,000 plants ha^{-1}. Seeding with the direct seeder was at 90 cm between rows and 25 cm within row and one seed per station (44,000 plants ha^{-1}). Seeding time was after the first substantial rains of more than 30 mm, in November or early December in each year (Table 2). Maize varieties were not kept the same throughout the study because farmers demanded new and improved varieties on a regular basis. Herbicides were not used and all weeding was carried out with hand hoes whenever weeds were 10 cm tall or 10 cm in circumference (usually 2–3 times per season).

2.2.2. Henderson

The experiment at Henderson consisted of one conventionally tilled control plot (CP) compared to three CA systems, in a randomised complete block design, initially with four replications. A fifth replication was added in the 2006/2007 crop season. The plot area was 160 m^2. The treatments at Henderson were as follows:

Table 3
Maize above-ground non-cob biomass yield (kg ha^{-1}) in each year at the continuous maize and rotation area, Henderson Research Station; 2005–2012.

	Maize biomass yield (kg ha^{-1})							
	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12
Henderson, continuous maize								
Conventional ploughing (CP)	2177 b	3606 a	4967 a	2458 a	1752 b	1598 a	4443 a	1951 a
Ripline seeding (RS)	2595 a	3903 a	4764 a	2492 a	3206 a	1906 a	5907 a	2394 a
Direct seeding (DS)	2390 ab	3618 a	5074 a	2451 a	2430 ab	1694 a	5266 a	2568 a
Ripline seeding + legume (RSL)	2292 ab	3382 a	4591 a	2630 a	2207 b	2105 a	5158 a	2320 a
LSD	331	772	1453	690	800	975	1677	939
P-Level	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Henderson, maize rotation								
Conventional ploughing (CPS)			4163 a	2474 a	2415 a	2090 a	5889 a	2787 a
Ripline seeding (RSS)			4121 a	2949 a	2988 a	2107 a	7909 a	3229 a
Direct seeding (DSS)			5041 a	2215 a	2649 a	1575 a	6771 a	3480 a
Ripline seeding + legume (RSLS)			5244 a	2300 a	2769 a	1678 a	5625 a	3410 a
LSD			1370	1479	923	653	2416	1384
P-Level			0.05	0.05	0.05	0.05	0.05	0.05

Note: Means followed by the same letter in column are not significantly different (LSD-test). Biomass material was kept on the soil as surface mulch in each year.

(1) Conventional mouldboard ploughing (CP). The soil was tilled just before seeding in one single pass. Residues removed and the remaining stubble incorporated with the plough.
(2) Ripping and hand-seeding (RS) of maize into a 10–15 cm deep rip-line opened by an animal traction ripper pulled by a pair of oxen. The rip-line seeded treatment was sub-soiled with the Palabana subsoiler in the first three cropping seasons and planted with maize in the sub-soiled lines and thereafter ripped with the Magoye ripper and planted into the rip-lines. Maize crop residues were retained in situ after each cropping season on the surface (Table 3).
(3) Direct seeding (DS) of sole maize, seeded with an animal traction direct seeder (2004–2006) (Irmãos Fitarelli, Brazil, model #12) or a manual jabplanter (2006–2010) (Irmãos Fitarelli, Brazil, model #9). Both implements allow direct seed and fertiliser placement in the soil through the mulch. Residues were retained as in RS.
(4) Ripping and hand-seeding (RSL) of maize with a legume intercrop was in a 10–15 cm deep rip-line opened by an animal traction ripper pulled by a pair of oxen. Residues were retained as in RS and DS.

All treatments were seeded to uniform maize in cropping seasons 2004/2005 and 2005/2006 except of the intercropping treatment RSL where velvet beans (*Mucuna prurience* L.) were intercropped from 2004 to 2006 and pigeonpea planted thereafter in the same rip-line between maize planting stations.

In 2006/2007 all plots were split into three sub-plots: on one sub-plot maize was planted continuously as a sole crop; on the other two plots both phases of a maize-sunnhemp rotation were planted from there onwards. Maize hybrid varieties were seeded in mid-November and harvested at the end of April in all years (Table 2). Velvet beans and later pigeonpea planted as intercrops were not harvested due to frost that killed the plants before they could set seed.

Sunnhemp was seeded in hand hoe lines spaced 45 cm apart and the seed dribbled at a rate of 30 kg ha^{-1}. At physiological maturity the sunnhemp was cut and spread on the soil surface as surface mulch (Table 4).

Maize crops were fertilised with the same amount of basal fertiliser as at the on-farm sites. The N top-dressing for maize was 69 kg ha^{-1} N applied in splits of 34.5 kg ha^{-1} 4 and 7 weeks after crop emergence. Weed control was initially done with glyphosate and atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) but since 2007 only manual weeding was carried out.

2.3. Soil carbon and bulk density

Soils were collected with a soil auger at three depth layers (0–10 cm, 10–20 cm and 20–30 cm) at Henderson and in four depth layers (0–10 cm, 10–20 cm, 20–30 cm and 30–60 cm) at Madziwa. Soil was collected from 6 (Henderson) and 10 (Madziwa) sampling points and mixed into a composite sample. Core samples were taken from each treatment to determine the bulk density. The composite samples were air dried, passed through a 2 mm sieve and a sub-sample sent for analysis. The total carbon was measured through dry combustion with a C.E. Elantech C/N analyser. Soil samples were collected in October 2008 in Henderson after four cropping seasons and in July 2010 at Madziwa after five cropping seasons. The percentage of soil carbon was converted to Mg ha^{-1} using the following formula described by Ellert and Bettany (1995):

$$\text{M element} = \text{conc} \times p_b \times T \times 10\,000\,\text{m}^2\,\text{ha}^{-1} \times 0.001\,\text{Mg kg}^{-1} \tag{1}$$

Table 4
Sunnhemp biomass yield (kg ha^{-1}) from rotational plots at Henderson Research Station, Zimbabwe 2007–2012.

Treatments	Sunnhemp biomass yield (kg ha^{-1})					
	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12
Conventional ploughing (CP)	7527 a	3356 a	9738 a	6142 ab	16,887 a	7472 a
Ripline seeding (RS)	8156 a	3466 a	8913 a	7644 a	20,516 a	6598 a
Direct seeding (DS)	6088 a	2517 a	6907 a	6701 ab	18,865 a	5957 a
Ripline seeding + legume (RSL)	5834 a	3258 a	7043 a	3232 b	13,007 a	6540 a
LSD	3866	1921	3581	3601	9033	2563
P-Level	0.05	0.05	0.05	0.05	0.05	0.05

Note: Means followed by the same letter in column are not significantly different at $P < 0.05$ probability (LSD-test). Biomass material was kept on the soil as surface mulch in each year.

where

M element = element mass per unit area (Mg ha^{-1})
conc = element concentration (kg Mg$^{-1)}$
p_b = field bulk density (Mg m^{-1})
T = thickness of soil layer (m)

2.4. Infiltration

Two infiltration methods were used in this study. At Henderson a rainfall simulator described by Amézquita et al. (1999) and Thierfelder and Wall (2009) was used. It measures how much runoff occurs in a simulated rainfall event in a small plot area of 32.5 × 40 cm (0.13 m^{-2}). The difference between water applied and runoff is recorded as infiltration. Infiltration measurements were repeated in January of each year when the maize crop was at, or just before, the tasseling stage. The soil was at field capacity and Horton's infiltration model was used to compare treatments (Kutilek and Nielsen, 1994). Measurements in each treatment were repeated twelve times to increase reliability. At Madziwa, the time-to-pond measurement described by Verhulst et al. (2011) and Thierfelder and Wall (2012) was used. A metal wire ring of 50 cm diameter was placed on the soil surface and water applied in the middle of the ring with a watering can. The time taken for water to flow out of the metal ring was measured and the time-to-pond calculated. Eighteen measurements were taken on each replication and the means calculated per treatment. Infiltration was then calculated using a regression curve developed at Henderson in March 2009, as both sites share a comparable soil texture. The linear relationship between both measurements was: $y = 22.3x - 43$. The r^2 of this relationship was 0.67. For more details on the procedure see (Thierfelder and Wall, 2012).

2.5. Soil erosion

Erosion and runoff plots were established at Henderson at a slope of 5–7%, which is described in detail by Thierfelder and Wall (2009). Only three treatments were equipped with run-off plots (CP, DS and RSL), which were 9 m long and 4.5 m wide (total area 40.5 m^2). Water erosion and runoff were measured from the second rainy season (2005/2006) onwards. Eroded soil was collected from the drains and settling tanks after each erosion event, weighed and the moisture content calculated. Soil moisture per cropping season was calculated and the cumulative soil loss calculated on a dry-weight basis.

2.6. Harvest procedure

The crops were harvested at physiological maturity at each site. Cobs and above-ground biomass were collected from 10 samples of 9 m^2 selected at random from each treatment in Madziwa and from 8 samples of 4.5 m^2 at Henderson. Samples were weighed in the field and sub-samples of 20 cobs (Madziwa) and 16 cobs (Henderson) per treatment were taken for determination of grain moisture content and calculation of yield in kg ha^{-1} at 12.5% moisture content. At all sites in Madziwa the performance of DS and RI was tested against CP on plots with continuous maize, maize in rotation with cowpea and maize intercropped with cowpea. At Henderson, all three CA treatments (RS, DS, RSL) were tested with continuous maize, intercropped with pigeonpea and rotated with sunnhemp. Yield benefits between CA and conventional treatments were calculated by subtracting the yield of the conventional plots from the CA plots. A positive result in (kg ha^{-1}) signifies a yield benefit of CA, a negative result shows that CP was better than CA. In addition, maize grain yields of different systems were plotted against each other at Henderson. A comparison that presents a dot on the 1:1 line signifies that both systems are the same, whereas dots above or below the 1:1 line favour the respective system in the analysis.

2.7. Statistical analysis

The analysis focussed on the yield differences of CA treatments over conventional control plots on CA treatments with maize only against CA treatments with all three principles and intercropped systems against rotations. Statistical analyses were carried out using STATISTIX for personal computers (Statistix, 2008). Infiltration, time-to-pond, total carbon and yield data were tested for normality and subjected to an analysis of variance (ANOVAs) using a completely randomised block design. The ANOVAs were also used to evaluate the effect of season, tillage treatment and rotation and their interaction on maize grain yield. Where the F-test was significant, a least significant difference (LSD) test was implemented at $P \leq 0.05$, if not stated otherwise, to separate the means.

3. Results

3.1. Soil carbon and bulk density

Results at Madziwa and Henderson showed significantly different carbon results between the conventional ploughed control and the CA treatments (Table 5). At Madziwa, soil carbon was greater in the DS plots in the 0–10 cm depth zone (4.5 Mg ha^{-1} in comparison to 3.2 Mg ha^{-1}) and 10–20 cm depth zone (3.2 Mg ha^{-1} versus 2.5 Mg ha^{-1}) after five cropping seasons, whereas no difference was discovered at depths of 20–30 and 30–60 cm. Over the whole investigated profile of 0–60 cm, soil carbon was 31% greater (14.7 Mg ha^{-1} versus 11.2 Mg ha^{-1}) than in the conventional control.

At Henderson, the smallest amount of soil carbon (7.1 Mg ha^{-1}) was found in the conventionally ploughed control (CP) in the top 10 cm, whereas the largest amounts were found in the rip-line seeded treatment with legume intercrop (RSL) (9.9 Mg ha^{-1}). In the 10–20 cm depth zone, only RSL was larger than all the other treatments. In the 20–30 cm depth zone, there was no significant difference. Summarising the carbon content in the whole 0–30 cm soil profile showed the largest amount of soil carbon in RSL and the smallest in CP (Table 5).

Bulk density between the DS treatments and CP at Madziwa was only different in 0–10 cm and 30–60 cm depth zones and the CA systems had a significantly lower bulk density than the conventional control plots (Table 5).

3.2. Infiltration

Infiltration measured at Madziwa using the time-to-pond measurement and the regression curve, showed significantly different results ($P < 0.01$) in all four years (Table 6). In all cases CP had the lowest infiltration, whilst the rip-line seeded (RS) and direct seeded (DS) treatments outperformed the CP. Infiltration was 145–331% higher on the CA plots.

At Henderson, infiltration was measured since 2006 and long-term data is available from plot areas with continuous maize (Table 6). Significant differences were discovered in all years. In 2006, infiltration was greatest in DS (47.2 mm h^{-1}) and smallest on CP (31.6 mm h^{-1}). In 2007, RSL was greatest (78.4 mm h^{-1}) while CP was again smallest (51.5 mm h^{-1}). From 2008 to 2010 and in 2012, all CA treatments outperformed CP. In 2011, only DSwas different from CP. The greatest difference between treatments was achieved in 2009, when DS exceeded CP by 209% and in 2012 when DS had 93% more infiltration than CP.

Table 5
Amount of soil carbon and bulk density in conventional ploughed and CA treatments in Henderson (2008) and Madziwa (2010), measured in different depth layers after 4 (5) years of cropping.

Site and treatment	Soil carbon (Mg ha^{-1})				
Madziwa	0–10 cm	10–20 cm	20–30 cm	30–60 cm	Total 0–60 cm
Conventional ploughing	3.2 b	2.5 b	1.7 a	3.8 a	11.2 b
Direct seeding (DS)	4.5 a	3.2 a	2.3 a	4.7 a	14.7 a
LSD	0.58	0.63	0.71	1.00	2.8
P-Level	0.05	0.10	NS	NS	0.05

	Bulk density (g cm^3)			
Conventional ploughing	1.27 b	1.25 a	1.29 a	1.39 b
Direct seeding (DS)	1.21 a	1.24 a	1.29 a	1.31 a
LSD	0.05	0.09	0.11	0.07
P-level	0.05	NS	NS	0.10

Henderson, sole maize	Soil carbon (Mg ha^{-1})			
	0–10 cm	10–20 cm	20–30 cm	Total 0–30 cm
Conventional ploughing (CP)	7.1 b	6.7 b	4.6 a	18.4 b
Ripline seeding (RS)	9.2 ab	7.6 ab	5.1 a	22.0 ab
Direct seeding (DS)	9.0 ab	7.3 b	5.3 a	21.5 ab
Ripline seeding + legume (RSL)	9.9 a	9.6 a	5.1 a	24.7 a
LSD	2.8	2.3	1.4	4.0
P-level	0.05	0.10	NS	0.05

Note: Means followed by the same letter in column are not significantly different at the respective probability (LSD-test); samples were all taken in October 2008 (Henderson) and July 2010 (Madziwa) after 4 (5) years of cropping. Samples were corrected for bulk density and calculated to Mg ha^{-1}.

In 2011 an additional infiltration measurement was done on the maize-sunnhemp rotation area. The difference between all CA and CP treatments was again highly significant ($P < 0.01$) (Table 6 and Fig. 1). The greatest difference of 135% higher infiltration was found between the DS treatment with no-tillage and residue retention (77.2 mm h^{-1}) and CP (32.8 mm h^{-1}). There was a marked difference between the comparisons of infiltration curves in the continuous maize plots compared with the plot under rotation. Whilst the final infiltration rate on CP treatment was almost the same in the comparison (36.5 mm h^{-1} and 32.8 mm h^{-1} in CP and CPS), the CA treatments under rotation maintained a greater infiltration than the CA plots with continuous maize (Fig. 1).

3.3. *Soil erosion*

Soil loss was largest on CP compared with DS and RSL and amounted to a cumulative loss of 61.7 t ha^{-1} on CP after seven cropping seasons, compared with 29.2 t ha^{-1} and 25.7 t ha^{-1} in the two CA cropping systems (Fig. 2a). The largest annual increases on CP plots were recorded in the 2007/08 and 2008/09 cropping seasons, where 15 t ha^{-1} and 14.5 t ha^{-1} of soil were lost, respectively (Fig. 2b). Soil loss on both CA treatments was much lower, although the threshold of 5 t ha^{-1} was exceeded in two cropping seasons at the beginning. This was in the cropping season 2005/06, when DS had 8 t ha^{-1} and RSL had 6.9 t ha^{-1} soil loss and in 2007/08, when the DS had 5.7 t ha^{-1} and RSL had 8.6 t ha^{-1} soil loss. However, in

Table 6
The effects of different conservation agriculture and conventional cropping systems on final infiltration rates measured on: continues maize, maize in rotation with sunnhemp and maize intercropped with legumes.

Site and treatment	Final infiltration rate (mm h^{-1})						
	2006	2007	2008	2009	2010	2011	2012
Madziwa							
Conventional ploughing (CP)				33.6 b	25.8 b	30.7 b	31.2 b
Ripline seeding (RS)				86.7 a	106.6 a	81.4 a	89.6 a
Direct seeding (DS)				85.6 a	111.2 a	82.7 a	86.3 a
LSD				21.9	16.5	25.4	13.4
P-Level				0.01	0.01	0.01	0.01
Henderson, continues maize							
Conventional ploughing (CP)	31.6 b	51.5 b	26.3 b	25.3 b	40.7 b	36.5 b	42.8 b
Ripline seeding (RS)	36.6 ab	69.7 a	50.5 a	63.3 a	60.0 a	44.6 ab	80.6 a
Direct seeding (DS)	47.2 a	74.8 a	50.3 a	78.2 a	67.1 a	54.3 a	82.7 a
Ripline seeding + legume (RSL)	41.5 ab	78.4 a	57.6 a	75.7 a	63.1 a	47.1 ab	81.3 a
LSD	13.6	14.9	11.4	16.3	21.5	13.8	9.5
P-Level	0.05	0.05	0.01	0.01	0.01	0.05	0.01
Henderson, maize rotation							
Conventional ploughing (CP)						32.8 b	
Ripline seeding (RS)						69.9 a	
Direct seeding (DS)						77.2 a	
Ripline seeding + legume (RSL)						74.7 a	
LSD						15.6	
P-Level						0.01	

Note: Maize is rotated with sunnhemp in Henderson, the ripline seeded treatment was intercropped with velvet beans in 2006 and 2007 and intercropped with pigeonpea thereafter; infiltration at Henderson was measured with a mini-rainfall simulator and in Madziwa with the time-to-pond methods; the infiltration rate was estimated using a regression curve described in Thierfelder and Wall (2012). Means followed by the same letter in column are not significantly different at the respective probability (LSD-test).

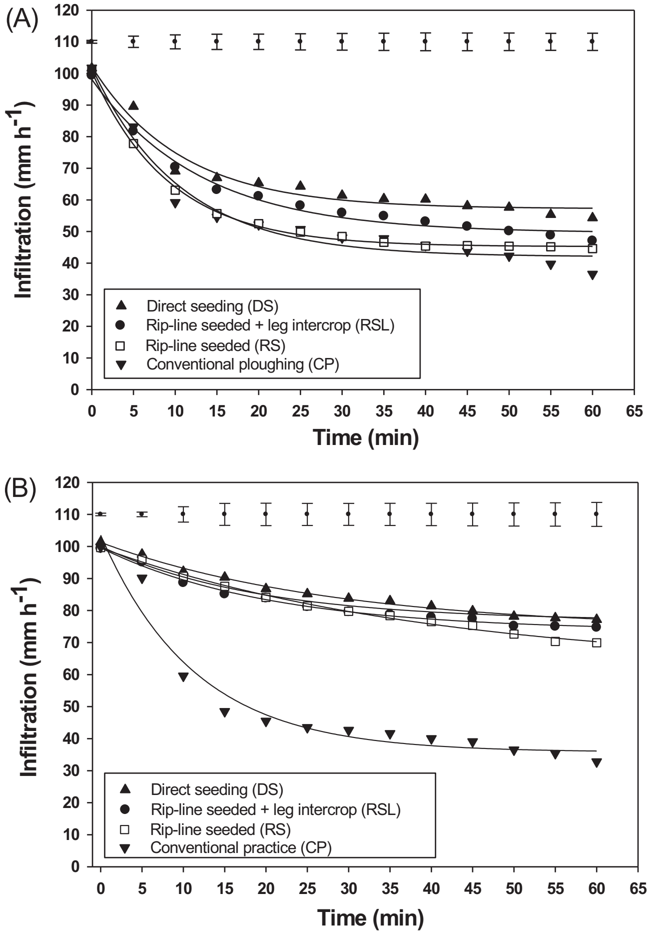

Fig. 1. Infiltration on three conservation agriculture and one conventionally ploughed system measured on plots with continues maize monocropping (a) and maize-sunnhemp rotation (b). Henderson Research Station, January 2011.

the last cropping season (2009–2012) there was little erosion measured on the CA treatments. Soil loss on CP was not greatly affected by the annual rainfall received (Fig. 2b) but was large during both low (700 mm) and high (1100 mm) rainfalls. The CA treatments closely followed the increase in annual rainfall. Soil loss was small during dry years and larger during wet years. Rainfall distribution, especially during drier years, was characterised by mid-season dry spells (Fig. 2c).

3.4. Yield data

3.4.1. Madziwa

Significant grain yield differences between the main treatments were observed in the continuous maize and intercropped maize in 2010 and between all strategies in 2012 at Madziwa (Tables 7a and 7b). In 2010, DS outperformed CP in the continuous maize and the intercropping maize comparison, whereas RI was intermediate. In 2012, DS was the significantly highest in all growth comparisons. However, yield benefits of CA were evident in both treatment comparisons compared with the conventional control (Fig. 3a and b). Benefits of crop rotation over continuous maize and intercropped maize were observed when the means of all tillage treatments were compared (Tables 7a and 7b). In 2011, the largest (64%) yield benefit between full rotation and continuous maize was recorded, followed by 2009 (35%) and 2010 (11%). In 2011, the average maize yield in rotation with cowpea across all treatments was 35% greater than the intercropped maize, followed by 2010 (14%) and 2009 (10%). Intercropping maize with a legume was advantageous in 2009 and 2011, where the intercropped maize outperformed sole maize by 23% and 22%, respectively. In 2010, there was a slight yield penalty of −3% of intercropping maize in comparison with sole maize, whereas a slight yield gain of 6% in 2012. In 2012, the average maize yield in rotation was slightly lower than both sole maize and intercropped maize mainly due to lower yield on the DS.

Cowpea yields on the rotational plots were different in cropping season 2009/2010 and 2011/2012. In both seasons yields of the rip-line seeded treatment exceeded CP, while DS was intermediate. Cowpea grain yields at Madziwa were low on the intercropped treatments, due to lower target population (i.e., cowpea rows are alternated with maize rows in the intercropped treatment, instead of planting them in 45 cm rows in the sole cowpea stand) and higher competition with the maize crop (Tables 7a and 7b). Significant differences on the intercropped cowpea were only discovered in the first cropping season where DS exceeded CP.

3.4.2. Henderson

In the first three years there was no significant treatment difference (Fig. 4). A full analysis was possible in 2008 after the maize-sunnhemp rotation was established in 2007. The first significant differences between treatments accrued from 2009 onwards. In 2009, all CA treatments were larger than the conventional ploughed control (CP) with no rotation but only RS had greater yields than the conventionally ploughed treatment with rotation (CPS). In 2010, this changed more in favour of the rotational plots.

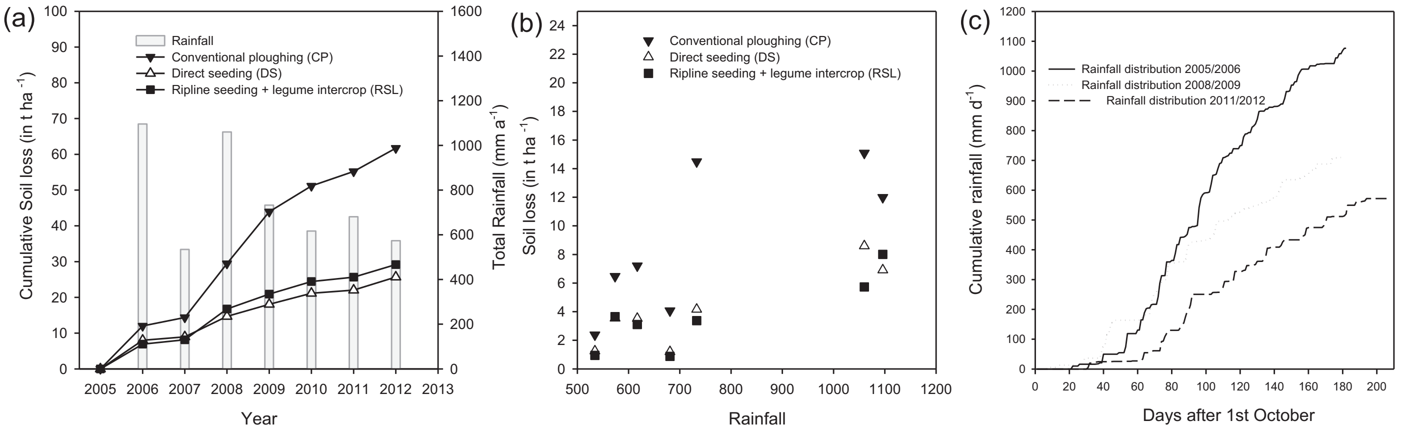

Fig. 2. (a) Cumulative soil loss in t ha^{-1} and corresponding measured rainfall, (b) the relationship between amount of rainfall and soil erosion, and (c) rainfall distribution for 1st, 4th and 7th season at Henderson Research Station, 2005–2012.

Table 7a
Maize yields on conventional and conservation agriculture cropping systems planted as continuous maize crops, as rotations with cowpea and intercropped with cowpea at Madziwa, Zimbabwe, 2006–2012.

Year	Treatment	Maize, continues	Maize rotation	Maize intercropped
2005/06	Conventional ploughing (CP)	3354		
	Ripline seeding (RS)	2710		
	Direct seeding (DS)	2285		
	Mean	2783		
2006/07	Conventional ploughing (CP)	3418		
	Ripline seeding (RS)	1757		
	Direct seeding (DS)	1151		
	Mean	2109		
2007/08	Conventional ploughing (CP)		2621 a	1140 a
	Ripline seeding (RS)		2597 a	1498 a
	Direct seeding (DS)		2450 a	1740 a
	Mean		2556	1459
	LSD		383	1390
2008/09	Conventional ploughing (CP)	1432 a	2000 a	1566 a
	Ripline seeding (RS)	1762 a	2063 a	2231 a
	Direct seeding (DS)	1524 a	2310 a	1987 a
	Mean	1573	2124	1928
	LSD	676	320	1286
2009/10	Conventional ploughing (CP)	2723 b	3224 a	2446 b
	Ripline seeding (RS)	3110 ab	3358 a	3041 ab
	Direct seeding (DS)	3493 a	3781 a	3572 a
	Mean	3109	3454	3020
	LSD	539	375	841
2010/11	Conventional ploughing (CP)	1662 a	2203 a	1554 a
	Ripline seeding (RS)	1701 a	2609 a	1952 a
	Direct seeding (DS)	1488 a	3148 a	2409 a
	Mean	1617	2653	1972
	LSD	1030	1030	1066
2011/12	Conventional ploughing (CP)	2106 b	2376 b	2655 b
	Ripline seeding (RS)	2666 ab	2861 a	2653 b
	Direct seeding (DS)	3341 a	2806 a	3297 a
	Mean	2704	2681	2869
	LSD	1110	412	456

Note: Statistical analyses were only carried out from 2008 to 2012 due to lack of sufficient replications in 2006 and 2007, all means were tested at $P < 0.05$ significance level. Means followed by the same letter in column are not significantly different at the respective probability (LSD-test).

Table 7b
Cowpea grain and biomass yield on conventional and conservation agriculture cropping systems planted as maize–cowpea rotation and as maize–cowpea intercropping at Madziwa, Zimbabwe, 2007–2012.

Year	Treatment	Cowpea in rotation		Cowpea intercropping	
		Grain (kg ha^{-1})	Biomass (kg ha^{-1})	Grain	Biomass
2006/07	Conventional ploughing (CP)	50	518		
	Ripline seeding (RS)	202	958		
	Direct seeding (DS)	157	594		
2007/08	Conventional ploughing (CP)	274 a	368 a		
	Ripline seeding (RS)	240 a	332 a		
	Direct seeding (DS)	288 a	376 a		
	LSD	221	181		
2008/09	Conventional ploughing (CP)	358 a	692 a	27 b	251 b
	Ripline seeding (RS)	425 a	789 a	54 ab	424 ab
	Direct seeding (DS)	356 a	796 a	90 a	779 a
	LSD	273	272	53	476
2009/10	Conventional ploughing (CP)	334 b	1569 a	13 a	270 a
	Ripline seeding (RS)	443 a	1303 a	19 a	322 a
	Direct seeding (DS)	391 ab	1367 a	25 a	484 a
	LSD	84	1433	22	401
2010/11	Conventional ploughing (CP)	486 a	764 a	56 a	487 a
	Ripline seeding (RS)	687 a	691 a	90 a	390 a
	Direct seeding (DS)	723 a	646 a	95 a	403 a
	LSD	335	202	57	178
2011/12	Conventional ploughing (CP)	704 b	815 b	236 a	n.a.
	Ripline seeding (RS)	990 a	1670 a	341 a	n.a.
	Direct seeding (DS)	879 ab	1461 ab	483 a	n.a.
	LSD	183	788	419	

Note: Statistical analyses were only carried out from 2008 to 2012 due to lack of sufficient replications in 2007, all means were tested at $P < 0.05$ significance level. Means followed by the same letter in column are not significantly different at the respective probability (LSD-test).

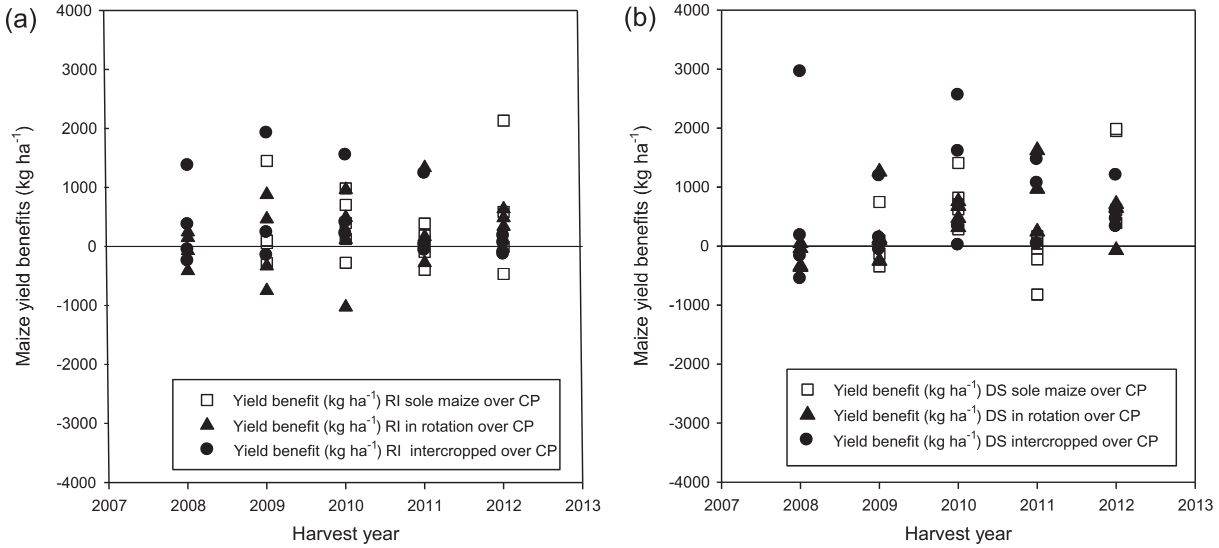

Fig. 3. Yield benefits of all ripline seeding (a) and direct seeding (b) strategies with continuous maize, rotating maize and intercropping maize over the conventional control strategy, Madziwa 2008–2012. *Note*: the CA practice with sole maize is compared to the conventional control with sole maize. The same applies to rotation and intercropping.

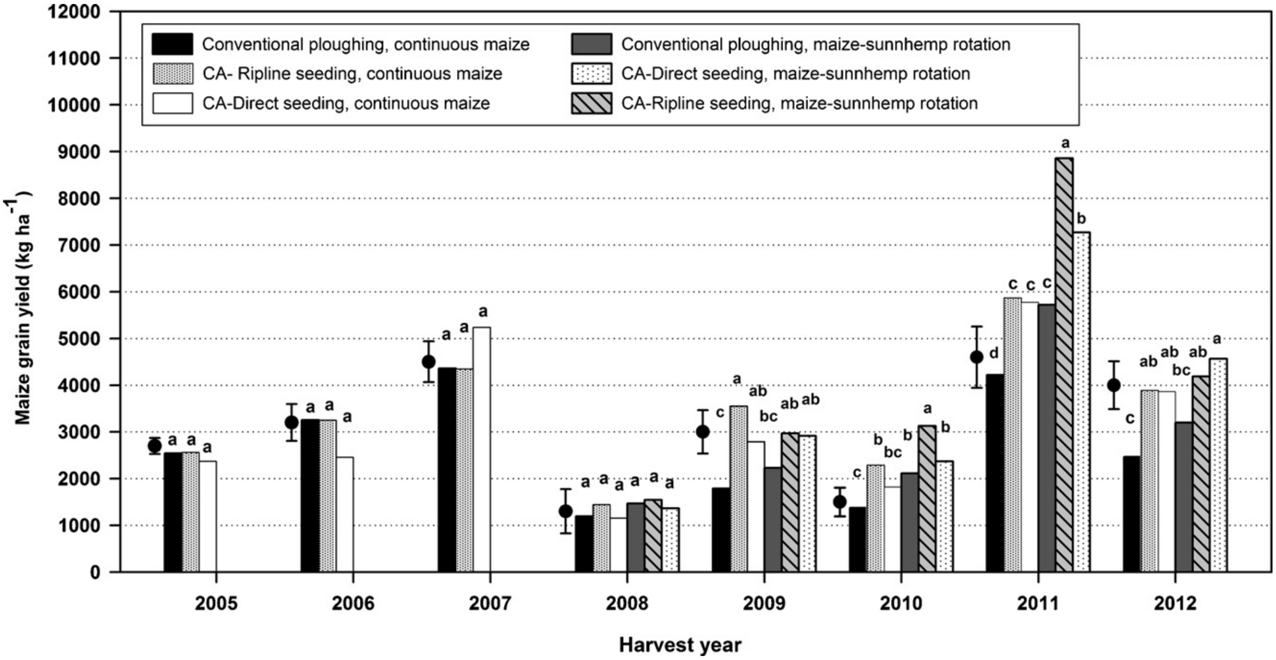

Fig. 4. Effects of two no-tillage treatments and a conventionally ploughed treatment planted with continuous maize and in a maize-sunnhemp rotation on maize grain yield (kg ha^{-1}), Henderson Research Station, 2005–2012.

The greatest yield was recorded in RSS followed by DSS, RS and the smallest yield was recorded in CP. In 2011, greatest yields were again recorded on RSS followed by DSS, then a group of RS, DS and CPS and the smallest yield was again on CP. In 2012, the direct seeded rotational maize plot (DSS) had the greatest yields, followed by RSS, RS and DS. CP again had the smallest yields.

Maize and sunnhemp biomass yields were recorded to quantify the amount of mulch, which was retained in each year (Tables 3 and 4), however significant treatment differences were only discovered at Henderson in cropping season 2004/2005 and 2008/2009 where the rip-line seeded plots with continuous maize cropping exceeded the control treatment CP. No other significant treatment differences were measured on continuous maize and maize in rotation with sunnhemp.

Sunnhemp biomass yield were variable between seasons (Table 4) depending on crop establishment and season quality. Significantly greater biomass yields were discovered only in one season where the RS out-yielded RSL.

A detailed analysis through ANOVAs separated the effects of tillage, rotation and cropping season on maize grain yield (Table 8). The results showed that all factors tested in the experiment were significant on maize grain yield. The cropping season had the strongest effect followed by rotation and treatment. The interaction between tillage and rotation was weak suggesting that rotational benefits can occur under both conventional and no-till. However, both rotational and tillage benefits were also dependent on the season; the interaction of all three factors was weak.

The mean yield benefits between CA treatments and CP of both continuous and rotated maize crops showed a clear upward trend

Table 8
Results of an ANOVA that combines the analyses the effect of tillage, rotation and cropping season on maize grain yield at Henderson Research Station, 2008–2012.

Factor	Significance
Tillage	$P < 0.0183$
Rotation	$P < 0.0121$
Season	$P < 0.0001$
Tillage * rotation	$P < 0.8955$
Tillage * season	$P < 0.0049$
Rotation * season	$P < 0.0008$
Tillage * rotation * season	$P < 0.9005$

(Fig. 5). While there was no yield benefit within the first three years, it appeared that from the fourth year onwards, the CA treatments with continuous maize and under rotation were performing better than the conventional control. This upward trend is visually supported by two regression curves fitted to the data (Fig. 5). Both curves show an upward trend but the regression curve of maize in rotation is steeper than the one for sole maize.

Yield differences between CP and CPS, CP and CA, CP and CAS, and CA and CAS were visualised in a comparative yield analysis between the different treatment combinations at Henderson (Fig. 6): (a) the data shows that there is a yield benefit with crop rotation even under CP, as yields were always greater under CPS; (b) there is a yield advantage of growing crops under CA as compared to CP; (c) the largest yield benefit can be expected when CP is compared with the CA treatment in rotation with sunnhemp (CAS); (d) CA has greater yields than CP but CA in rotation with sunnhemp has the greatest positive difference.

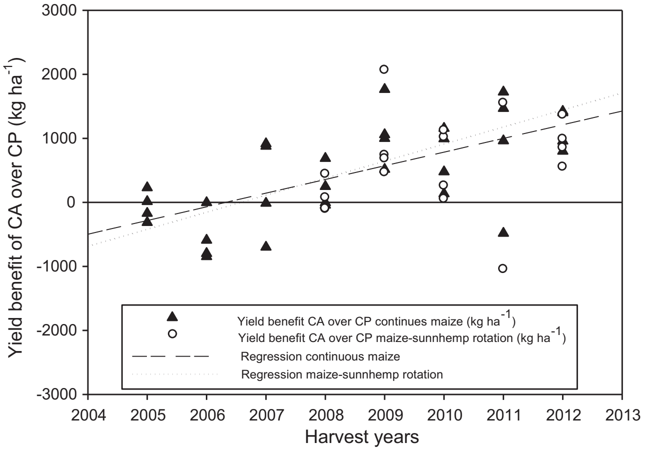

Fig. 5. Yield benefit of CA over CP (kg ha^{-1}) in both continuous maize and maize in rotation with sunnhemp, Henderson Research Station, 2005–2012.

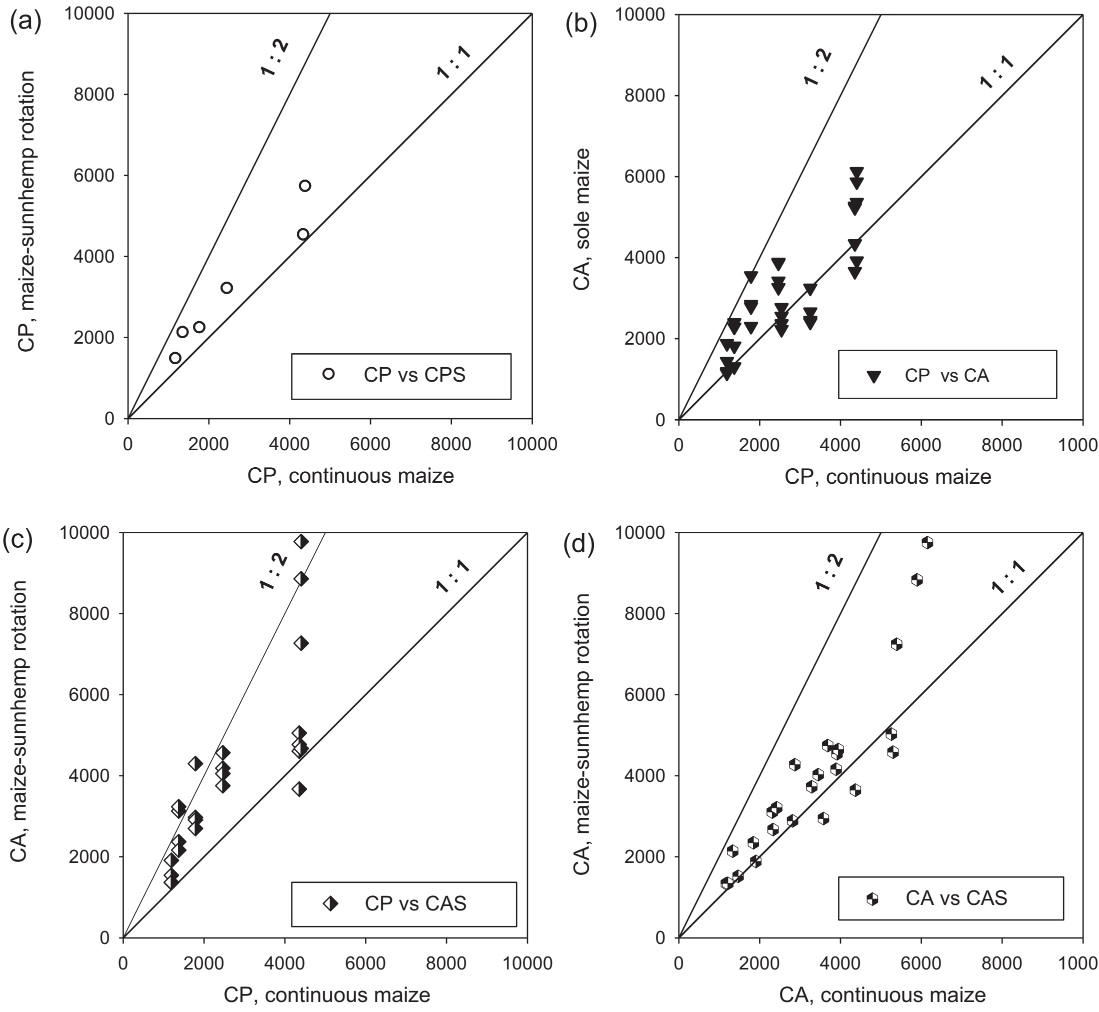

Fig. 6. Yield comparison between different management strategies at Henderson Research Station. CP, conventional ploughing continuous maize; CPS, continuous ploughing maize-sunnhemp rotation; CA, conservation agriculture treatments in no-tillage with residue retention and maize; CAS, conservation agriculture treatments in no-tillage with residue retention and maize-sunnhemp rotation, 2005–2012.

4. Discussion

4.1. *Infiltration*

As previously highlighted, infiltration is one of the most immediate benefits of CA systems especially when measured on rotational plots (Thierfelder and Wall, 2009; Nyamadzawo et al., 2003) and reveals the potential of a soil to utilise water instead of losing it to run-off (Rockström et al., 2001). Our results confirm this data as the benefit of CA on infiltration occurred almost immediately; larger infiltration rates were measured at both Henderson and Madziwa. Roth (1985) attributed the increased infiltration to both the retention of crop residues and the associated improvements in soil pores through biological activity. Larger biopores, especially macropores through the activity of earthworms have also been mentioned by Ehlers (1975). Thierfelder and Wall (2010b), investigating a long-term trial in Monze, Zambia, found significantly larger earthworm numbers in CA treatments, especially in rotations of cotton and sunnhemp, which suggests that residue retention and crop rotations apart from no-tillage play a significant role in the increase in biological activity. Kladviko et al. (1986) stressed the importance of earthworms in this respect. The results in 2011 at Henderson, confirm that rotations with sunnhemp had a significantly positive effect on infiltration under CA.

4.2. *Soil carbon and bulk density*

The soil carbon and bulk density analysis at Madziwa and Henderson show small differences between treatments. Carbon accumulates mostly in the first horizons on the CA treatments suggesting some stratification, as highlighted by Giller et al. (2009) and Thierfelder and Wall (2012). However soil carbon at Henderson was greater in the intercropped treatment in the first 0–30 cm, suggesting additional carbon input from the intercropped legumes. When comparing the depth of 0–60 cm at Madziwa and 0–30 cm Henderson in the fifth and fourth years after initiation of the trials, there is relatively more soil carbon in both profiles, suggesting that organic matter originating from surface crop residue retention is slowly being incorporated into the soil by biological processes (e.g., earthworms and termites) (Baker et al., 2007; Luo et al., 2010). Bulk density in Madziwa was significantly lower in the top soil and in deeper soil horizons, which confirms previous results (Mazvimavi et al., 2008), although some other studies showed few, or inconsistent trends (Ismail et al., 1994; Logsdon and Karlen, 2004).

4.3. *Erosion*

The greatest benefit of CA, that has been stated by many authors, is the reduction in soil erosion compared with the conventional plough-based system (Lal, 1974; Derpsch et al., 1991; Munyati, 1997; Landers, 2001; Thierfelder and Wall, 2009). It is therefore not surprising that soil loss on the conventionally ploughed fields at Henderson was more than double the amount recorded on the CA treatments. The soil loss amount from the CA plots was large in the initial years due to the sandy soil texture and disturbance of the soil surface by manual hoe weeding at this particular site (Thierfelder and Wall, 2009). This rate is far below the threshold of soil erosion in temperate regions, commonly accepted at about 5 t ha^{-1}. For more erodible areas in tropical environments a rate of 1–2 t ha^{-1} was suggested based on a lower soil formation rate (Lal, 1982; Morgan, 1995), which suggests that the final rates now recorded on CA plots at Henderson are in the acceptable range.

4.4. *Comparative yield analysis*

The results from the comparative analysis of on-farm sites at Madziwa show that there were no immediate significant yield differences of CA over CP but after five cropping seasons, the first significant differences were observed. Nevertheless, results in Fig. 3 show that it is more advantageous to grow crops under CA than CP:

There are marked yield benefits in rotating crops (i.e., 11–64% higher yield) or intercropping (10–35% higher yield) compared with continuous maize cropping. Intercropping maize with cowpea had a much lower effect on the associated maize yield than full rotations and in some cases, there was even less yield on the intercropped CP compared with the CP with continuous maize. Each crop in full rotation can take complete advantage of space and natural resources, whilst intercropping entails competition with the main crop, resulting in lower yields on the maize or the subcrop (Hauggaard-Nielsen et al., 2008; Kimaro et al., 2009). Over time there can be additional yield benefits from the intercropped legume (N-accumulation through BNF and leaf litter and weed suppression through the intercrop) but this does not benefit the maize crop in the present year but only in subsequent years (Sakala et al., 2000). There was also a gradual maize yield increase on the intercropped treatments in Madziwa and Henderson in cropping season 2011/2012 however the associated cowpea yields remained small due to large competition between both crops (Jeranyama et al., 2000). Rotations on the other hand are much riskier for farmers especially if green manures are involved in the rotation. Green manures (i.e., velvet beans or sunnhemp) are often grown to benefit the succeeding crop as they do not have other commercial value but if a drought occurs in the second year all the investment is lost leaving the farmer with no harvest of a marketable crop for two years.

The yield analysis from Henderson shows incremental benefits of CA and rotations over time. After five cropping seasons, the first significant differences were observed and continued from there on. This means that CA benefits are not instant (Thierfelder and Wall, 2012) and that there is some lag phase necessary until the benefits materialise. The lack of immediate yield benefits of CA has been highlighted by Giller et al. (2009) and Gilbert (2012) as a major bottleneck for the widespread uptake of CA in southern Africa. However farmers do not evaluate their cropping systems only based on grain yield. Other advantages such as reductions in labour (i.e., for land preparation and weeding) as reported from Malawi (Ngwira et al., 2012) can facilitate faster adoption of this cropping system.

The comparative analysis between CA and CP treatments in Fig. 6 shows that: (a) crop rotation is better than continuous sole cropping in both CA and conventional systems; (b) comparing CP with CA without rotations is more beneficial for CA, in some cases up to double the yield can be achieved; (c) the best strategy will be CA in full rotation against CP with continuous maize. Finally, rotations and intercropping systems are an important component of the CA farming systems. If this is left out (d) there will be a yield penalty to pay. In summary, a full CA system including all principles (minimum soil disturbance, residue retention and crop rotation) will outperform CP with continuous maize.

4.5. *Constraints to the adoption of rotations and intercropping systems*

In Southern Africa, the benefits of rotations and associations in CA systems beyond pest and disease reduction (i.e., greater water infiltration, increased biological activity, higher available soil moisture, nutrient cycling and better structure) have been demonstrated

(Thierfelder and Wall, 2010b). However, these benefits are only measured at the field scale and lack proper integration at the farm and community level (Snapp et al., 2010).

In areas with land constraints, such as Malawi, farmers prefer intercropping systems to rotations because they believe that the overall yield penalty and loss of area dedicated to maize would be minimal. Large areas of southern Malawi and northern Mozambique are therefore planted with maize, intercropped with pigeonpea or cowpeas. Pigeonpea is an ideal crop in this environment; it is a slow starter and competes very little with the main crop during critical crop establishment stages (Sakala, 1994; Snapp et al., 2010). Once the maize is mature, pigeonpea starts growing with limited yield penalty to the maize crop. Late maturing pigeonpea offer increases in nitrogen through leaf litter and biological nitrogen fixation, as well as firewood (Sakala, 1998; Sakala et al., 2000). There is a good market for grain in the region and in India. Nevertheless, the effects of associations on the suppression of pests and disease is uncertain and very little work has been done in this respect (Thierfelder et al., 2012). Work from Zimbabwe shows that farmers rotate crops even in conventional systems (e.g., in a maize-groundnut rotation) but the rotation frequency and relative space on smallholder farms is small compared to maize (Waddington et al., 2007)

Cowpeas grow well in most small-scale farming environments and even on granitic sandy soils. They perform best as rotational crops and show yield depressions when intercropped with maize especially when planted at the same time as the maize due to the shading effect of the maize leaves (Ofori and Stern, 1987; Jeranyama et al., 2000). Cowpea are very susceptible to pests, especially aphids (*Aphis craccivora* Koch), which can significantly affect the overall performance of the crop. Nevertheless, diversification of the maize systems with cowpeas can reduce the risk of complete crop failure in times of drought as was shown through results from Mozambique (Rusinamhodzi et al., 2012). Cowpea may also provide substantial amounts of residual N through biological nitrogen fixation (Rusinamhodzi et al., 2006; Jeranyama et al., 2000).

Farmers prefer rotational crops with “multiple-purpose” uses (Giller et al., 2009), such as soyabean, groundnut and cowpea (N-fixation, nutrition and cash crops) and to a certain extent cash crops like cotton and tobacco. However, they are hesitant to rotate maize with crops of no immediate economic benefit, which makes the introduction of highly potential green manure cover crops (GMCCs) very challenging. There are a number of GMCCs available in southern Africa e.g., velvet beans, lablab (*Lablab purpureus* L.) or several sunnhemp (*Crotalaria* ssp) species that are very well adapted to the farming systems and could easily be used. GMCCs can significantly increase the level of residual nitrogen; amounts of more than 250 kg N ha^{-1} for tropical environments have been previously reported (Giller and Wilson, 1991). Although the literature has identified a number of associated benefits with GMCCs, farmers rarely grow them with the exception of some areas in Zambia (GART, 2006; Thierfelder and Wall, 2010b), Zimbabwe (Waddington, 2003) and Malawi (Snapp et al., 2010). In Mozambique, the use of GMCCs is practically unknown by farmers. Our results from Henderson show that there are huge benefits in rotating maize with sunnhemp. Given a residual N content of approximately 1.5–2% in the stover and roots (Balkcom et al., 2005) and the amount we gained in form of biomass (Table 4), sunnhemp can potentially fix between 37 and 307 kg ha^{-1} of nitrogen on a sandy soil, depending on the season quality and sunnhemp growth. This is a substantial amount for small-scale farmers, which can leverage the quantity of mineral fertiliser that they have to buy.

Conservation agriculture systems without rotations or intercropping systems are unlikely to give the full benefits in the long run (Mupangwa et al., 2012; Ngwira et al., 2012) and will only lead to more pest and diseases (e.g., white grubs, root and foliar diseases).

The challenges of introducing legumes into the farming system have been identified by Snapp et al. (2010) and Thierfelder et al. (2012) as perceived loss of land area, perceived risk of crop failure, lack of knowledge on how to grow and use rotational crops, lack of seed for specific crops, and lack of functional markets for produce.

Smallholder farmers' agricultural experiences in southern Africa have led them to conclude that every season brings the same unmanageable uncertainty on crop productivity. Reducing the risk of crop failure through more stable cropping systems (i.e., CA) may be an opportunity for farmers to get away from continuous maize cropping (Thierfelder and Wall, 2011). Farmers currently dedicate large areas of the farm to maize in anticipation of food shortages and excess maize always has a market, albeit at lower prices. Maize also guarantees food security for the family once 1.2–1.5 t per household has been harvested.

In areas of low production risks, productivity can be increased through the concentration of management and inputs and reduction in the area dedicated to maize. If farmers can reduce the area allocated to maize, they can use the freed-up land for grain legumes, cash crops and/or GMCCs, as they require small investments in seed costs although it will need some additional labour for planting and harvesting. Fallows can also be improved and used more effectively by planting highly productive GMCCs. Other socio-economic constraints, such as better access to markets (both input and output markets) and knowledge gaps on how to grow and integrate those species into CA farming systems however need to be addressed. There are a number of research and development organisations who are addressing these constraints through training and awareness building, linking farmers to credit (i.e., through micro credits and revolving funds) and markets (i.e., via contract farming). However the introduction of micro-credits and revolving funds to farmers has been tried in the past and it has proved to be very challenging to manage such components effectively and sustainably.

5. Conclusion

The results of this study in southern Africa show that CA generally increases infiltration and reduces erosion. CA plots had relatively more carbon than conventionally ploughed plots; lack of greater build-up in the whole profile suggest that it requires time until the organic material from the surface is incorporated. Bulk density was also lower on CA treatments in the first horizon and in the subsoil. Separation of the effects of rotation and/or intercropping from continuous maize showed that there are additional benefits to crop yield if crops are rotated, or at least intercropped with leguminous crops. The effect of season was greatest on maize grain yield followed by rotation and tillage at Henderson Research Station. The results also show that rotations are equally beneficial for CA and conventional systems. Managing CA systems in full rotation with cowpea or green manure cover crops, such as sunnhemp, can lead to large yield increases of over 100% compared with the conventional control. CA without rotation also gives benefits but they will be greater with full CA, i.e., practising all the three principles. Our results show that the benefits increase over time and therefore, if farmers can practice CA in the long-term, the greater will be the benefits. Nevertheless, there are reasons why farmers do not practice rotation and the constraints are more at the farm and community level rather than at the field scale. Better land-use planning that dedicates smaller areas to maize will increase available areas to rotational crops, which could even benefit the use of green manure cover crops, which need very small capital investments.

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