ROTATION IN CONSERVATION AGRICULTURE SYSTEMS OF ZAMBIA: EFFECTS ON SOIL QUALITY AND WATER RELATIONS

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SUMMARY

Conservation agriculture (CA) systems are based on minimal soil disturbance, crop residue retention and crop rotation. Although the capacity of rotations to break pest and disease cycles is generally recognized, other benefits of crop rotations in CA systems are seldom acknowledged and little understood. We monitored different conventional and CA cropping systems over the period from 2005 to 2009 in a multi-seasonal trial in Monze, southern Zambia. Both monocropped maize and different maize rotations including cotton and the green manure cover crop sunnhemp (*Crotalaria juncea*) were compared under CA conditions, with the aim of elucidating the effects of crop rotations on soil quality, soil moisture relations and maize productivity. Infiltration, a sensitive indicator of soil quality, was significantly lower on conventionally ploughed plots in all cropping seasons compared to CA plots. Higher water infiltration rate led to greater soil moisture content in CA maize treatments seeded after cotton. Earthworm populations, total carbon and aggregate stability were also significantly higher on CA plots. Improvements in soil quality resulted in higher rainfall use efficiency and higher maize grain yield on CA plots especially those in a two- or three-year rotation. In the 2007/08 and 2008/2009 season, highest yields were obtained from direct-seeded maize after sunnhemp, which yielded 74% and 136% more than maize in the conventionally ploughed control treatment with a continuous maize crop. Even in a two-year rotation (maize-cotton), without a legume green manure cover crop, 47% and 38% higher maize yields were recorded compared to maize in the conventionally ploughed control in the two years, respectively. This suggests that there are positive effects from crop rotations even in the absence of disease and pest problems. The overall profitability of each system will, however, depend on markets and prices, which will guide the farmer's decision on which, if any, rotation to choose.

INTRODUCTION

Since the mid 1990s, there has been a series of initiatives by foreign donor organizations to promote conservation agriculture (CA) in Southern Africa. Zambia has been at the forefront of introducing CA to local farmers through technical support from the Conservation Farming Unit of the Zambian National Farmers Union, the Golden Valley Agricultural Research Trust and the Ministry of Agriculture and Cooperatives (Haggblade and Tembo, 2003). This work has been funded by the World Bank, the Swedish Government, the European Union and the Norwegian Government, among others, with the aim of improving rural livelihoods through sustainable intensification of crop production. The Conservation Farming Unit reported about 60 000–180 000 farmers practicing CA in various regions of Zambia (D. Gibson, personal communication, 2008). It should be noted that the number of farmers

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practicing CA in the true sense (minimum soil disturbance, crop residue retention and crop rotations) is much lower than the maximum number of farmers who experiment with only one or two components of CA.

Conservation agriculture, a cropping system originally developed in the Americas and Australia on large-scale commercial farms, is based on three principles: a) minimum soil disturbance, and therefore no soil inversion with the hoe or plough; b) permanent surface soil cover through crop residues and/or living plants; and c) crop rotations with different plant species (FAO, 2002). Numerous studies have highlighted the benefits and challenges of CA (see recent reviews by Bolliger *et al.*, 2006; Derpsch, 2008; Hobbs, 2007; Kassam *et al.*, 2009; Reicosky and Saxton, 2007; Wall, 2007); however, only a few studies have focussed on the contribution of rotations to soil quality improvements and other benefits of the CA system.

Increases in plant-specific pests and diseases over time are a major concern in agriculture production. Monocropping, defined as continuously growing one crop species season after season, leads in many cases to an increase in plant-specific pests and diseases, and is therefore not sustainable. About 61% of the total cropped land area in Zambia is planted to maize (CSO, 2004). Maize, the staple food crop for southern African farmers, is often planted in monoculture and accounts for approximately 50% of the caloric intake (Dowswell *et al.,* 1996). The build-up of pests and diseases is often a combination of factors: in CA systems, reduced tillage and surface crop residue retention may lead to more infection by necrotrophic diseases (Brévault *et al.,* 2009; Govaerts *et al.,* 2007) while, at the same time, enhancing soil biological activity through a better micro-climate (cooler temperatures, moister conditions below the residues) that may favour antagonistic soil microbial populations that suppress pest and diseases (Cook, 1990).

Rotations of maize with other crop species are widely acknowledged to reduce pests and diseases. Previous studies have highlighted the reduction in plant-specific nematodes when crops are rotated (Govaerts *et al.,* 2006). Rotational crops such as sunnhemp (*Crotalaria juncea*) are reported to stop the carry-over of nematodes completely (Wang *et al.,* 2003). Reductions in root rots on wheat and maize have been reported from rotations under CA in Mexico (Govaerts *et al.,* 2007). Rotations have also been associated with positive soil fertility effects on succeeding crops especially when nitrogen-fixing legumes are involved (Giller, 2001). Substitution of nitrogen fertilizers through biological nitrogen fixation by legumes in rotations can be a huge benefit to resource-constrained farmers, who may not be able to purchase inorganic fertilizers (Maltas *et al.,* 2009).

However, other benefits from crop rotations are often little understood and seldom acknowledged in the literature. Rotations may improve soil quality and deep rooting crops can lead to better soil structure, aggregation and pore continuity, with positive effects on infiltration and soil moisture in rainfed agricultural situations (Shaxson and Barber, 2003). Better nutrient distribution in the soil profile could be a consequence of exploitation of the root zone in different layers through rotation of crops with different rooting depths. Root exudates from some crops may enhance soil structure benefiting other crops in the rotation.

An increase in soil biological activity due to increased soil organic matter and the populations and diversity of soil fauna and flora may have further beneficial effects on crop growth. In CA systems, a balanced rotation is crucial to produce and maintain sufficient surface residues. One common example is a rotation of crops whose residues have a high C:N ratio (e.g. cereals) and break down slowly with crops with low C:N residues that are short-lived (e.g. legumes) but enhance soil fertility.

Rotations may play an important role in diversifying farmers' incomes and spreading the risk of crop failure (Helmers *et al.*, 2001). Price fluctuations of different crops generally differ, and therefore financial returns can be stabilized by producing diverse crops. The design of crop rotations, and the sequence of crops within the rotation, will depend largely on overall financial returns, market demand for specific crops and market prices. Farmers often rotate crops with different peak labour requirements (i.e. maize before sweet potatoes, sunflower and beans) to spread the need for farm labour.

Many factors will influence farmer decisions on crop rotation, and the size of landholdings is a critical factor: farmers in Malawi, who are generally land constrained (average landholding = 1.2 ha) (World Bank, 2007), are hesitant to replace their staple crop, maize, with other crops because of the effects this may have on their food security, whereas farmers in Zambia, who have larger landholdings (average landholding = 2.8 ha) (Jayne *et al.,* 2004), are more likely to be able to plant other crops and still produce sufficient maize.

The objective of this study is to investigate the effects of different conventional and conservation agriculture cropping systems both with monocropped maize and planted in different rotations on soil quality, water relations and maize productivity. The aim is to assist farmers in making better decisions on a rotation in order to improve their soils and their livelihoods.

MATERIAL AND METHODS:

Site characterization

The study was carried out at the Monze Farmer Training Centre (MFTC), Southern Province, Zambia (16.24°S; 27.44E°; altitude: 1103 m asl, mean annual rainfall 748 mm a^{-1}) from 2005 to 2009. Predominant soil types are Lixisols (FAO, 1998), and basic soil characteristics of a reference profile at MFTC are shown in Table 1. The trial was initiated in May 2005 after the site had been sown to a uniform maize crop for several years. Maize (*Zea mays*) is the principal subsistence crop in this area. Other crops like cotton (*Gossypium hirsutum*), soyabeans (*Glycine max*) and cowpeas (*Vigna unguiculata*) are also important cash crops for smallholder farmers. Green manure cover crops such as sunnhemp or velvet beans (*Mucuna pruriens*), although known in the area for a long time, have often been associated with colonialism and have only become part of the extension efforts in recent years (GART, 2006). However, these cover crops may be used in maize-based cropping systems as rotational, inter- or relay crops. Rainfall during the crop season (October–April) at MFTC was close to the annual mean in

Table 1. Some soil properties of reference profile D, ferric Lixisol; Monze Farmer Training Centre, 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

Note. CECpot – potential cation exchange capacity; BS – base saturation; Corg – organic carbon.

Table 2. Treatment description and crops seeded from 2005 to 2009 at Monze Farmer Training Centre, Zambia; maize crops in bold are presented in this paper.

Treatments	Cropping season			
	2005/2006	2006/2007	2007/2008	2008/2009
Conventional ploughing (CPM)	**Maize**	**Maize**	**Maize**	**Maize**
Direct seeding (DSM)	**Maize**	**Maize**	**Maize**	**Maize**
Direct-seeded 2-year rotation (DS-MC)	**Maize**	Cotton	**Maize**	Cotton
Direct-seeded 2-year rotation (DS-CM)	Cotton	**Maize**	Cotton	Maize
Direct-seeded 3-year rotation (DS-MCS)	**Maize**	Cotton	Sunnhemp	**Maize**
Direct-seeded 3-year rotation (DS-CSM)	Cotton	Sunnhemp	**Maize**	Cotton
Direc-seeded 3-year rotation (DS-SMC)	Sunnhemp	**Maize**	Cotton	Sunnhemp
Conventional ploughed rotation (CP-MC)		Cotton	**Maize**	Cotton
Conventional ploughed rotation (CP-CM)		**Maize**	Cotton	**Maize**

2005/2006 (734 mm) and 2008/2009 (761 mm), but lower in 2006/2007 (551 mm) and much higher in 2007/2008 (1033 mm).

Description of the long-term trial

The experiment consists of 10 treatments in a randomized complete block design with four replications, but results from only five of the treatments are reported in this paper. A list of all treatments and seeded crops in each year is provided in Table 2.

The five treatments investigated consist of a conventional farmers' practice (CPM) in which crop residues were removed, the land ploughed with a mouldboard plough, and the crop hand-seeded with maize each season. The conventional treatment was compared with four direct-seeded CA treatments where residues from the previous crop(s) are retained on the soil surface and the maize crop is direct seeded into the mulch with an animal traction direct seeder from Irmãos Fitarelli Máquinas Agricolas, Brazil. The CA treatments are seeded either with a continuous annual maize crop (DSM), with the maize-phase of a two-year maize-cotton rotation (DS-CM) or the maize-phase of a three-year maize-cotton-sunnhemp rotation (DS-CSM). Cotton and sunnhemp in the other rotation phases were manually seeded into shallow grooves opened with an animal-drawn ripper tine. In 2006/2007, the maize-phase of a conventionally tilled maize-cotton rotation (CP-CM) was included for comparison. Although, the DSM treatment is an incomplete CA system, as an

important component (the rotation) is missing, it is included in this paper as a 'CA' treatment for comparison with DS-CM and DS-CSM.

Commercial hybrid maize varieties were seeded in the four cropping seasons (SC513 in 2005/06 and 2006/07 and MRI624 in 2007/08 and 2008/09). Locally available varieties of cotton and sunnhemp were used. Sunnhemp produced between 6.9 and 9.3 t ha^{-1} and cotton between 3.1 and 7.3 t ha^{-1} of above-ground dry matter. In the conventionally ploughed cotton-maize rotation, cotton residues were removed, but in the direct-seeded treatments they remained on the soil surface, as did the sunnhemp residues.

All crops except the sunnhemp were fertilized with a basal dressing of 163 kg ha^{-1} Compound D (10N:20P$_2$O$_5$:10K$_2$O) at seeding. In the manually sown treatments it was placed alongside the planting station, while in the other treatments it was dribbled in the row by the direct-seeding equipment. Top-dressing of 200 kg ha^{-1} urea (46% N) was applied to all treatments except the sunnhemp as an equally split application at four and seven weeks after crop emergence. Therefore all treatments except the sunnhemp received the same amount of fertilizer.

Maize was seeded in rows spaced 90 cm apart. In the manually seeded control plot, seed was placed in the rows with 50 cm between planting stations and three seeds per station, later thinned to two plants per station (44 444 plants ha^{-1}). The direct seeder was calibrated to seeds spaced every 20 cm in the row and later thinned to approximately 44 444 plants ha^{-1}. Cotton was also seeded in rows spaced 90 cm apart and with 50 cm between plant stations. Five seeds of cotton were placed in the riplines, and later thinned to two living plants per station (44 444 plant ha^{-1}). Sunnhemp was dribbled at a rate of 40 kg ha^{-1} in riplines spaced 90 cm apart in 2005/2006 and 45 cm apart in 2006/2007 to achieve a more even crop stand and better weed control.

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 whenever weeds were 10 cm tall or 10 cm in circumference. After three seasons, only spot application of glyphosate was necessary to control couch grass (*Cynodon dactylon*) in few areas. A remarkable reduction in all other weed species was observed in the plots and future herbicide applications can be kept to a minimum.

Below ground faunal biomass

Three soil monoliths of 25 cm × 25 cm × 30 cm depth were taken from each reported treatment of the four replications in January 2007, March 2008 and January 2009. Samples were divided into three depth layers (0–10 cm, 10–20 cm and 20–30 cm) and hand-sorted for macrofauna (termites, earthworms and beetles) (Anderson and Ingram, 1993).

Total carbon and aggregate stability

Total carbon was measured through dry combustion with a C.E Elantech C/N analyser. Soil samples were collected from 0–30 cm depth layer in July 2005 and

October 2008 from CPM, DSM, DS-CM and DS-CSM treatments only, and results as well as changes between both periods summarized.

Surface soil samples were taken from the same treatments in April 2009; 50 g of a soil sub-sample was placed on a 2-mm sieve and soaked for 10 min in water in the laboratory. After soaking, the samples were agitated in water for 10 min at 48 strokes per min with strokes of 35 mm. Aggregates that remained on the sieve were dried at 105 °C and weighed, and the percentage of water stable aggregates calculated.

Infiltration measurements

In all four cropping seasons, infiltration was measured on all plots using a small rainfall simulator as described by Amézquita *et al.* (1999). Simulated rainfall of approximately 100 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 carried out in January of each year when the maize crop was close to the tasselling stage. Infiltration was measured on three sites in each plot, mainly in the inter-row space. Sites for the infiltration tests were wetted the night before the test, and the surface covered with a plastic sheet to ensure that the soil was at field capacity.

Soil moisture

Three access tubes were installed in three replicates of five treatments at Monze, including the CPM, DSM and DS-CM treatments. Moisture content was measured twice per week during the cropping season to 1 m depth with a capacitance probe (PR-2 probes, Delta-T Devices Ltd., UK). Data from the 0–10 cm, 10–20, 20–30, 30–40 and 40–60 cm horizons are reported in this paper. Mean soil moisture in vol. % of each soil depth layer was determined over the cropping season, and mean soil moisture content (mm) and the available soil moisture (mm) in the profile was calculated.

Harvest procedure

The maize crop was harvested at physiological maturity; cobs and above-ground biomass were collected and weighed, and sub-samples taken for determination of moisture content. A sample of 20 cobs per plot was shelled to calculate grain yield, which was then calculated on a per hectare basis at 12.5 % moisture.

Statistical analysis

Statistical analyses were carried out using STATISTIX for personal computers (Statistix, 2008). Soil fauna, total carbon, aggregate stability, final infiltration rate, 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 $p \leq 0.05$ if not stated otherwise. Where significance was detected, means were compared using a least significant difference (LSD) test.
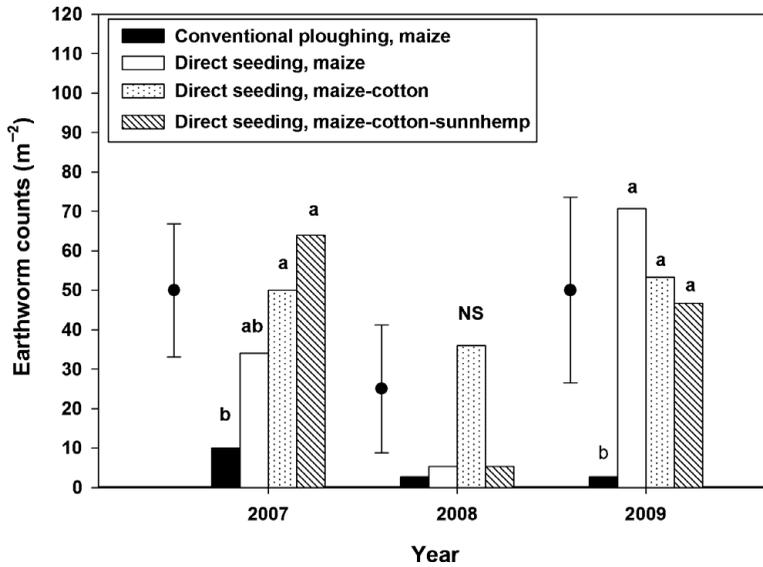
Figure 1. Impact of conventional and conservation agriculture on earthworm counts (m^{-2}) from 0–30 cm soil depth in three consecutive years. Monze Farmer Training Centre, Zambia (2007–2009). Means represented by bars indicated by different letters are significantly different using the LSD test ($p < 0.05$).

RESULTS

Earthworm populations

Differences between treatments were only significant with respect to earthworms, and therefore only results from this faunal group are presented in this paper. Variability of populations of other faunal groups, including termites, was extremely high, and therefore treatment differences were not significant.

In all three seasons earthworm populations were higher in the top 30 cm of soil of the CA fields than on CPM (Figure 1). However, results were only significant in 2007 and 2009. Sampling in both years was carried out when soil moisture content was good leading to high earthworm populations. The later (March) sampling in 2008 had drier soil and counts were low: we presume that earthworms had already followed the moisture gradient into deeper layers. In 2007, the direct-seeded treatments with crop rotation had significantly higher earthworm populations than the conventionally tilled control, with the highest populations (213 earthworms m^{-3}) in the maize seeded after sunnhemp. In 2009, all CA treatments had significantly higher earthworm populations than the control, with the highest populations in the DSM treatment (237 earthworms m^{-3}).

Total carbon and aggregate stability

Total carbon (C_{tot}) measured in 0–10 and 0–30 cm horizons was not significantly different at the onset of trial establishment in July 2005 (Table 3). This changed in October 2008: increases in C_{tot} were measured in all CA treatments and decreases in

Table 3. Change in total carbon (%) in 0–10 and 0–30cm soil depth and the level of aggregate stability (%) measured at different times in one conventionally tilled and three conservation agriculture treatments, Monze Farmer Training Centre, Zambia.

	Total carbon (%)			Total carbon (%)			Aggregate stability (%)
Treatments and sites	2005 0–10cm	2008 0–10cm	Change (%)	2005 0–30cm	2008 0–30cm	Change (%)	2009 0–10 cm
Conventional ploughing (CPM)	0.67	0.56 b	−16.4	0.58	0.54 c	−7.3	23.7 b
Direct seeding (DSM)	0.72	0.76 a	+5.6	0.69	0.75 a	+9.4	45.2 a
Direct-seeded 2-year rotation (DS-CM)	0.64	0.68 ab	+6.3	0.61	0.61 bc	+0.6	45.1 a
Direct-seeded 3-year rotation (DS-CSM)	0.68	0.77 ab	+13.2	0.63	0.68 ab	+8.3	41.5 a
LSD		0.19			0.12		14.2
Probability level (PF)	n.s.	1%		n.s.	1%		6%

Note. Means within the same column followed by the same letter are not significantly different at given probability level, LSD test.

Table 4. Effect of conservation agriculture on final infiltration rate in the maize crop after 60 min of simulated rainfall of 100 mm h^{-1} intensity, Monze Farmer Training Centre, Zambia.

	Cropping season			
Treatments	Jan 2006 Final infiltration (mm h^{-1})	Jan 2007 Final infiltration (mm h^{-1})	Jan 2008 Final infiltration (mm h^{-1})	Jan 2009 Final infiltration (mm h^{-1})
Conventional ploughing (CPM)	33.6 b	25.3 c	9.6 c	9.6 c
Direct seeding (DSM)	52.7 a	47.4 b	33.5 ab	46.5 b
Direct seeded 2-year rotation (DS-CM)	–	47.6 b	31.1 b	48.7 ab
Direct seeded 3-year rotation (DS-CSM)	–	71.3 a	40.7 a	61.7 a
Conventional 2-year rotation (CP-CM)	–	–	28.4 b	48.4 ab

Note. Means followed by the same letter in column are not significantly different at $p \leq 0.05$ probability level.

the conventionally tilled control plots. Highest C_{tot} in the first 10 cm was measured in DS-CSM (0.77%) and lowest in CPM (0.56%). More important than total percentage was the increase of 13.2% in the DS-CSM treatment in the first 10 cm between 2005 and 2008. At 0–30 cm depth, DSM had the highest C_{tot} (0.75%) as compared to 0.54% in the conventionally tilled control. While DSM increased its C_{tot} by 9.4%, it decreased in CPM by 7.3%.

Aggregate stability was greater on CA than CPM plots. (Table 3). Aggregate stability on DSM, DS-CM and DS-CSM ranged from 41 to 45% and was significantly higher than the 24% of CPM.

Infiltration rate

The final infiltration rate after 60 min of simulated rainfall was significantly higher on CA plots in all years compared to CPM (Table 4). In 2006, the first year of the trial,

Table 5. Mean integrated soil moisture content (mm) over the crop season in one conventionally ploughed and several conservation agriculture treatments in four consecutive cropping seasons at the Monze Farmer Training Centre, Zambia.

	Soil horizon					
	0–10 cm	10–20cm	20–30cm	30–40cm	40–60cm	Total (0–60 cm)
2005/06 season						
Conventional ploughing (CPM)	18.4 b	21.4 a	20.9 b	22.7 a	51.4 a	134.7 a
Direct seeding (DSM)	19.9 a	21.3 a	22.9 a	22.5 a	45.8 b	132.5 a
2006/07 season						
Conventional ploughing (CPM)	14.1 b	18.0 c	18.6 b	21.7 c	51.7 b	124.1 c
Direct seeding (DSM)	16.2 a	18.7 b	21.6 a	23.9 b	46.7 c	127.2 b
Direct seeded maize after cotton (DS-CM)	15.8 a	19.5 a	21.1 a	25.3 a	53.6 a	135.2 a
2007/08 season						
Conventional ploughing (CPM)	14.6 b	18.8 b	20.2 c	23.0 b	54.2 b	130.8 b
Direct seeding (DSM)	15.1 a	19.2 b	21.4 b	22.8 b	49.6 c	128.1 b
Direct seeded maize after cotton (DS-CM)	15.3 a	20.6 a	23.0 a	24.9 a	55.6 a	139.4 a
2008/09 season						
Conventional ploughing (CPM)	13.7 c	19.4 c	22.5 c	26.1 b	60.5 a	142.2 b
Direct seeding (DSM)	16.5 b	22.5 b	28.6 a	27.8 a	54.8 c	150.2 a
Direct seeded maize after cotton (DS-CM)	17.5 a	23.5 a	26.6 b	27.6 a	57.8 b	153.0 a

Note. Means followed by the same letter in column are not significantly different at $p \leq 0.05$ probability level.

the only valid comparison was between DSM and CPM. In later years the DS-CSM treatment always had the highest infiltration rates: in 2007 it was significantly higher (71.3 mm h^{-1}) than all other treatments, especially CPM (25.3 mm h^{-1}). In 2008 the infiltration rate in DS-CSM was significantly greater than CPM but not different to DSM, and in 2009 it was not significantly higher than the maize treatments in two-year rotations. The CP-CM treatment was only started in 2006, but infiltration rates in 2008 and 2009 were significantly greater than CPM and not significantly different to DS-CM (Table 4).

Infiltration curves were fitted to the Horton infiltration model (Thierfelder *et al.,* 2005) and graphs drawn for two seasons (Figure 2). Results from January 2008 and January 2009 show distinctly lower infiltration rates on CPM and higher rates in DS-CSM.

Soil moisture

Soil moisture followed the seasonal rainfall trends. Available soil moisture (mm) in the various treatments in the 2008/2009 season is shown in Figure 3. Soil moisture content was lower on CPM than the DS treatments over the entire season from the 0–40 cm horizon but had higher moisture content than the DS treatments in the 40–60 cm horizon. Similarly the mean integrated soil moisture content (mm) was higher on CA treatments in most soil depth layers and years compared to CPM (Table 5), but from the 40–60 cm horizon, it had higher soil moisture throughout the cropping season than for the CA treatments.
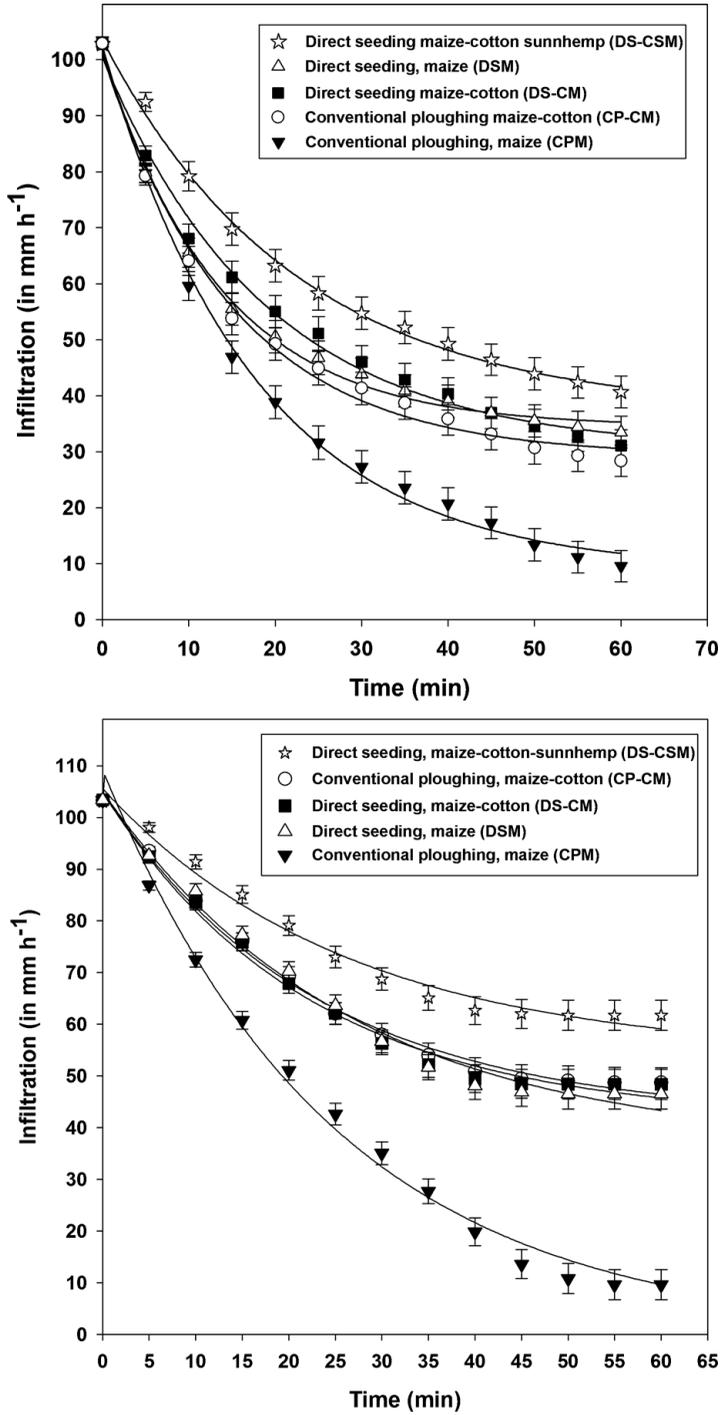
Figure 2. Infiltration curves measured by mini-rainfall simulator in January 2008 (top) and 2009 (bottom) in three conservation agriculture and two conventional treatments, Monze Farmer Training Centre, Zambia. Curves are fitted to Horton's infiltration model.
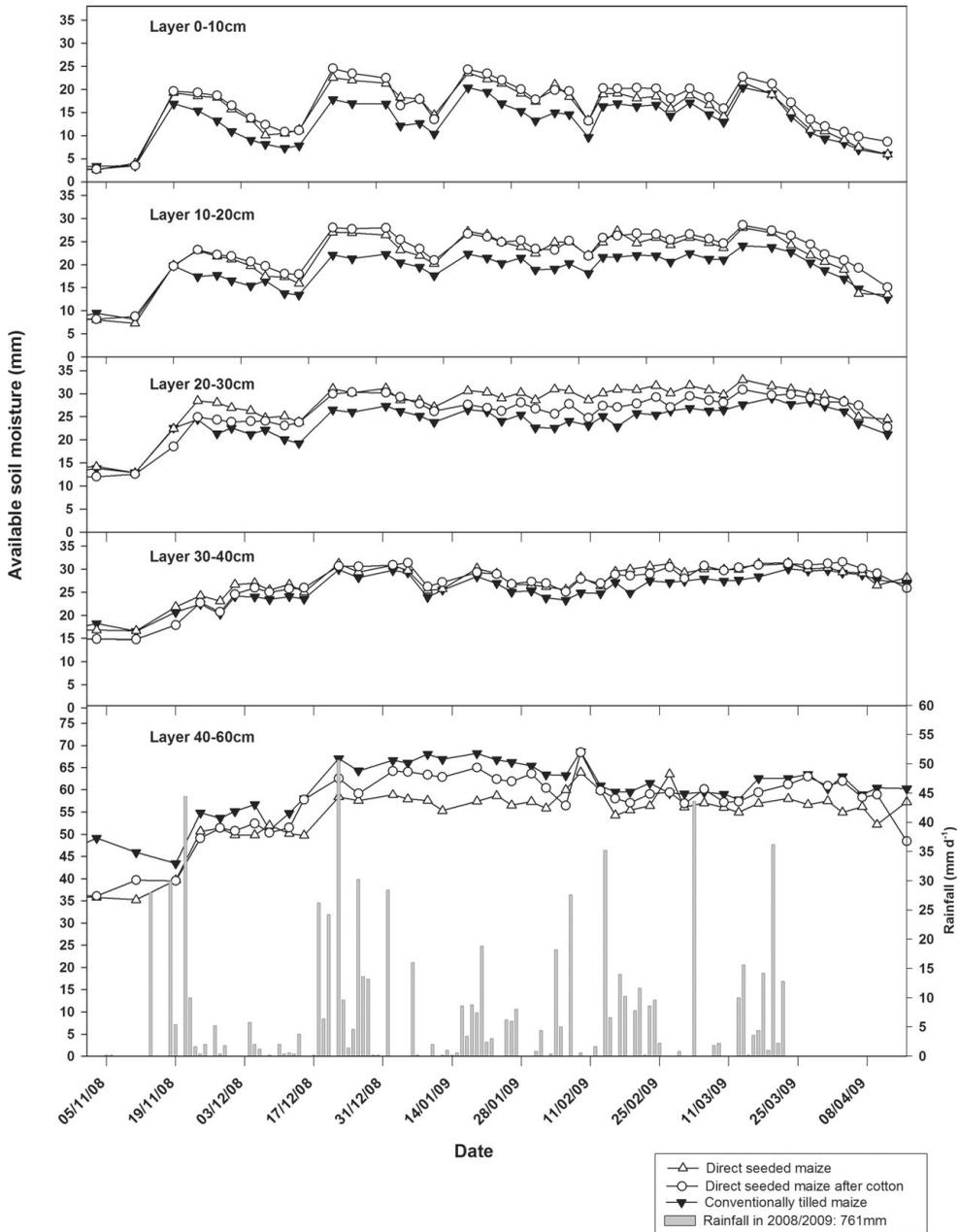
Figure 3. Seasonal development of available soil moisture (mm) in one conventional and two CA treatments in five different soil depth layers (0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm and 40–60 cm). 1 November 2008–16 March 2009, Monze Farmer Training Centre, Zambia.

The available soil moisture (mm) in the top 60 cm of soil in the 2008/2009 season is shown in Figure 4, together with the permanent wilting percentage, 50% available soil moisture and field capacity. Over most of the season all treatments had greater
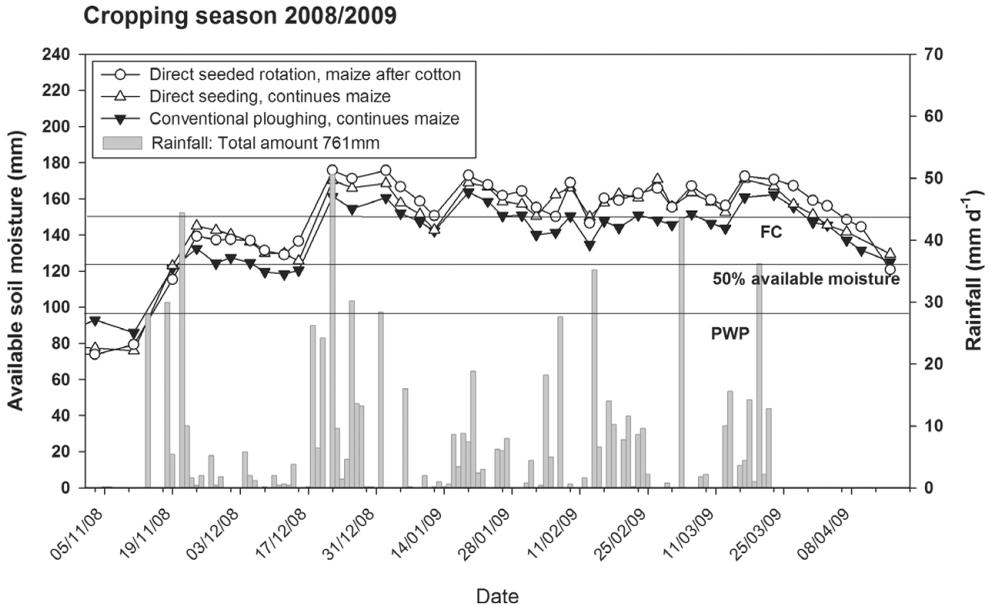
Cropping season 2008/2009

Figure 4. Available soil moisture (mm) above the permanent wilting percentage (PWP) in the first 60 cm in one conventionally ploughed and two conservation agriculture treatments, 1 November 2008–16 March 2009. FC: field capacity.

than 50% available moisture, but for a short period from 24 November 2008 to 18 December 2008, during initial crop establishment, the available moisture content in the top 60 cm of soil in CPM dropped below 50% available moisture.

Grain harvest and rainwater use efficiency

In all years we found lowest maize grain yield on the conventionally ploughed continuous maize treatments (Figure 5). In one year (2005/2006), DSM was significantly better than CPM. In all other years, significantly higher grain yields were only found between the two CA rotations maize-cotton and maize-cotton sunnhemp and the conventional control. Yield of DS-CSM was by far the highest throughout: it had 74% and 136% higher yields than CPM and 56% and 100% higher yields than DSM in 2007/2008 and 2008/2009, respectively. The yield of CP-CM was only slightly lower than DS-CM in 2007/2008 and was similar to it in 2008/2009. DS-CM had 47% and 37% higher yields than CPM and exceeded DSM by 31% and 16% in 2007/2008 and 2008/ 2009, respectively. The positive effect of rotation is also obvious in CP-CM in which maize yielded significantly 31% and 44% more than CPM in both 2007/2008 and 2008/ 2009.

All CA treatments produced more grain than CPM in all seasons and so rainfall use efficiency (RUE) was higher in the CA treatments (Table 6). Overall, the mean of the CA treatments had 36%, 26%, 48% and 62% higher RUE than CPM in the four

Table 6. Rainfall use efficiency in kg grain mm^{-1} of rain at MFTC in 2005/2006 and 2006/2007.

Treatments and sites	Season 2005/2006	Season 2006/2007	Season 2007/2008	Season 2008/2009
kg grain mm^{-1} of rain	734	551	1033	761
Conventional ploughing (CPM)	4.9 b	8.9 b	3.9 d	4.4 c
Direct seeding (DSM)	6.7 a	9.3 ab	4.5 cd	5.1 bc
Direct seeded 2-year rotation (DS-CM)		11.3 a[†]	5.9 ab	6.0 b
Direct seeded 3-year rotation (DS-CSM)		13.0 a	7.0 a	10.3 a
Conventional 2-year rotation (CP-CM)			5.3 bc	6.3 b
Mean	5.8	10.6	5.32	9.52

Note. 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.
[†]Crops in the maize cotton rotation consisted of maize after maize in 2005/06 and maize after cotton in 06/07
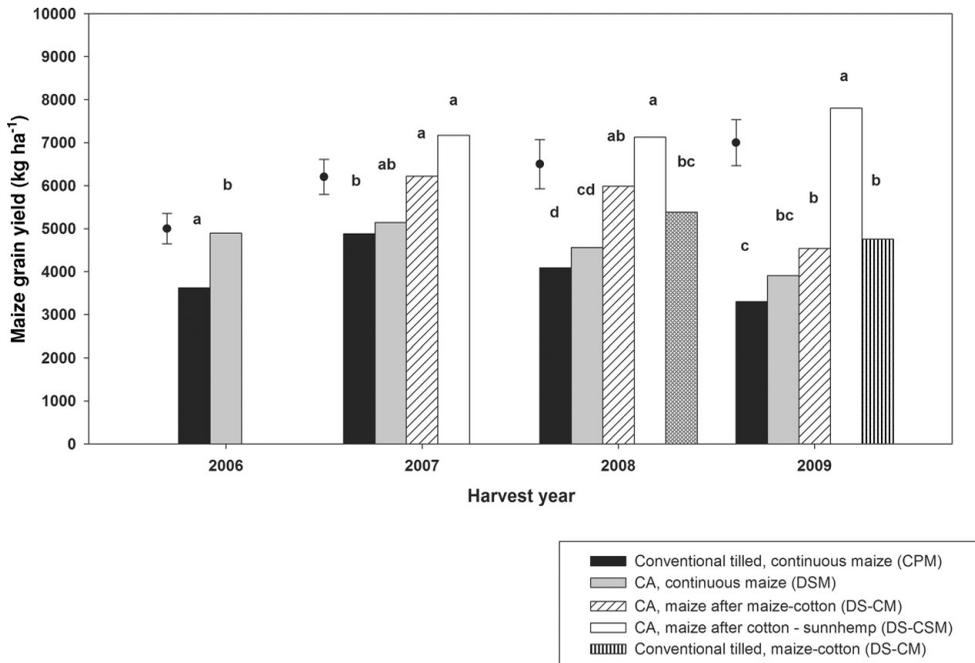

Figure 5. Maize grain yield of different conservation agriculture and conventionally ploughed treatments at the Monze Farmer Training Centre, Zambia (2006–2009). Error bars in the graph represent *s.e.d.* of treatment means within each year. Means represented by bars indicated by different letters are significantly different using the LSD test ($p < 0.05$).

seasons. However, differences in RUE were only significant between DS with crop rotation and CPM. For CMC, RUE was higher than CPM in both years.

DISCUSSION

The results of this study show marked positive effects of CA technologies on earthworm counts, total carbon, aggregate stability, soil water infiltration, soil moisture and maize

grain yield. The difference in total carbon between CA and the conventional control plot in October 2008 was greater in the first 10 cm than in the first 30 cm. It is assumed that ploughing in the previous seasons in CPM has mixed the carbon-rich soil from the surface with deeper soil layers thus reducing the overall carbon content. A significant reduction was, however, still evident in the 0–30 cm comparison. These benefits were apparent after only a short period (1–4 years) of the application of treatments.

Roth *et al.* (1988) also found that mulch cover provides benefits in water infiltration even from the first season, especially under dry or moisture-limited conditions, and Pagliai *et al.* (2004) found changes in soil physical structure in the short term associated with stopping tillage. Govaerts *et al.* (2006) conclude from their studies in Mexico that about 30% of the maize yield increases on zero tillage fields with residue retention can be explained by higher infiltration and favourable moisture dynamics.

However, in the studies presented here the greatest improvements were seen on plots with crop rotation: both with CA and conventional agriculture. Maize planted in a three-course rotation following cotton and sunnhemp performed best in this environment. Maize provides grain and residues, the deep rooting cash crop cotton appears to improve the soil structure, and the legume sunnhemp improves the physical, chemical and biological status of the soil. We harvested 6.9–9.3 t ha^{-1} of above-ground biomass of sunnhemp in each of the three years before the maize was planted, which will probably have resulted in an additional 138–186 kg N ha^{-1} (assuming an N content of 2% in the sunnhemp biomass) for the following maize (Balkcom *et al.*, 2005). This, however, excludes sunnhemp root biomass, which was not measured in this study, and if it was included, the benefits would have been even greater. Therefore it is not surprising that the maize planted after the very productive green manure cover crop outyielded all the other treatments, as was also the case in the studies of Balkcom *et al.* (2005). However, the question still remains as to whether the higher maize grain yields observed in the trials can be attributed only to the higher available N or whether other factors such as higher infiltration or increased available soil moisture may have also benefited maize yield.

One very interesting aspect in this study was the effect of cotton in the two-year rotations. Cotton is a deep-rooting shrub that does not have symbiotic nitrogen fixation and therefore did not provide any additional nitrogen to the following maize crop. However, maize grown after cotton in CA and conventional tillage had higher grain yield than the monocropped treatments. Similar results were obtained by Hulugalle *et al.* (2004) in Australia. The deep-rooting cotton crop may have improved the structure in the soil profile; however, unlike the three-year cotton-sunnhemp-maize rotation, no significantly higher infiltration was discovered in the two-year maize-cotton rotation in the years investigated. The cotton crop may have been involved in some nutrient cycling, bringing nutrients from deeper layers to the surface when the cotton residues decompose. The cotton crop may have also suppressed other pest and diseases that were, however, not discovered. Further research is necessary to better separate those effects. The maize planted after cotton in the conventional rotation (CMC) also benefited from the rotation and had higher yields. Nevertheless we expect, in the longer term, that these benefits will be lower than on a CA

maize-cotton rotation as cotton residues from this treatment will generally be removed or burned.

In most southern African countries, by law, cotton residues must be uprooted and burned after harvest to avoid the carry-over of diseases and pests. However, these laws were developed based on conditions of conventional agriculture. The increase in biological activity in conservation agriculture fields might not require burning of the residues: in the four years of this trial in Monze we did not discover any significant increase in pests and diseases. This needs to be confirmed to catalyse a change in the legislation on cotton residue burning to reap the potential of cotton production under CA.

Given the biophysical benefits of rotational crops in the agricultural system, will farmers adopt crop rotations? Maize is the staple food of the Zambian population and therefore paramount to food security. The likelihood that farmers include other crops such as cotton or sunnhemp in the farming system will largely depend on their perception of risk (Helmers *et al.*, 2001), the availability of functional markets, the price of each crop in the rotation and the landholding size of the farmer. Sunnhemp as a rotational crop has become interesting to farmers in Zambia in recent seasons as prices for sunnhemp grain, sometime ranging up to 2.5 US\$ kg^{-1}, have made this a very attractive rotational crop (GART, 2006). However, benefits from the crop in the rotation will be smaller if the grain, and therefore much of the nitrogen, is exported from the fields. Sunnhemp could be considered as an intercrop in the established maize or cotton crop; however, competition between the main crop and the intercrop is very high due to the vigorous growth of sunnhemp, which normally leads to yield depression on the maize and cotton. This was observed in the field when sunnhemp was relay planted up to six weeks after the maize. More research is needed to better incorporate sunnhemp into the cropping system to reduce competition with maize and maximize the benefits from this promising green manure cover crop.

CONCLUSIONS

The present study showed clear benefits of CA practices with residue retention and crop rotation over conventionally ploughed practices. As we discovered no serious pests or diseases in the trial, the study highlighted that there are many more benefits of crop rotations than just pest and disease reduction. All soil quality indicators measured showed positive responses to residue retention and reduced tillage, but the effect of rotation on those indicators was even greater. Conservation agriculture plots in general possessed higher populations of earthworms, higher total carbon and more water stable aggregates. Higher infiltration rates were, however, only found in some rotations and more available soil water on CA plots only in some years. The highest maize yields came from a CA treatment with a three-course cotton-sunnhemp-maize rotation, followed by a two-course cotton-maize rotation. Rotational effects were also apparent in a conventional cotton-maize rotation suggesting that farmers should incorporate rotations in their cropping system even if they do not intend to practice conservation agriculture. However, profitability and suitability of each rotation will depend on

available markets, risks, prices for different products and average landholding of each farmer.

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