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Maize-based conservation agriculture systems in Malawi: Long-term trends in productivity

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ABSTRACT

In Malawi and throughout much of Africa, maize yields have declined over the past several decades due to continuous cultivation, often in monocropping with little or no inputs. As a result, soil degradation has been aggravated by the loss of valuable top soil caused by rainwater runoff due to the absence of effective conservation practices. To combat this trend, Conservation Agriculture (CA) systems were introduced using a pointed stick or hand hoe to plant directly into untilled soil with crop residues as surface mulch. The objective of this study was to compare the effects of different cropping systems (CA and conventional) on soil physical and chemical parameters and long-term maize productivity in target communities of the southern and central regions of Malawi. This study analysed the effects of CA on soil parameters and maize yield over eight cropping seasons. The biophysical variability of the communities was explored through principal component analysis. Results showed that maize yields in CA systems were strongly affected by rainfall infiltration, which was 24–40% greater compared with the conventional ridge and furrow system. In some cases, maize yields in CA plots were double that of conventional tillage plots. The larger water infiltration observed in CA plots relative to conventional tillage indicated that CA systems may increase access to soil water by the crop and offset the negative effects of seasonal dry spells. Yield benefits of CA over conventional tillage systems were greater especially from the 5th season although, in some instances, greater yields on CA were recorded almost immediately. CA can be practiced in diverse environments from sandy to clay soils, nutrient rich to infertile soils and from low to high rainfall areas as long as adequate inputs (fertilizer, herbicides and labour) are available with good extension support to farmers, especially in the initial years.

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1. Introduction

Agricultural productivity is important in Malawi because agriculture contributes nearly 35% of the gross domestic product (GDP) while employing more than 80% of the total labour force (Ngwira et al., 2012a). The United Nations Human Development and Poverty Index ranks Malawi 153 out of 169 countries with 74% of the population earning less than \$1.25/day and 53% living in severe poverty (UNDP, 2010). Most farmers are small-scale farmers with land holdings ranging from 0.2 ha in the densely populated areas of the south, to 3 ha in the north where the population density is lower (Ellis et al., 2003). Maize (*Zea mays* L.) is the main and preferred staple food crop dominating the farming systems with about 75–85%

of land area (Smale et al., 1991). The continuous maize cultivation often leads to a decline in yields due to little or no nutrient inputs, poor land and water management practices, and lack of crop rotations.

Conservation Agriculture systems were first introduced in Malawi by Sassakawa Global 2000 (Ito et al., 2007). Since 2004, there have been several other initiatives to promote CA mostly in the southern and central regions of Malawi in response to the challenges of food insecurity due to low crop productivity. Malawi has low livestock densities which makes the retention of crop residues in CA systems more feasible due to low demand for fodder to feed animals (Ngwira et al., 2012a,b). However, the impact of improved CA management practices on soil biophysical properties has not been properly documented in Malawi. Agronomic and soil research in southern Africa has often focused on the short-term effects of CA, and few examples (i.e. from Zimbabwe) exist of long-term trends on soil quality and crop productivity (Thierfelder and Wall, 2012).

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Often the research results were generated on experimental stations in controlled environments, which limits their applicability to the wider farming context, especially among poor smallholder farmers (Baudron et al., 2012). There is an urgent need to document existing data on CA, generated in the last decade to increase knowledge about this promising cropping system.

Conservation Agriculture (CA) systems are being promoted as productive and sustainable crop management systems in southern Africa (Thierfelder and Wall, 2009) in light of continuous soil degradation (Sanginga and Woomer, 2009), and the need to adapt to a changing climate (Lobell et al., 2008). At the same time, some authors rightfully argue that the promotion of CA systems without sufficient research evidence on plot and farm-level benefits could lead to poor use of donor funding and rejection of the technology by small-scale farmers in southern Africa (Bolliger, 2007; Giller et al., 2009). The promotion of CA as a common, fixed, one-size-fits-all package has also been criticized by various authors because it neglects the need to refine and adapt CA to local circumstances (Wall, 2007; Erenstein et al., 2012; Tittonell et al., 2012). Adaptation of CA principles at the farm level is critical for the long-term success and adoption of CA among farmers in southern Africa, or indeed any area of the world.

In southern Africa, emergency and relief organizations have targeted CA as a system that alleviates poverty for resource-constrained smallholder farmers. The expected full benefits of the system when adequate resources (fertilizers, improved seeds, pesticides) are available are largely unknown (Mashingaidze et al., 2006; Mazvimavi et al., 2008). Despite the abundance of literature on CA from across the world (Bolliger et al., 2006; Hobbs, 2007; Kassam et al., 2009) there is relatively little documented evidence of CA benefits from southern Africa. A detailed research agenda was therefore proposed by Giller et al. (2011) to close these important knowledge gaps.

According to the internationally accepted definition, CA is a cropping system based on three principles: (a) minimum or no soil disturbance by no-tillage seeding; (b) retention of adequate amounts of crop residues or live mulch on the soil surface; and (c) crop rotations with different plant species (Hobbs, 2007; Kassam et al., 2009). Available data on CA systems confirm that a number of short and long-term benefits can be expected when farmers shift from conventional tillage systems to CA (Wall, 2007). Results from the region and around the world show that CA has immediate biophysical and socio-economic effects such as increased water infiltration into the soil due to the protection of surface structure by mulch (Thierfelder and Wall, 2009), reduced water run-off and loss of top soil by maximizing the capture of rainfall and resulting increased infiltration from the ponding effect of the residues (Roth et al., 1988), reduced evaporation of soil moisture as the crop residues protect the surface from solar radiation (Lal, 1974), improved crop water balance (Farooq et al., 2011), less frequent and intense moisture stress because of the increased infiltration and reduced evaporation (Mupangwa et al., 2008; Thierfelder and Wall, 2010a), reduced traction and labour requirements for land preparation and for weeding if herbicides are used, hence saving costs of manual labour, animal draft and fuel, depending on the farming system used (Sorrenson et al., 1998; Ngwira et al., 2012a).

Long-term effects of CA such as increased soil organic matter resulting in better soil structure, higher cation exchange capacity and nutrient availability, and greater water-holding capacity have also been reported (Sidiras et al., 1983; Derpsch et al., 1986; Sisti et al., 2004; Bescansa et al., 2006; Thierfelder and Wall, 2010b). However, the results are variable and depend largely on management intensity, application of all principles of CA and the bio-physical environment (Govaerts et al., 2009; Thierfelder and Wall, 2012). It is often hypothesized that improvements in soil quality will eventually lead to higher and more stable yields, reduced

production costs and increased biological activity in the soil and aerial environment, which could also reduce pest and disease pressure. However there are only few examples of published literature from southern Africa available to support this.

The objective of this study was to compare the effects of different cropping systems (CA and conventional) on soil physical and chemical parameters and long-term maize productivity in target communities of the southern and central regions of Malawi. In addition, the benefits of CA were analysed across different agro-ecologies as defined by annual rainfall, soil type and altitude.

2. Materials and methods

2.1. Description of target communities

The study was carried out between 2004 and 2012 in nine target communities of central and southern Malawi (Fig. 1). Malawi is a sub-tropical country with a sub-humid climate situated between latitude 9° and 18°S and 33° and 36° in South Eastern Africa and is divided into three main regions: north, central and south regions. The communities were selected in five districts of Machinga, Balaka, Dowa, Salima and Nkhotakota (Table 1). The first experiments were conducted at Malula in Balaka district, where the study started in 2004. In 2005, Chipeni in Dowa district, Zidyana and Mwanambo in Nkhotakota district were initiated. In 2006, Lemu and Herbert in Balaka district and Matandika in Machinga district followed. The last selected communities were Linga in Nkhotakota in 2007 and Chinguluwe in Salima in 2008. The communities are characterized by a distinct rainfall gradient. Most of the communities around Balaka are in low rainfall areas (600–800 mm) and are prone to drought. The communities of Dowa and Salima are intermediate (800–1000 mm) and the communities in Nkhotakota have higher rainfall (1000–1300 mm). Matandika in Machinga district is an exception as it is influenced by the Zomba plateau with annual rainfall averaging between 800 and 1000 mm (Table 1). Soil textures range from loamy sands in Balaka to sandy clay loams in Nkhotakota. The study areas are all deforested due to high population pressures for growing crops and collecting wood for fuel and building material. Maize is the main food crop grown in all areas, often in a monoculture but sometimes intercropped with pigeonpea (*Cajanus cajan* L. Millsp) and cowpea (*Vigna unguiculata* L. Walp). Groundnuts (*Arachis hypogaea* L.) and cassava (*Manihot esculenta* Crantz) are also important food and cash crops. Other cash crops are mostly tobacco (*Nicotiana tabacum* L.), cotton (*Gossypium hirsutum* L.) and some horticultural crops.

2.2. Experimental design

Six experiments were established in each target community. Each experiment had three treatments at one farm and was treated as a replicate, plot sizes were 0.1 ha per treatment. Similar trials have previously been described by Ngwira et al. (2012a). The treatments were as follows:

- Conventional ridge and furrow system with maize (CPM): Ridges were formed each year approximately 75 cm apart. Residues from the previous maize crop were placed in the furrow before forming the ridges. The ridge is then built on top of the buried residues. The in-row spacing was 25 cm to achieve a plant population of 53,333 plants ha⁻¹ as the target population. Planting was done with a hand hoe in CPM on the ridges prepared in September and October. Weed control was achieved by traditional methods with the hand hoe through re-ridging and banking, which are all meant to rebuild the ridges and achieve a weed free seedbed. Weeding in this treatment was limited to two and sometimes

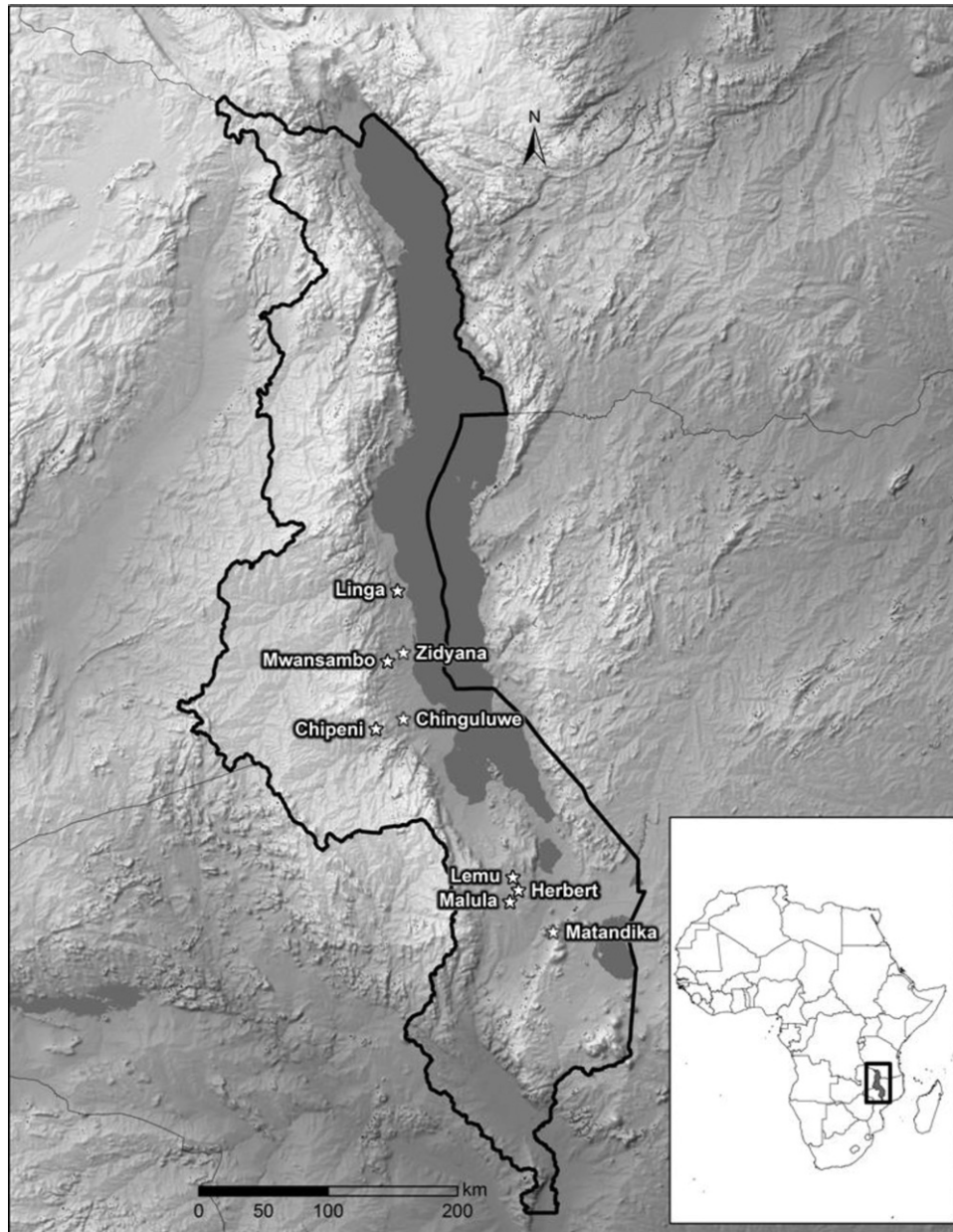


Fig. 1. Geographical locations of target communities in Malawi.

three operations and stopped only when the maize reached the tasseling/silking stage.

- Conservation Agriculture with maize (CAM): This plot was under no-tillage and crop residues were retained on the soil surface. Maize was planted with a pointed stick (dibble stick) in rows

spaced 75 cm apart as with the conventional tillage plot with in-row spacing of 25 cm to achieve the same plant population of approximately 53,333 plants ha⁻¹. Previous ridges were not maintained and in subsequent years maize was planted on top of the (old) deformed ridges. In year 1, crop residues in the

Table 1
General characteristics of the experimental sites in Malawi.

Village	District	Latitude (degrees)	Longitude (degrees)	Altitude (masl)	Texture 0–30 cm	Soil type	Average rainfall (mm)
Matandika	Machinga	–15.17	35.28	688	SL	Cambic Arenosols	1099
Malula	Balaka	–14.96	34.98	605	LS	Eutric Fluvisols	764
Lemu	Balaka	–14.79	35.00	720	SL	Chromic Luvisols	851
Herbert	Balaka	–14.88	35.04	635	SL	Chromic Luvisols	671
Chipeni	Dowa	–13.76	34.05	1166	SL	Chromic Luvisols	822
Chinguluwe	Salima	–13.69	34.24	657	SCL	Eutric Cambisols	848
Mwansambo	Nkhotakota	–13.29	34.13	632	SCL	Haplic Lixisols	1276
Zidyana	Nkhotakota	–13.23	34.24	535	SCL	Haplic Luvisols	1266
Linga	Nkhotakota	–12.80	34.20	491	SL	Alluvialsoils	1078

form of maize stalks were imported and applied at a rate of 2.5 t ha⁻¹ because the residues had been removed or burned. After the first season, the maize stalks harvested from the experiments were retained in situ as crop residues (Table 2). Weed control was achieved through the in situ application of a mixture of 2.5 l ha⁻¹ glyphosate (N-(phosphono-methyl) glycine) and 6 l ha⁻¹ of Bullet® (25.4% Alachlor (2-chloro-N-(2,6-diethylphenyl)-N-(methoxymethyl) acetamide) and 14.5% atrazine (2-Chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine)) was applied as a pre-emergence herbicide after planting. If weeds reappeared after the herbicide application, spot weeding with a hand hoe was done. In the experimental sites in Central Malawi, the application rate of bullet was reduced to 2.5 l ha⁻¹ based on observations that this level was adequate to control weeds. In 2010, Bullet was replaced by the residual herbicide Harness® (acetochlor (2-ethyl-6-methylphenyl-d11)) at a rate of 1 l ha⁻¹. In South Malawi, Bullet was maintained at the rate of 6 l ha⁻¹.

- Conservation Agriculture with maize and a legume intercrop (CAML): This plot was under no-tillage and retention of crop residues (Table 2). Maize was intercropped with either pigeon pea or cowpea. Maize plant spacing was the same as in CAM. The intercropped legumes were planted between the maize rows at 40 cm (cowpea) or 50 cm (Pigeonpea) in-row spacing. As in CAM a pointed stick was used to plant by making two small holes for the seed and fertilizer at each planting stations. Weed control was achieved through the application of glyphosate at 2.5 l ha⁻¹ post-planting followed by manual weeding as in CAM. No bullet or harness was applied to these plots.

All treatments at all experiment sites were kept weed free, and there was no major build-up of weeds in any plot. The major difference between treatments was that weeds were controlled solely through manual hand hoe weeding in CPM and through both chemical means and occasional manual hand hoe weeding in both CA treatments.

2.3. Management of experiments

Experiments were managed by farmers with local support from extension officers from Total Land Care and Ministry of Agriculture. Planting was done after the first effective rains in each area which usually occurred between the last week of November and mid-December of each year. Maize varieties, DKC8033 and DKC8053 were planted in the south, whereas SC403, DKC8053 and DKC9089 were seeded in central Malawi. The variety of maize was uniform for all plots within a particular site. All treatments received a uniform fertilizer application rate of 69 kg N ha⁻¹ which was supplied as 100 kg N:P:K ha⁻¹ (23:21:0+4S) at planting and 100 kg urea ha⁻¹ (46% N) at approximately three weeks after planting. The correct fertilizer amount was initially weighed per plot and later applied with a calibrated fertilizer cup at each planting hill to achieve the desired application rate. The fertilizer application was based on the general recommendation currently used by the Ministry of Agriculture in Malawi.

2.4. Soil aggregate distribution and stability

In 2011, all experiments, except the community Linga, were sampled for soil chemical and physical parameters. A composite soil sample from 0 to 10 cm soil depth was taken from each experiment, dried and later analysed. Soil aggregate distribution was determined by shaking a composite surface soil sample, for 10 min on a set of eight different sieves. The weight of aggregates left on each

sieve was weighed and a mean weight diameter (MWD) calculated using the following formula (1) (Kemper and Rosenau, 1986):

$$\text{MWD} = \sum_{i=1}^n \bar{x}_i \cdot w_i/w_t \quad (1)$$

where MWD, mean weight diameter; \bar{x}_i , mean diameter of each size fraction (mm); w_i , weight of each fraction (g); w_t , total weight of initial sample (g).

Soil aggregate stability was measured as well based on a composite surface soil from 0 to 10 cm soil depth. A sample of the soil was placed on a nest of sieves (4.5 mm, 2 mm, 1 mm, 0.5 mm, 0.212 mm) 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 a 35 mm stroke length. Aggregates that remained on the sieves were dried at 105 °C, weighed and a mean weight diameter according to formula (1) calculated (Kemper and Rosenau, 1986).

2.5. Infiltration measurements

Time-to-pond was measured from June to August 2011 during the winter season as a proxy for infiltration (Govaerts et al., 2006). In this method, a metal wire ring of 50 cm diameter was placed on the soil surface between two maize rows and water was supplied to the centre of the ring with a watering bucket and the time until the water flows out of the ring recorded. The method had earlier been calibrated with simulator measurements, and time-to-pond was highly correlated with infiltration measured by a mini-rainfall simulator (Ngwira et al., 2012b; Thierfelder and Wall, 2012). Six measurements were taken in each treatment plot at each experiment.

2.6. Soil chemical analyses

All communities except Linga were sampled for soil chemical parameters (extractable P, K, Ca, Mg, Na, Zn, NH₄, ZN, CEC and SOC) in 2011. Six sampling positions were randomly selected within each treatment and soil samples were collected from four soil depth layers (0–10 cm, 10–20 cm, 20–30 cm and 30–60 cm). Undisturbed soil cores were also collected from these depths for bulk density analysis. Soil pH was analysed in a 1:1 soil water mixture (Soil Survey Staff, 2004; Sikora and Moore, 2008). Soil extractable P, Ca, Mg, K, Na, Zn and NH₄ were determined using Mehlich 1 extractant and analysed by inductively coupled plasma (ICP) atomic emission spectroscopy on a Perkin-Elmer 5300 DV ICP (Mehlich, 1953). Cation exchange capacity (CEC) was determined with NH₄OAc buffered at pH 7.0 using automatic vacuum extraction (Sumner and Miller, 1996; Soil Survey Staff, 2004). Base saturation was determined mathematically from summation of cation concentrations.

Total soil organic C was determined on a <60-mesh sample and was analysed through dry combustion (Soil Survey Staff, 2004) on a CE Elantech Flash EA 1112 analyser. The amount of carbon (in mg ha⁻¹) was calculated from the carbon concentration, thicknesses and bulk densities of the horizons (Ellert and Bettany, 1995):

$$\text{M element} = \text{conc} \times p_b \times T \times 10,000 \text{ m}^2 \text{ ha}^{-1} \times 0.001 \text{ mg kg}^{-1} \quad (2)$$

where M element, element mass per unit area (mg ha⁻¹); conc, element concentration (kg mg⁻¹); p_b , field bulk density (mg m⁻³); T , thickness of soil layer (m).

2.7. Harvest procedures

Maize yield was estimated from 10 sub-samples of 7.5 m² per treatment. Harvest was done at physiological maturity and the fresh cobs and biomass weighed in the field. The dry cobs, biomass

Table 2

Maize biomass yield in two conservation agriculture and one conventional ridge and furrow system in target communities of Malawi, 2005–2012. Crop residues were retained in CAM and CAML plots and removed from CP plots, amount shown in table represents the total residues retained for the following seasons in CAM and CAML plots.

Community	Treatment	2005	2006	2007	2008	2009	2010	2011	2012
Malula	CPM	2130 b*	7677 a	1790 b	3797 b	2226 a	4114 a	2574 c	4531 b
	CAM	3322 ab	5704 a	3231 a	6390 a	2895 a	4700 a	5232 a	6651 a
	CAML	5422 a	5408 a	2472 ab	5252 ab	2898 a	5517 a	4549 b	6461 a
	LSD ($P < 0.05$)	3063	5482	859	1513	1459	2401	573	770
Chipeni	CPM		4394 a	4086 b	4057 a	2867 a	2680 a	3660 b	2258 b
	CAM		4216 a	3734 b	3693 a	3189 a	2885 a	4278 a	3252 a
	CAML		4909 a	4765 a	3521 a	2652 a	2804 a	4422 a	3264 a
	LSD ($P < 0.05$)		1061	585	815	946	318	554	583
Mwansambo	CPM		3669 b	2544 a	3333 a	3623 a	2840 a	4066 a	4413 b
	CAM		7211 a	2443 a	3131 a	3428 a	2781 a	3567 a	4579 ab
	CAML		7339 a	2874 a	2895 a	4075 a	2999 a	4206 a	5627 a
	LSD ($P < 0.05$)		1753	840	584	1055	822	976	1137
Zidyana	CPM		4062 b	2215 a	2787 a	5363 a	4564 a	4116 a	3790 a
	CAM		4584 ab	2798 a	2718 a	4950 a	6076 a	4815 a	4023 a
	CAML		5127 a	2713 a	2794 a	5396 a	5615 a	4874 a	3602 a
	LSD ($P < 0.05$)		554	636	480	865	1551	519	1311
Lemu	CPM			2774 b	3205 b	1630 a	2416 b	2913 b	3404 b
	CAM			5472 a	4241 ab	1865 a	5404 a	3800 a	5130 a
	CAML			5109 a	3637 a	1943 a	4982 a	4126 a	5008 a
	LSD ($P < 0.05$)			1098	745	496	1237	657	1089
Matandika	CPM			1891 b	3544 b	1489 b	5073 a	4980 a	3075 b
	CAM			3097 ab	5713 a	2254 a	5651 a	4863 a	6133 a
	CAML			4062 a	5956 a	2392 a	5818 a	5522 a	6118 a
	LSD ($P < 0.05$)			2093	1460	378	1214	925	1923
Herbert	CPM				3557 b	2113 a	3908 a	4822 a	2255 a
	CAM				5431 a	2942 a	4604 a	4494 a	2761 a
	CAML				5281 a	3013 a	3996 a	4152 a	2909 a
	LSD ($P < 0.05$)				918	982	1177	1178	1030
Linga	CPM				2171 a	8657 a	5073 a	4008 b	3485 b
	CAM				2795 a	8504 a	5651 a	4644 ab	4258 a
	CAML				2526 a	8833 a	5818 a	5285 a	4048 ab
	LSD ($P < 0.05$)				828	1487	1214	725	780
Chinguluwe	CPM					6314 a	3612 b	3706 a	2087 b
	CAM					7720 a	4663 a	3479 a	2959 a
	CAML					6485 a	4563 ab	3951 a	2779 a
	LSD ($P < 0.05$)					1504	1017	1195	396

* Followed by different letters at each site and year are significantly different at $P < 0.05$ probability level.

and the shelled grain were weighed after four weeks and a grain moisture measurement taken. The yield data was then converted into maize grain yield in kg ha^{-1} at 12.5% moisture content, and biomass yield kg ha^{-1} on dry weight basis. Intercropped cowpea and pigeonpea on CAML were harvested at physiological maturity. Yields on the intercropped cowpea were low due to attacks by aphids (*Aphis craccivora* Koch) on the legume and/or strong competition between the maize crop and the intercropped legume. Pigeonpea grain was harvested in August/September if not affected by elegant grasshoppers (*Zonocerus elegans* Thunberg), which is a common problem in southern Malawi. In this paper we report on maize yields only.

2.8. Calculations and statistical analysis

Yield benefit of CA was calculated as the grain yield differences (CA-CP) of CAM and CAML compared with CPM. A comparative analysis of carbon/yield benefits as well as time to pond/yield benefits was done graphically. Relative yield of CA and CPM were also plotted and the advantage of each treatment was evaluated through construction of a 1:1 line. When CA yields were larger than corresponding CPM yields, the data point were above the 1:1 line and vice versa. The generalized linear model (GLM) in SAS 9.2 (TS2MO) of the SAS System for Windows © 2002–2008 was used to test the individual and interactive effects of cropping system, experimental site, duration and season on crop yield. The interactions

tested were cropping system \times season, site \times cropping system, and duration \times cropping system. In the analysis, cropping system and duration of experiment were considered fixed factors while site and season were considered as a random factors. When the F -test was significant, an LSD test ($p \leq 0.05$) was used to separate the means.

Variables such as clay + silt content, concentrations of SOC, Na, Zn, CEC, K, P, Ca, Mg as well as altitude, annual rainfall were measured per each site, auto-scaled and their influence on site variability explored through principal component analysis (PCA) in SAS 9.2 (TS2MO) of the SAS System for Windows © 2002–2008. In 2010/2011, measurements of yield, SOC, time to pond, aggregate distribution, and aggregate stability were used in principal component analysis to cluster the tillage management strategies based on the short and long-term effects. Eigenvalues of the covariance matrix, which describe the proportion of total variance attributable to their respective principal components, and the corresponding Eigenvectors of the principal components, which describe the weight attributable to the measured traits for those principal components, were used for retaining PCs.

3. Results

3.1. Biophysical variability of the study sites in Malawi

Using the soil quality indicators and biophysical characteristics of the communities, the variability among these communities

Table 3
Rotated loading on the principal components of the different environmental parameters after partial component analysis.

	Principal components						
	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalues	5.44	2.54	1.54	0.98	0.21	0.19	0.10
Influence	0.49	0.23	0.14	0.09	0.02	0.02	0.01
Rotated loadings the retained three PCs							
Clay + silt	0.19	-0.93 ^a	-0.09				
SOC	0.93 ^a	-0.07	0.31				
Na	-0.56	0.53	-0.55				
Zn	-0.41	0.39	0.63 ^a				
CEC	0.97 ^a	0.06	0.04				
K	0.83 ^a	0.36	-0.18				
P	-0.07	0.67 ^a	0.37				
Ca	0.95 ^a	0.06	0.08				
Mg	0.82 ^a	-0.12	-0.50				
Altitude	0.82 ^a	0.13	0.37				
Rainfall	-0.42	-0.79 ^a	0.40				

^a Parameters with the most significant loadings for each principal component, PC with an Eigenvalue of greater than 1 were retained.

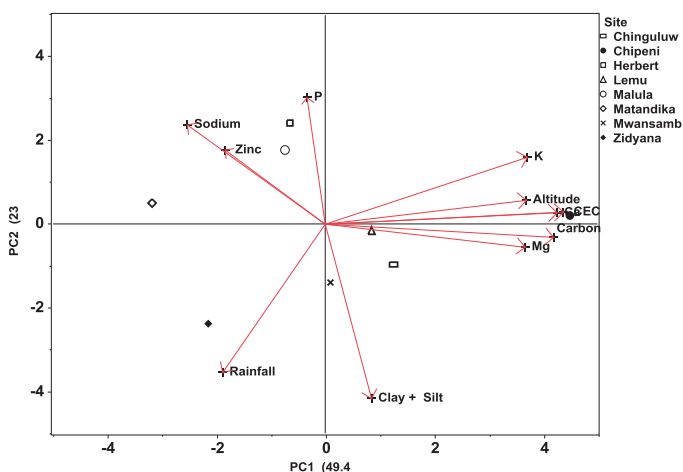


Fig. 2. The PCA-biplot showing the clustering of experimental sites based on clay + silt content, SOC, sodium, zinc, cation exchange capacity, potassium, phosphorous, calcium, magnesium concentrations, altitude and rainfall in Malawi.

through principal component analysis (PCA) was explored. The large proportion (49%) of variability between communities was explained by PC1 (Table 3). The PC1 was strongly related to the amount of SOC, CEC, Ca, K, Mg and altitude; PC2 explained 23% of the variability and was strongly related to extractable P concentration in the soil but negatively related to clay + silt content and rainfall. The third principal component (PC3) was strongly related to the amount of Zn in the soil.

Table 4
Output of a generalized linear model that combines the effects of cropping system, duration and cropping season on maize grain yield at nine on-farm sites in Malawi, 2006–2012.

Factor	DF	F value	Pr > F
Experimental site	8	18.94	<0.0001
Season	7	8.22	<0.0001
Cropping system	2	6.67	0.0013
Duration	7	2.1	0.0417
Duration*Cropping system	14	0.28	0.9955
Experimental site*Cropping system	16	1.2	0.2608
Season*Cropping system	14	0.93	0.5290

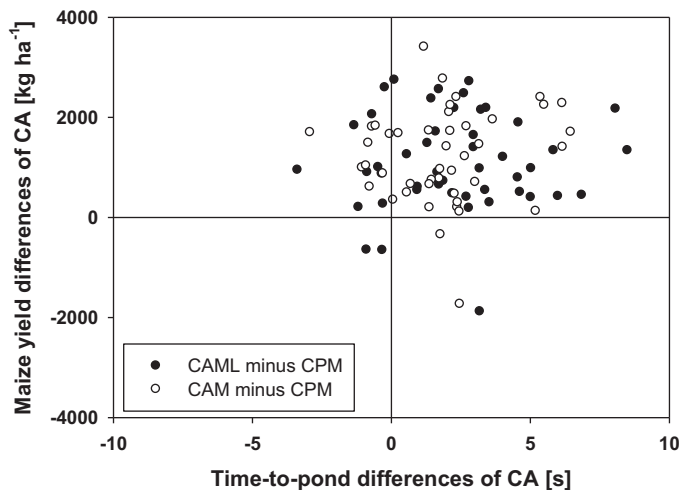


Fig. 3. Comparison of infiltration benefits (mm h^{-1}) and maize yield benefits (kg ha^{-1}) on conservation agriculture treatments as compared to the conventional ridge and furrow system, Malawi 2011.

The biplot of principal components identified five site clusters (Fig. 2): (a) Zidyana site received more rainfall but was very poor in nutrients as well as SOC, (b) Chipeni site was rich in SOC, Ca and Mg but received little rainfall, (c) Mwansambo, Chinguluwe and Lemu were clustered together and characterized by favourable biophysical conditions, (d) Malula and Herbert, rich in Zn and P but poor SOC and rainfall, and (e) Matandika received higher rainfall but has sandy soil with small nutrient concentrations except Na and Zn.

All single factors tested in the experiment were significant on maize grain yield (Table 4). The major sources of variation in yield were due to the differences in site characteristics ($P < 0.0001$). The seasonal effect on yield was also significant ($P < 0.0001$) as was the cropping system ($P = 0.0013$). The duration of practising CA was also significant ($P = 0.0417$) although less important than site, season and cropping system in determining crop yields. The interaction of cropping system \times season was not significant ($P = 0.5290$). Practising CA in the long-term did not appear to influence maize grain yield in the different cropping systems in Malawi. The interaction between cropping system and duration of CA was not significant.

3.2. Soil quality indicators

The analysis of soil quality indicators showed significant differences in time-to-pond between treatments at Mwansambo, Zidyana, Lemu, Herbert and Chinguluwe, while at other communities there were no differences (Table 5). At all communities except Herbert, where significant differences were observed, both CA treatments had greater infiltration than the conventional control. At Herbert, only CAML was different from CPM. Infiltration on these five communities was 24–40% greater than CPM with the greatest difference recorded at Zidyana (40%) and the smallest (24%) at Lemu.

There were positive yield differences of CA plots compared with CPM (Fig. 3) and time-to-pond was also greater on CA plots. Most of the data points in the graph were nested in the upper right quadrante (i.e. there were both maize yield benefits and time to pond benefits for both CA treatments).

Soil carbon in the whole profile (0–60 cm) was very variable between experiments and communities and only one site (i.e. Chinguluwe) showed a significantly higher amount of carbon for CAML relative to CPM and CAM.

Table 5
Summary of time to pond (sec) in nine different target communities of Malawi, 2011.

Treatment	Malula	Chipeni	Mwansambo	Zidyana	Matandika	Lemu	Herbert	Chinguluwe
	TtP (s)							
CPM	11.8 a	13.8 a	12.2 b	11.6 b	10.6 a	9.9 b	10.7 b	11.5 b
CAM	12.2 a	14.6 a	14.8 a	14.9 a	11.5 a	12.1 a	12.3 ab	14.6 a
CAML	12.4 a	15.3 a	15.0 a	16.2 a	11.1 a	12.3 a	13.5 a	15.2 a
LSD	2.0	1.6	2.3	2.1	1.3	2.1	1.5	2.4

Note: Means followed by different letters at the same site in each year are significantly different at $P < 0.05$.

Table 6
Maize grain yield in two conservation agriculture and one conventional ridge and furrow system in the four oldest target communities of Malawi, 2005–2012.

Village	Treatment	2005	2006	2007	2008	2009	2010	2011	2012
Malula	CPM	1986 b	4181 a	2454 a	3052 b	2247 a	3928 a	3068 b	2132 b
	CAM	3098 ab	3303 a	3410 a	5279 a	2889 a	4856 a	4802 a	5260 a
	CAML	5057 a	3390 a	2948 a	4486 ab	3084 a	4666 a	4614 a	5119 a
	LSD ($P \leq 0.05$)	2857	2295	1242	1805	1527	1888	745	1173
Chipeni	CPM		4098 a	7083 a	6076 a	4670 a	3699 b	4109b	2634 b
	CAM		3932 a	6906 a	6161 a	4522 a	4036 ab	5099 a	3882 a
	CAML		4578 a	7102 a	6422 a	4900 a	4253 a	5010 a	4049 a
	LSD ($P \leq 0.05$)		990	777	977	518	522	784	449
Mwansambo	CPM		3422 b	2877 a	3909 a	5468 a	3803 b	5273 b	4676 b
	CAM		6726 a	2706 a	4335 a	5364 a	4135 a	5865 a	5629 a
	CAML		6845 a	3509 a	3813 a	6040 a	4340 a	6120 a	6059 a
	LSD ($P \leq 0.05$)		1635	1328	852	1073	237	262	584
Zidyana	CPM		3788 b	2924 b	4911 a	6018 a	5555 b	4141 b	2215 b
	CAM		4275 ab	4224 a	4693 a	6876 a	8206 a	5903 a	3363 a
	CAML		4782 a	3849 a	4374 a	6031 a	7155 a	6099 a	3469 a
	LSD ($P \leq 0.05$)		517	565	808	1825	932	605	580

Note: Means followed by different letters at the same site in each year are significantly different at $P < 0.05$.

3.3. Long-term crop yields

Maize grain yields at most communities showed no significant yield differences between treatments in the initial years (Tables 6 and 7). At Malula, the site on loamy sands (Table 1), there were significant differences in the first year (2004/2005) between CAML and CPM (Table 6). Further significant differences were found only in year four (2007/2008) when yields in CAM were greater than CPM and in the last two seasons 2010/2011 and 2011/2012, when both CA treatments were superior to CPM. No significant

differences between both CA treatments were found throughout the whole period. At Chipeni, it took five years until the first significant differences were discovered between the CA plots (Table 6). The first differences were recorded in 2009/2010, with CAML producing higher yields than CPM. Thereafter both CA treatments were different from the conventional control plot but there was no significant difference between the two CA treatments. At Mwansambo, the first season (2005/2006) showed significantly greater yields on both CA treatments and again in the last three cropping seasons (2009–2012) (Table 6). At Zidyana, yields were different between

Table 7
Maize grain yield in two conservation agriculture and one conventional ridge and furrow system in the five younger target communities of Malawi, 2007–2012.

Village	Treatment	2007	2008	2009	2010	2011	2012
Matandika	CPM	1953 b	3997 b	1441 b	4866 b	4704 a	2422 b
	CAM	4793 a	6524 a	2290 a	6751 a	4748 a	4452 a
	CAML	5048 a	6880 a	2420 a	6581 a	4871 a	5106 a
	LSD ($P \leq 0.05$)	812	1278	478	580	1737	1327
Lemu	CPM	3195 b	2917 b	1935 b	2040 b	2545 b	2544 b
	CAM	5214 a	4181 a	2518 a	4762 a	4359 a	5004 a
	CAML	5256 a	4075 a	2793 a	4340 a	4291 a	4886 a
	LSD ($P \leq 0.05$)	731	963	565	682	611	997
Herbert	CPM		2866 b	3226 b	2206 b	1887 b	1627 b
	CAM		4059 a	4226 a	3651 a	2889 a	2458 a
	CAML		3548 ab	3701 ab	3353 a	2846 a	2686 a
	LSD ($P \leq 0.05$)		727	984	622	667	459
Linga	CPM		2218 b	5103 a	4866 b	4144 b	2522 b
	CAM		2432 ab	5538 a	6751 a	5141 a	3807 a
	CAML		2617 a	5581 a	6581 a	5558 a	3768 a
	LSD ($P \leq 0.05$)		257	1402	580	507	278
Chinguluwe	CPM			6112 ab	3810 b	4772 b	1592 b
	CAM			7366 a	5814 a	5849 a	2921 a
	CAML			5797 b	5176 a	5461 ab	2870 a
	LSD ($P \leq 0.05$)			1276	784	733	475

Note: Means followed by different letters at the same site in each year are significantly different at $P < 0.05$.

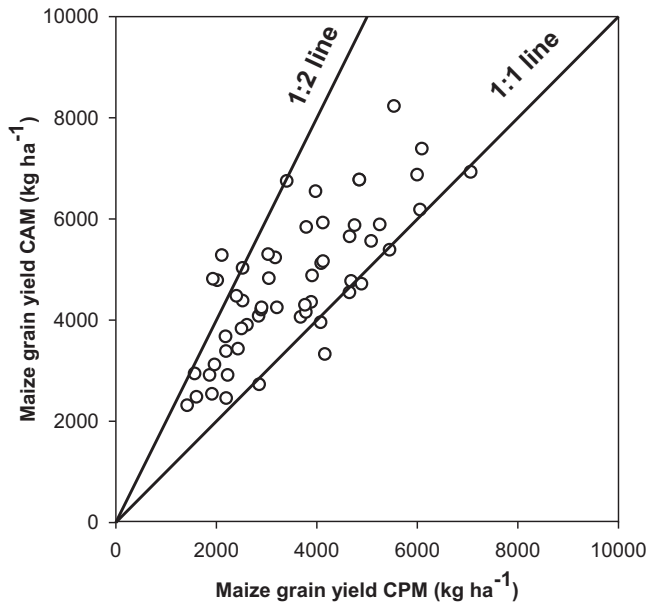


Fig. 4. Effects of direct seeded maize in conservation agriculture as compared to the conventional ridge and furrow system, Malawi (2005–2012).

CAML and CPM in 2005/2006 and between both CA treatments and CPM in 2006/2007 as well as in the last three cropping seasons.

At Matandika, yield differences between both CA treatments and CPM were found in all years but one (2010/2011) (Table 7). At Lemu, the yields on both CA treatments were significantly higher in all cropping seasons. At Herbert, there were greater yields with CAM and CPM in the first two cropping seasons (2007/2008 and 2008/2009) while in all other years the CA treatments outperformed CPM. At Linga, there were significant differences between CAML and CPM in 2007/2008 and again between both CA treatments and CPM from 2009 to 2012. In the youngest site Chinguluwe, there were significant yield differences between CAM and CAML in the first season. In all other seasons CAM yields were greater than CPM (Table 7).

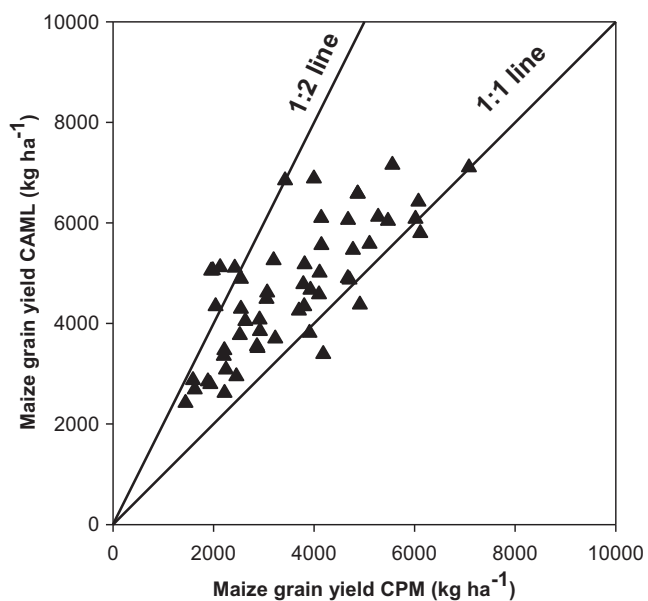


Fig. 5. Effects of direct seeded maize-legume intercropping in conservation agriculture as compared to the conventional ridge and furrow system, Malawi (2005–2012).

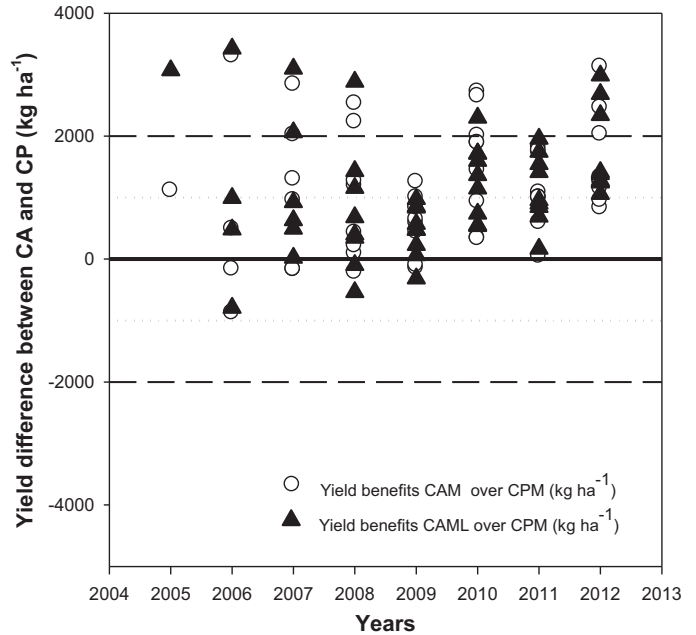


Fig. 6. Maize yield benefits of two CA systems as compared to the conventional ridge and furrow system, Malawi (2005–2012).

3.4. Comparative yield analysis

The average maize grain yields from all communities of CAM were plotted against CPM (Fig. 4). Most of the data points were above the 1:1 line meaning that maize grain yields were often higher in CAM than in CPM. In three cases, the data points were above the 1:2 line, meaning that the yield of the maize on CAM was more than double the yield of CPM. A similar picture was found in the comparison CAML against CPM (Fig. 5). Most of the data points were above the 1:1 line and few above the 1:2 line.

Yield differences (in kg ha⁻¹) between CA treatments and CPM (Fig. 6) showed variability in the initial years, but the yield trends were clearly positive towards CA in the long term. Furthermore, variability between study communities diminished, and from 2008/2009 onwards there was a clear increase in maize grain yield benefits on CA plots.

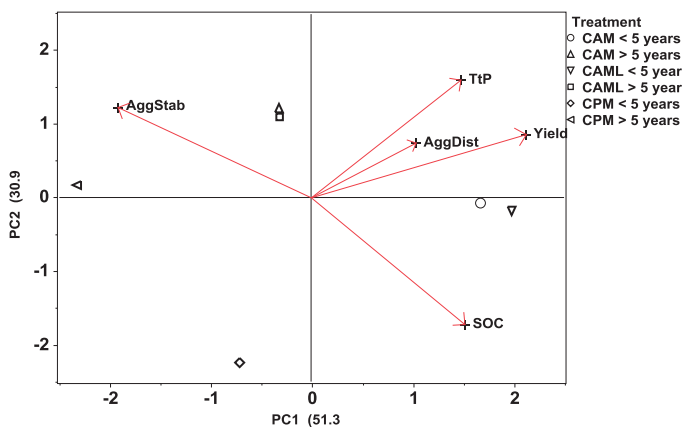


Fig. 7. The PCA-biplot showing the clustering of tillage management strategies in short (less than 5 years) versus long-term (≥ 5 years) fields. CP is conventional tillage with continuous maize, CAM is conservation agriculture with continuous maize, and CAML is conservation agriculture with maize-legume intercropping.

Table 8

Rotated loading on the principal components of the different measured maize parameters after partial component analysis.

	Principal components				
	PC1	PC2	PC3	PC4	PC5
Eigenvalues	2.5628	1.5426	0.863	0.023	0.0086
Influence	0.51	0.31	0.17	0.005	0.002
	Rotated loadings the retained two PCs				
Yield	0.92 ^a	0.37			
SOC	0.66 ^a	−0.74 ^a			
TtP	0.64 ^a	0.69 ^a			
AggDist	0.45	0.32			
AggStab	−0.83 ^a	0.53 ^a			

^a Parameters with the most significant loadings for each principal component, PC with an Eigenvalue of greater than 1 were retained.

3.5. Measured parameters versus yield

The PC1 was responsible for 51% of the variability of the maize yield results. On this axis, yield, SOC and time to pond were strongly positive (Table 8). Aggregate stability was strongly negative on the same axis. The PC2 accounted for 31% of the variability; it was strongly related to the time to pond but negatively related to the amount of SOC. The PCA-biplot identified and divided the management strategies into clusters: (a) long-term CAM and CAML characterized by longer time to pond and stable aggregates, (b) long-term CP characterized by poor yields and less SOC, (c) short-term CP with greater SOC but poor soil aggregation and shorter time to pond, and (d) short-term CAM and CAML characterized by greater yields but poor aggregate stability (Fig. 7). The results also show that the time to pond in infiltration measurements was strongly related to yield, and weakly related to SOC and aggregate stability. The angle between yield and time to pond was small suggesting a stronger relationship between these variables.

4. Discussion

The objective of this study was to provide evidence of soil fertility and crop productivity improvement under CA on communities with highly variable bio-physical characteristics. Our results indicate that the study communities varied greatly as a result of the biophysical characteristics such as seasonal rainfall, soil type, soil organic carbon, and concentration of N, P, K, Ca, Mg and Zn in the soil. These attributes are important as they influence crop productivity and the performance of new technologies. Despite this variability, yield benefits from CA systems were universal across the communities, especially in the long term.

Previous research on sandy soils in Zimbabwe and Ethiopia with underlying bedrocks and/or dense clay layers has shown that increased infiltration associated with CA systems may lead to waterlogging due to limited downward and lateral drainage under high rainfall (Thierfelder and Wall, 2009; Araya and Stroosnijder, 2010) which could affect maize yields (Thierfelder and Wall, 2012). Reduced yield benefits in high rainfall areas such as Zidyana and Mwansambo were thus expected but were not observed in this study. The nutrient management strategies in our study appear sufficient to offset nutrient limitations in the soil because CA systems require adequate nutrient inputs for yield and biophysical benefits to accrue (Rusinamhodzi et al., 2011). Lastly the common periodic stress from drought experienced at each site further illustrates the critical role of soil type and its intrinsic properties on maize productivity.

It is evident from our analyses that yield benefits were very distinct over the long term. In 2011/2012, there was no site in the whole data set where CA plots yielded significantly less than CPM. The yield differences between treatments are most likely a result

of improved infiltration and water conservation observed in the CA plots and agrees with previous findings (Thierfelder and Wall, 2009). Another important aspect is the long-term improvement in soil fertility and general management. Most of the communities did not reveal significant yield differences in the early years, but this was evident after three to five seasons (Thierfelder and Wall, 2012).

The analysed indicators of soil quality showed that time-to-pond was more affected by soil tillage and residue retention than soil carbon. The analysis of time-to-pond measurement supports the observation that limitations in available soil water were due partly to low infiltration rates and subsequent runoff through the furrows, which leads to a shortage of soil moisture on CPM (Ngwira et al., 2012a,b). The ridge and furrows were introduced many decades ago to reduce water runoff and soil erosion in high rainfall areas, but these practices are clearly ineffective at conserving moisture during seasonal dry spells. The soil on ridges is exposed to drying by wind and direct sunlight. In addition, maize roots are commonly disturbed and cut by hand hoes during weed control as farmers need to reconstruct the ridges and furrows. During these activities, there are acute deficits in soil moisture, especially under conditions when evaporation increases without protection from surface mulch.

The graph of maize yield advantage against time-to-pond advantage of CA over CPM (Fig. 3) showed that yield benefits were strongly affected by the difference in time-to-pond between CA and CP. The results suggest that crop production in these environments is generally water-limited, especially during seasonal dry spells (Harmsen, 2000). The results also show that water is one of the critical limiting factors that lead to reduced yields under conventional ridge and furrow systems. Where maize yield benefits of CA were greatest there were also large time-to-pond benefits. Previous results have shown increases in infiltration and associated maize grain yields on CA fields (Thierfelder and Wall, 2009) due to the effect of mulching (Roth et al., 1988), biological activity (Ehlers, 1975; Kladviko et al., 1986) and high levels of available soil moisture (Bescansa et al., 2006). Tillage on the other hand may lead to soil crusting and sealing and the destruction of continuous soil pores that will reduce water infiltration (Thierfelder et al., 2005).

Soil carbon showed no clear trend, which is in line with results reported by Ngwira et al. (2012b), who also found no significant carbon differences on trials in Malawi. There are various explanations for these observations. As stated before, the traditional cropping systems in Malawi are based on the ridge and furrow system. Farmers have two ways of managing the remaining crop residues in this system. They burn the residues during or before ridge formation (and bury the ashes) or alternatively they bury the crop residues beneath the newly formed ridge. Breaking and forming new ridges is done every year. In the CA systems we studied, residues were left on the soil surface where they could decompose (Table 2). Valid comparisons between the two residue management strategies are

therefore difficult. It will depend a lot on the way the soil is sampled for carbon and the way residues are managed in these experiments to find significant differences. Also the amount of C input into the system may be too small to increase carbon significantly in the longer term (Thierfelder and Wall, 2012). In-depth studies on soil carbon are required to understand better the dynamics on both systems.

In most cases, the results from this long-term study showed that maize yields in the initial years were in most cases not significantly different between treatments. Immediate yield benefits of CA were observed only in some communities such as Lemu. In other communities, yield benefits took longer to establish a clear upward trend, e.g. in Malula. All communities eventually showed distinct yield increases, but this took up to five years in some cases. The reason is believed to be related to the time to build soil fertility and to adapt to the new CA system – a phenomenon called “age hardening” for soils transitioning from intensive tillage to no-till (Dexter and Horn, 1988). Explanations for communities where yield differences were slow to materialize could be similar to reasons summarized by Wall (2007) and Thierfelder and Wall (2012): This study in Malawi was carried out on-farm and, although each farming community forms one trial with a fairly similar agro-ecological environment, there is considerable variability between experimental sites (and between farmers), which is natural for a diverse small-scale farming environment. It is therefore difficult to obtain uniform results from experimental sites that are heterogeneous. On the other hand, results from on-farm research provide far more useful information about the performance of a technology under real farm conditions compared with results from on-station trials (Giller et al., 2009; Baudron et al., 2012). The results also point to the level of management and precision at each trial location and, as this research is done in collaboration with extension officers, depends a lot of the capacity and skills of the person responsible at each experimental site (Wall, 2007). However, these human variables are real and further illustrate the importance of on-farm research where CA technology needs to be adapted at the farm level. Without this adaptation, it is highly likely that CA will fail due to the variability in soils, climate, farmer perceptions and management.

It has often been stated that the increases in maize yield on CA fields occur only in the long-term and short-term solutions need to be developed to satisfy farmer needs (Giller et al., 2009; Gilbert, 2012). This study confirms that biophysical CA benefits may not occur in one growing season and the full benefit may take five or more years to develop (Thierfelder and Wall, 2012). The results from Malawi suggest that abandoning the ridge and furrow systems and using herbicides for weed control can lead to significant labour reductions as reported elsewhere (Ngwira et al., 2012a). Saved labour is potentially available to do off-farm work, increase the value of certain farm products, and increase the land area (if available), and diversify to more labour intensive horticulture crops and selling those products at the local market. Therefore, labour savings in the initial years can help to offset the small yield increases associated with the transition from the conventional tillage systems to CA. More economic analyses will be important to determine the monetary benefits to the farmer in relation to the yield advantages reported.

5. Conclusion

The results of this study clearly showed that maize grain yields increase significantly over time under no-tillage with the retention of crop residues on the surface compared with the traditional ridge and furrow system. There was no yield penalty for intercropping maize with legumes compared with maize monocropping under CA, suggesting little or no competition between maize and the

companion legume crop. The comparative analyses showed that yield benefits were more related to improved rainfall infiltration. The amount of soil carbon in the soil did not significantly affect the yield benefits between conventional and conservation tillage practices. The PCA-biplot confirmed that maize yields were strongly related to time-to-pond and weakly related to soil carbon and aggregate stability. Detailed long-term studies on soil carbon under CA systems are required to better understand the lack of a clear pattern of carbon observed in this study. The bio-physical variability of communities involved in this study demonstrates that CA has application across a diverse range of environments from sandy to clay soil, from nutrient rich to infertile soils, and from low to high rainfall areas as long as adequate inputs (fertilizer, herbicides and labour) are available with good extension support to farmers, especially in the initial years.

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