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Article

Evidence and Lessons Learned from Long-Term On-Farm Research on Conservation Agriculture Systems in Communities in Malawi and Zimbabwe

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Abstract: A long-term study was carried out in the Zidyana Extension Planning Area (EPA), Malawi and in the Zimuto Communal Area, Zimbabwe, to evaluate the effect of different conservation agriculture (CA) systems on crop productivity, soil quality and economic performance. Maize productivity results from Zidyana showed that CA systems out-yielded the conventional system in seven out of nine cropping seasons. Labour savings relative to the conventional control ranged from 34–42 labour days·ha^{-1} due to reduced time needed to make manual ridges and for weed control, leading to higher net benefits of 193–444 USD·ha^{-1}. In Zimuto, yield benefits were apparent from the second season onwards and there was a much clearer trend of increased yields of CA over time. Greater net benefits (in USD·ha^{-1}) were achieved on CA systems in Zimuto compared with conventional control treatments due to overall higher yields from CA systems. In Zimuto, both increased infiltration and a gradual increase in soil carbon were recorded, which may have contributed to the greater yield response of CA in this area. In Zidyana, yield increases were attributed primarily to enhanced water infiltration since no increases in soil carbon levels were measured. Farmers highlighted critical challenges to the adoption of CA. These will have to be addressed in future research and extension to provide effective solutions to farmers.

Keywords: maize productivity; direct seeding; soil quality improvements; yield benefits; gross margins; economic benefits; farmer perception

1. Introduction

Conservation agriculture (CA) has been promoted in southern Africa since the late 1990s with the aim of reversing the effects of declining soil fertility and productivity in current farming systems as well as adapting to projected increases in climate variability and change [1,2]. CA aims to remove the unsustainable aspects of current conventional tillage-based systems by minimizing excessive soil movement; replacing monocropping with diversified crop rotations and/or crop associations and finally protecting the soil with living or dead plant material instead of burning or removing the mulch [3,4]. There is increasing evidence that CA provides a wide range of short and long-term benefits to the soils and the environment [5]. Research results from the southern African region show that CA maintains high levels of water infiltration thereby increasing available soil moisture for crops, which is a benefit in seasonal dry-spells [6–9]. However, greater water infiltration may also lead to increased waterlogging and nutrient leaching, which can negatively affect plant growth in very wet years [6]. CA has also been shown to improve different parameters of soil quality such as soil fauna, aggregate stability, soil carbon amongst others which all lead to increased productivity in the medium to long-term [7,10–13].

However, the adoption of CA is often constrained by various factors related to the diversity of farming systems and the socio-economic circumstances and limited resources of smallholder farmers in southern Africa [14–17]. These constraints for example lack of access to critical inputs (improved seed, fertilizers, herbicides and specialized tools or machinery) and dysfunctional markets [18,19] which are general limitations to all farming enterprises in the area. More specifically to CA, these constraints are competition for crop residues in mixed crop-livestock systems [20–22], weed control in the absence of effective herbicides [23–27] and also the mindset of farmers that agriculture is only possible and adequate if the soil is tilled [1,28].

Smallholder farmers in Zimbabwe and Malawi grow maize (*Zea mays* L.) on the majority of their arable land area (50%–90%) [29]. In large parts of the communal land of Zimbabwe, soils are derived from granitic sands with high sand content (>90%) and low soil organic matter levels (<0.5%). Average yields are below 1 $t \cdot ha^{-1}$ [30,31]. In Malawi, soils are more fertile and farmers have access to a government implemented fertilizer subsidy program leading to relatively higher average maize grain yields (±2 $t \cdot ha^{-1}$) as compared with Zimbabwe [9]. However, the dependency of farmers to the fertilizer subsidy program also raised concerns [32,33] as it has large budgetary implications for the Malawi Government. Farmers in conventional agriculture systems of southern Zimbabwe rarely break even [30] whereas Malawian farmers, especially if beneficiaries of the subsidy program have greater gross margins per hectare [9].

Due to the complexity of smallholder farming systems in sub-Saharan Africa, which are related to multiple crops grown on the farms and integration of livestock to varying degrees [34], the aforementioned constraints, the mindset and beliefs of farmers, lack of consistent messages and approaches in the extension of CA [5], the adoption of CA practices on larger farm areas has been lower than in other parts of the world. Furthermore, adoption of CA e.g., in the Americas and Australia occurred primarily on commercial and large-scale mechanized farms [35,36], which are not common in sub-Saharan Africa.

It is widely acknowledged that the drivers for increased uptake of CA in the Americas and Australia had economic reasons such as reduced fuel use with no-till systems while maintaining yields at similar levels [5,37]. For smallholder farmers in Africa, reduced fuel costs are not a primary concern as most farming systems are based on manual or animal traction systems of planting. Nevertheless, farmers in the manual systems of Malawi have appreciated labour reductions on weeding and planting as they do not have to construct ridges that are commonly used for planting crops [38]. In the manual CA systems of Malawi, seeding is normally done on the flat with a dibble stick, or on the top of old ridges when converting to CA. Weed control with herbicides adds another labour saving aspect for farmers—which preferentially benefits women while reducing soil disturbance [1,9,24,39–41]. However, where these immediate benefits are not apparent, it is important to identify the drivers of adoption while simultaneously overcoming the major barriers through appropriate adaptive research and extension.

This paper summarizes the lessons learned from 2004 to 2014 on the performance of CA systems in two contrasting on-farm communities in Malawi and Zimbabwe. The aim of this study was to better understand the feasibility of CA under different agriculture and socio-economic environments and to identify the key challenges limiting widespread experimentation and adoption of cropping systems in southern Africa. The work is embedded in a large initiative on facilitating the widespread adoption of CA systems in Eastern and Southern Africa which was started by CIMMYT in 2004.

2. Experimental Section

2.1. Study Area

The study was conducted at Zidyana in Nkhotakota District of Malawi (13.11 S, 34.15 E) with the assistance of the regional non-governmental organization Total LandCare (TLC) and the Ministry of Agriculture and Food Security from 2005 to 2014 on fertile *Luvisols* (Table 1). The second site was at Zimuto Communal Area in Masvingo District of Zimbabwe (19.85 S; 30.88 E). Research in this area was conducted with the help of the Ministry of Agriculture Extension, AGRITEX from 2004 to 2013 on very sandy *Arenosols*. Both sites are characterized by a unimodal rainfall distribution with an annual average rainfall of 1344 mm (991–1547mm) in Zidyana and 685 mm (382–1401 mm) in Zimuto Communal Area. It is evident from the rainfall distribution that Zidyana receives higher and more reliable rainfalls while Zimuto has lower and more erratic rainfalls (Table 2).

The traditional farming system in Zidyana is based on the construction of annual ridges 75–90 cm apart using hand hoes for land preparation. Crop residues are usually removed or burned. Farmers grow maize (*Zea mays* L.) on most of their land but also undertake rotations to a certain extent with groundnuts (*Arachis hypogaea* L.), cowpeas (*Vigna unguiculata* (Walp)), beans (*Vicia faba* L.) and other legumes. In wetter, low lying areas subject to inundation, rice (*Oryza sativa* L.) and cassava (*Manihot esculenta* Crantz) are commonly grown, the latter on large ridges or mounds.

In Zimuto, the land is traditionally ploughed with animal traction mouldboard ploughs or cultivated by hand hoes before planting [42]. Maize is the dominant food security crop but farmers also grow sorghum (*Sorghum bicolor* (L) Moench), finger millet (*Eleusine coracana* L.), groundnuts, cowpeas, sweet potatoes (*Ipomoea batatas* L.) and sunflower (*Helianthus annus* L.). Crop residues are typically grazed or removed from the land.

Table 1. General characteristics of the experimental sites in Malawi and Zimbabwe.

Country	Village	District	Latitude	Longitude	Altitude (masl)	Texture (0–30 cm)	Soil Type	Average Rainfall (mm)
Malawi	Zidyana	Nkhotakota	−13.23	34.24	535	SCL	Luvisols	1344
Zimbabwe	Zimuto	Masvingo	−19.85	30.88	1223	S	Arenosol	685

Notes: S = sand; SCL = sandy clay loam.

Table 2. Annual rainfall of the two target communities in Zidyana, Malawi and Zimuto, Zimbabwe.

Communities	Cropping Season									
	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14
Zidyana		1477	1310	991	1233	1547	1203	1100	1887	1222
Zimuto	408	1056	382	1401	481	635	544	503	481	

2.2. Experimental Design

At both sites, a cluster of on-farm validation trials were established, comprising two CA treatments and one conventional control [25]. The design at each site was a completely randomized block with six replications in Zidyana and seven to nine replications in Zimuto. The farmers were used as blocks in the analysis. The size of each farmer replicate was 3000 m^2 subdivided into treatments of each 1000 m^2 (for more details on the design consult [30] and [40]. At Zidyana the treatments were as follows:

(a) Conventional ridge and furrow system (CRF) with manual hoe seeding of sole maize into previously created planting ridges 75 cm apart and 25 cm in-row spacing (53,000 plants·ha^{-1}).
(b) Conservation agriculture seeded with a dibble stick with sole maize (CAM), planted on the flat in lines 75 cm apart and a 25 cm in-row spacing (53,000 plants·ha^{-1}).
(c) Conservation agriculture seeded with a dibble stick with a maize-cowpea intercrop (CAML) at the same spacings as for CAM. The intercropped cowpea was seeded between the maize rows with an interplant spacing of 25 cm (53,000 plants·ha^{-1}).

All treatments were fertilized using the rates recommended by the Ministry of Agriculture, Irrigation and Water Development of 69 kg·ha^{-1} N:21 kg·ha^{-1} P_2O_5:4 kg·ha^{-1} S, applied as basal dressing (23 kg·ha^{-1} N:21 kg·ha^{-1} P_2O_5:4 kg·ha^{-1} S) at planting and as top-dressing (46 kg·ha^{-1} N) at 4 weeks after planting. Weeds were controlled with pre-emergence (glyphosate) in CAML and a mixture of both glyphosate and a residual herbicides (Bullet® and in later years Harness®) at recommended rates in CAM only. In the conventional treatment, weed control was achieved with manual hoe weeding. For more information on the treatments, please consult [40]. At Zimuto the treatments were as follows:

(a) Conventional mouldboard ploughed control treatment, seeded with maize (CP) in rows 90 cm apart, 60 cm in-row spacing, 2 seeds per station and a target plant population of 37,000 plants·ha^{-1}.
(b) Ripline seeded maize treatment (RI) in lines using an animal drawn ripper with the same row and in-row spacing as above.

(c) Direct seeded maize (DS) with a Fitarelli animal drawn direct seeder (http://www.fitarelli.com.br/) with a row spacing of 90 cm but an in-row spacing of 30 cm with one seed per planting station (37,000 plants·ha^{-1}).

All treatments were routinely intercropped with cowpeas, although yields of cowpeas stayed at very low levels. The crop was fertilized with 80 kg·ha^{-1} N:23 kg·ha^{-1} P_2O_5:12 kg·ha^{-1} K_2O applied as basal dressing (11 kg·ha^{-1} N:23 kg·ha^{-1} P_2O_5:11 kg·ha^{-1} K_2O) at planting and a split applied top-dressing of 69 kg·ha^{-1} N at 4 and 7 weeks after crop emergence. Weeding was done with hand hoes due to the very sandy soil texture which did not allow for effective glyphosate applications. For more information on the treatments, please consult [30] and [42].

2.3. Field Measurements

Both research sites were sampled for soil carbon and water infiltration. The soil was sampled for carbon in 0–30 cm at Zidyana and 0–20 cm in Zimuto. Soil samples in Zimuto were collected in October 2004, 2008, and 2011. In Zidyana samples were collected in 2011 only. Total carbon was measured through a CE Elantech Flash EA1112 dry combustion analyser. Soil carbon (in Mg·ha^{-1}) was calculated from the carbon concentration, thicknesses and bulk densities of the horizons [43]:

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

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)

In the “time-to-pond” measurement previously described by [42] and [44] a metal wire ring of 50 cm diameter was placed on the soil surface between two maize lines and water applied in the centre of the ring with a watering can that had a rose nozzle. The time taken for water to flow out of the metal ring was measured and recorded as the “time to pond”. Six measurements were taken on each plot of each treatment and averaged per treatment.

Maize grain yield was measured at the end of each cropping season using standard harvesting procedures. The crop was harvested at physiological maturity from 10 sub-samples of 9 m^2 per treatment in Zimuto and 7.5 m^2 in Zidyana. Cobs and above-ground biomass were collected, weighed, and sub-samples taken for determination of grain moisture content. A sample of 20 cobs per plot was shelled to calculate the shelling percentage (ratio of grain to total cob weight) and grain yield was then calculated on a per hectare basis at 12.5% moisture content.

Yield benefits of CA treatments *versus* the conventional control were evaluated in relation to the number of years of practice under CA. The mean difference in yield between the treatment and control (Equation (2)) was used because of its ease of interpretation and relevance for comparing potential yield gains [10,45].

$$Mean\ difference(MD) = mean_{treated} - mean_{control} \quad (2)$$

2.4. Socio-Economic Studies

In addition to the biophysical measurements, intensive focus group discussions were conducted in both sites to identify drivers and barriers to the adoption of CA in areas where the practice has been promoted since 2004 (2005). These discussions were conducted with small groups of farmers (10–15) with equal representation of males and female. The discussions were held at the different sites during annual field tours, study tours and evaluation meetings in each locality with the assistance of local extension officers, who served as translators.

The data used for economic analyses were from four planting seasons (2010–2013) in Zimuto and three seasons (2011–2014) for sites in Malawi based on data collection by extension officers on labour, input and output costs. The gross margin analysis was done by recording the total variable costs (TVC) in USD·ha^{-1}, which were the labour and input costs, and subtracting this value from the gross receipts. Gross margin analysis was used to assess the potential net benefits of planting maize under CA using different seeding systems.

2.5. Statistical Methods

Results from all biophysical measurements were subjected to a test of normality and homogeneity of variance before conducting an analysis of variance (ANOVAs) using completely randomized block design. Where the F-test was significant, a least significant difference (LSD) test was used at $p \leq 0.05$, if not stated otherwise, to separate the means. Pearson regression analysis was used to assess the increase in maize yield benefits over time at both locations using the yield difference between the CA system on-site and the conventional control treatment and the years of practice as variables.

3. Results

3.1. Effects of CA on Maize Grain Yield

The long-term effects of CA systems on maize grain yield were analysed from 2006–2014 in Zidyana and from 2005 to 2013 in Zimuto (Figures 1 and 2). The results in Zidyana showed no initial clear trend in yields on CA plots compared with the conventional ridge tillage fields. However, a consistent significant difference between CA and conventional treatments became apparent from the fifth cropping season onwards (Figure 1). The CA sole maize treatment outyielded the other treatments in only one season (2009/2010) while in all other seasons there was no significant difference between the two CA treatments. The average yield for all three systems in each particular year depended on the quality, amount and distribution of rainfall. Visual assessments of germination on CA systems showed an earlier and more even germination on CA systems, contributing to the yield advantages. The 2009/2010 season was a particularly wet year (1547 mm annual rainfall) giving a yield benefit of 29%–47% from the CA treatments whereas the 2011/2012 season was much drier for this agro-ecological zone (1100 mm annual rainfall) with a yield benefit of 51%–56%.

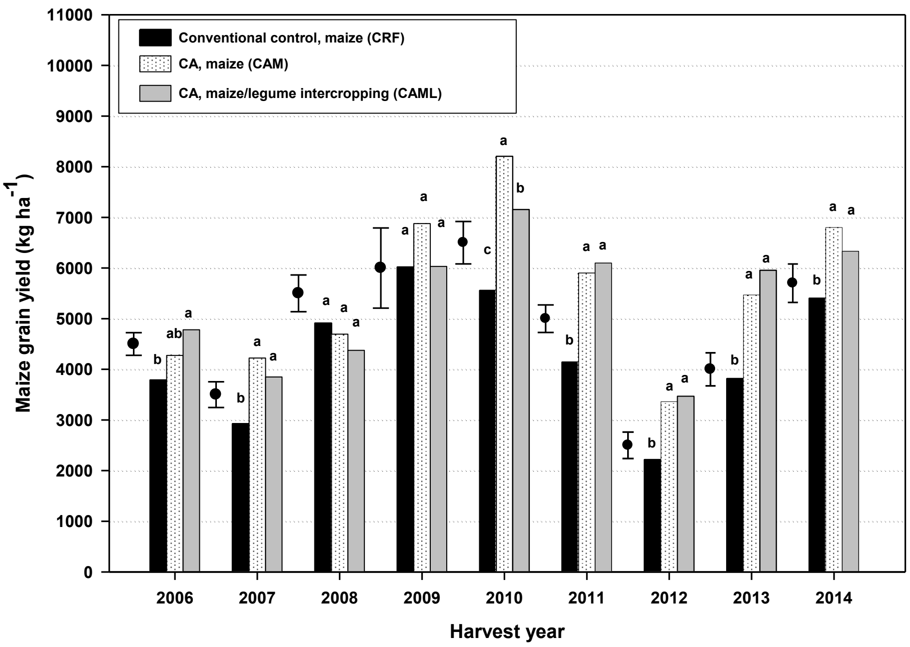

Figure 1. Long-term effects of a conventional and two conservation agriculture treatments on maize grain yield (kg·ha^{-1}) in Zidyana, Nkhotakota District, Malawi, 2006–2013. The error bars indicate the standard error of the difference (SED) at $p \leq 0.05$. adapted from [40].

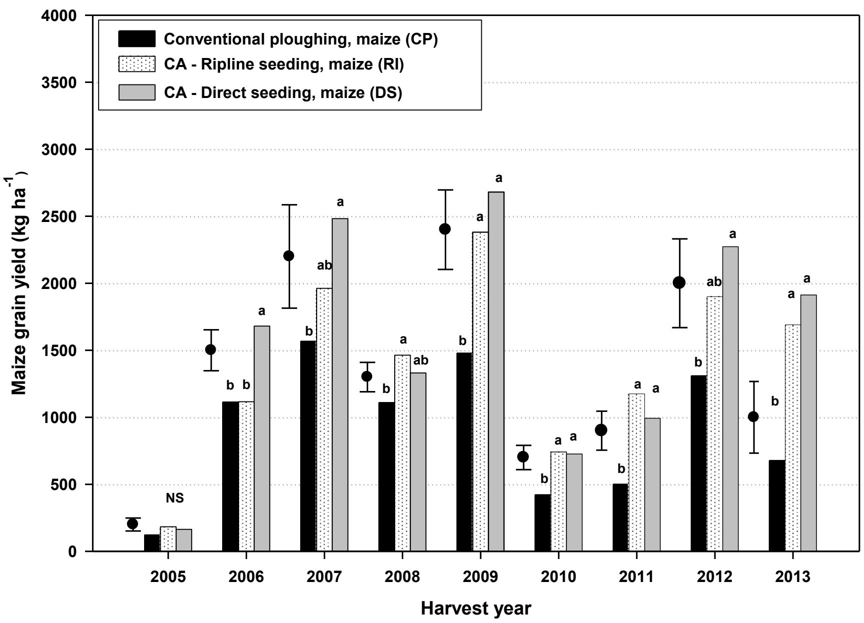

Figure 2. Long-term effects of a conventional and two conservation agriculture treatments on maize grain yield (kg·ha^{-1}) in Zimuto Communal Area, Masvingo Province, Zimbabwe, 2005–2013. The error bars indicate the standard error of the difference (SED) at $p \leq 0.05$. Adapted from [30].

In Zimuto, the season quality had a much stronger influence on the performance of maize (Figure 2) and early and more even germination of maize seedlings was noticed on CA fields. Maize yield benefits on the research plots were recorded basically from the second season onwards. The treatment on animal drawn direct seeding outperformed the conventionally ploughed control in almost all seasons, except 2007/2008, where the ripline seeding exceeded the conventional control. On average, yields were lowest in 2004/2005, 2009/2010 and 2010/2011, with associated annual rainfall of 408, 635 and 544 mm, respectively (Table 2). However, it was discovered that the distribution of rainfall especially early in the season rather than the actual amount was the deciding factor when good maize yields were recorded. High rainfall at the beginning of the season often led to waterlogging, which affected plant growth.

Analysis of the yield benefit (Figure 3) showed an increase in yield benefit with increased years of practicing CA at both sites. This was more pronounced in Zimuto (Figure 3b) relative to Zidyana (Figure 3a) as indicated by the steeper regression curve in the former.

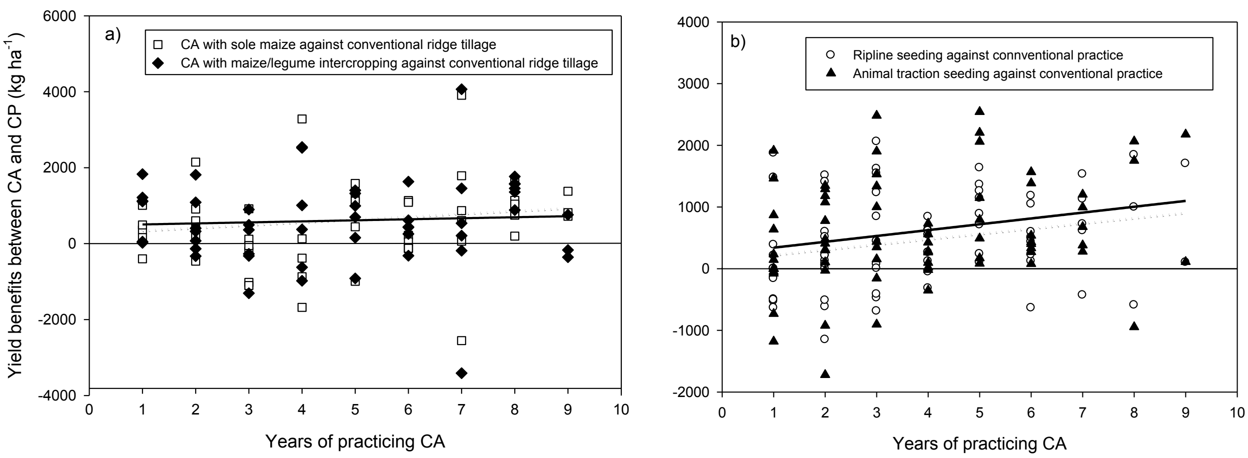

Figure 3. Yield benefits of conservation agriculture systems against a conventional practice on-site in response to increased years of practice at Zidyana, Malawi (**a**) and Zimuto, Zimbabwe, (**b**) Yield benefits are calculated as yields of the CA system minus yield of the conventional system.

3.2. Effects on Some Soil Quality Parameters

Treatment benefits were most visible when assessing the effect of CA on water infiltration as measured by the "time to pond" method (Table 3). In Zimuto, this parameter was captured in four consecutive seasons (2007–2011). In Zidyana, financial constraints limited measurements to only two seasons (2008/09 and 2010/11). In all seasons when infiltration was measured, infiltration was significantly higher in CA systems than in the conventional control. Average infiltration across all treatments was generally higher in Zidyana relative to Zimuto with the exception of the 2007/08 season.

Soil carbon, on the other hand, did not show such clear differences between treatments (Table 4). In Zidyana, the only year with available data, no carbon increase was measured between the conventional and CA plots. In Zimuto, we sampled soil carbon in 2004, 2008 and 2011. At project inception (2004), no difference between treatments was measured in total carbon. In 2008, soil carbon increased in both direct seeded and rip-line seeded treatments in contrast to the conventional control where the carbon levels stayed at low levels. In 2008, the direct seeding treatment had 93% more soil carbon than the conventional control. Similar increases in soil carbon values were recorded in 2011 where the direct seeding treatment exceeded the conventional control by 97%.

Table 3. Influence of conservation agriculture and conventional cropping systems on the time to pond (s) in Zimuto Communal Area, Masvingo, Zimbabwe 2008–2011 and Zidyana, Nkhotakota, Malawi 2008 and 2011.

Treatments	Time to Pond (s)			
	2007/08	**2008/09**	**2009/2010**	**2010/2011**
Zidyana				
Conventional ridge tillage		7.6 [b,*]		11.6 [b]
CA-Dibble stick sole maize		10.5 [a]		14.9 [a]
CA-Dibble stick, maize/legume		10.3 [a]		16.2 [a]
p		0.01		0.01
LSD		1.28		2.1
Zimuto				
Conventional ploughing	6.6 [b,*]	3.1 [b]	3.2 [b]	3.0 [b]
Rip-line seeding	11.5 [a]	5.5 [a]	6.2 [a]	5.1 [a]
Direct seeding	10.8 [a]	5.4 [a]	6.0 [a]	5.1 [a]
p	0.01	0.01	0.01	0.01
LSD	2.7	0.8	0.9	0.7

* means followed by the same letter (a, b) in column are not significantly different at the respective probability (*p*) level. LSD stands for Least Significant Difference.

Table 4. Changes in total soil carbon content in 2004 and 2008 (Zimuto) and 2011 (Zidyana) in two conservation agriculture and one conventional treatment.

Treatments	Depth (cm)	Total Carbon (Mg ha^{-1})	Total Carbon (Mg ha^{-1})	Total Carbon (Mg ha^{-1})
Zidyana		2004	2008	2011
Conventional ridge tillage	0–30			28.0 [a,*]
CA-Dibble stick sole maize	0–30			23.4 [a]
CA-Dibble stick, maize/legume	0–30			24.5 [a]
Mean				25.2
LSD				3.8
Zimuto				
Conventional ploughing	0–20	6.5 [a,*]	6.9 [b]	6.5 [b]
Rip-line seeding	0–20	5.4 [a]	9.5 [a,b]	8.4 [a]
Direct seeding	0–20	5.8 [a]	13.3 [a]	12.8 [a]
Mean		6.5	9.9	9.3
LSD		5.2	4.9	4.3

Note: Means followed by the same letter (a, b) in column are not significantly different at $p \leq 0.05$ probability; Samples were all taken in October of each respective year before the cropping sea.

3.3 Assessment of Economic Benefits

The analysis of economic net benefits from sites in Zidyana and Zimuto showed that CA systems had positive economic net benefits in most years. In Zidyana, CA systems showed lower labour costs for land preparation and weeding (Table 5). In terms of labour, the analysis of the three cropping systems showed a savings of 52%–65% for CA (34–42 labour days). However, the use of herbicides increased the variable costs on CA systems. In the 2012/13 season, the price for legume seed increased the overall variable costs of CA+ maize/legumes. Despite the increase in these variable costs, gross margins were still higher on CA systems as compared with the conventional ridge tillage as follows: 318 USD·ha^{-1} and 394 USD·ha^{-1} on CA with sole maize and CA with maize/legume intercropping in 2011–2012; 337 USD·ha^{-1} and 444 USD·ha^{-1} in 2012–2013 and 259·USD ha^{-1} and 193 USD·ha^{-1} in 2013–2014.

In Zimuto, where land preparation was done with the plough on the conventional treatment and weeds were not controlled with herbicides, there was no labour benefit to CA systems in most years (Table 6). Due to low yields and unfavourable weather conditions, gross margins for the conventional systems were negative in all seasons except of 2011–2012. Gross margins were highest for the direct seeded treatment in 2011–2012 and 2012–2013 when 374 USD·ha^{-1} and 463 USD·ha^{-1} more was received with the direct seeded treatment as compared with the conventional control (Table 6).

Table 5. Gross margin analysis (in US$·ha^{-1}) of different cropping systems practiced under on-farm trials at Zidyana, Malawi, 2011–2014.

		2011–2012			**2012–2013**			**2013–2014**		
	Unit	**CP Maize**	**CA+ Maize**	**CA+ Maize/Legume**	**CP Maize**	**CA+ Maize**	**CA+ Maize/Legume**	**CP Maize**	**CA+ Maize**	**CA+ Maize/Legume**
Gross receipts	USD	718.16	1030.67	1086.70	1054.73	1402.4	1558.51	1414.88	1661.67	1623.94
Variable costs (VC)										
Seed	USD	45.45	45.45	45.45	47.92	47.92	103.42	45.45	45.45	87.01
Fertiliser	USD	265.45	265.45	265.45	294.42	294.42	294.42	265.45	265.45	265.45
Herbicides & Pesticides	USD	0.00	47.27	25.97	0.00	58.30	50.54	0.00	47.27	25.97
Labour										
Land clearing	Days/ha	1.00	0.50	0.68	1.00	0.60	0.60	1.00	1.00	1.00
Land preparation	Days/ha	32.05	0.00	0.00	29.00	0.00	0.00	31.00	0.00	0.00
Sowing	Days/ha	3.00	2.00	3.00	4.17	2.00	2.00	3.00	1.50	3.00
basal fertiliser	Days/ha	1.62	1.62	1.62	1.62	0.82	1.62	1.62	1.62	1.62
Mulching	Days/ha	0.00	5.00	5.00	0.00	6.75	6.65	0.00	3.33	4.54
Herbicide application	Days/ha	0.00	0.60	0.56	0.00	0.63	0.63	0.00	1.00	1.00
Pesticide application	Days/ha	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00
Thinning and gap filling	Days/ha	0.21	0.33	0.15	0.25	0.17	0.25	0.00	0.00	0.00
Weeding1	Days/ha	10.00	2.00	2.00	12.00	2.00	2.00	11.25	1.67	3.33
Weeding2	Days/ha	6.00	6.00	6.00	3.09	4.25	4.00	3.33	0.00	1.67
Weeding3	Days/ha	2.00	1.00	1.00	1.60	0.75	0.25	3.33	0.00	0.00
Top dressing	Days/ha	1.00	1.00	1.00	1.00	0.00	0.25	1.00	1.00	1.00
Harvest and threshing	Days/ha	6.57	6.46	6.46	8.48	10.50	11.35	8.05	10.96	10.57
Total labour	Days/ha	63.45	26.51	27.47	62.22	28.68	29.60	63.58	22.08	27.73
Labour unit price	USD	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Labour costs	USD/ha	90.80	37.90	39.30	89.00	41.00	42.40	91.00	31.60	39.70
Total VC	USD/ha	401.71	396.12	376.19	431.38	441.68	490.75	401.90	389.78	418.13
Gross Margin	USD/ha	316.44	634.55	710.51	623.35	960.69	1067.77	1012.97	1271.88	1205.81

Notes: VC: variable costs, TVC: total variable costs, CP = conventionally ridge tillage; CA + maize = conservation agriculture treatment seeded with a dibble stick and sole maize; CA + maize / legume = conservation agriculture treatment seeded with a dibble stick and maize-cowpea intercropping; The labour data is an aggregate from 6 farmers in the area.

Table 6. Gross margin analysis (in US$·ha^{-1}) of different cropping systems practised under on-farm trials at Zimuto Communal Area, 2009–2013.

		2009–2010			**2010–2011**			**2011–2012**			**2012–2013**		
	Unit	**CP**	**Ripper**	**DSeeder**	**CP**	**Ripper**	**DSeeder**	**CP**	**Ripper**	**DSeeder**	**CP**	**Ripper**	**DSeeder**
Gross receipts	USD	97.30	289.92	182.02	141.96	378.17	278.36	376.58	562.28	751.27	271.00	680.85	770.80
Variable costs (VC)													
Seed	USD	66.00	66.00	66.00	76.00	76.00	76.00	60.00	60.00	60.00	76.00	76.00	76.00
Fertiliser	USD	243.50	243.50	243.50	216.40	216.40	216.40	215.00	215.00	215.00	216.40	216.40	216.40
Labour													
Pre-season weeding	Days/ha	0.00	3.20	2.23	0.00	3.20	2.23	0.00	3.00	2.00	0.00	3.00	2.00
Land preparation	Days/ha	3.19	0.99	1.45	3.19	1.00	1.45	3.19	1.00	1.50	3.00	1.00	1.45
Basal fertilizer	Days/ha	1.08	1.15	0.00	1.08	1.15	0.00	1.00	1.15	0.00	1.08	1.20	0.00
Seeding	Days/ha	2.71	3.00	1.00	2.71	3.00	1.00	3.00	3.00	1.00	3.00	2.00	1.00
First weeding	Days/ha	8.75	6.90	14.60	6.94	10.63	10.63	11.15	7.23	6.77	8.50	12.80	12.60
Second weeding	Days/ha	1.02	6.15	8.76	4.16	6.38	6.38	6.69	4.34	4.06	8.60	8.90	7.70
Third weeding	Days/ha	0.38	5.00	5.84	2.78	4.25	4.25	4.46	2.89	2.71	5.80	5.70	5.60
Top dressing	Days/ha	1.69	1.84	1.81	1.69	1.84	1.81	2.00	2.00	2.00	1.30	1.70	1.10
Mulching	Days/ha	0.00	7.00	7.00	0.00	7.00	7.00	0.00	7.00	7.03	0.00	4.00	4.00
Harvest and threshing	Days/ha	1.22	3.95	2.41	1.74	4.80	3.45	4.74	7.06	9.43	2.70	6.76	7.65
Total labour	Days/ha	20.03	39.17	45.09	24.28	43.24	38.19	36.24	38.67	36.51	33.98	47.06	43.10
Labour unit price	USD	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	4.00	4.00	4.00
Labour costs	USD/ha	60.09	117.50	135.27	72.84	129.71	114.58	108.71	116.01	109.54	135.94	188.22	172.41
Total VC	USD/ha	369.59	427.00	444.77	365.24	422.11	406.98	383.71	391.01	384.54	428.34	480.62	464.81
Gross margin	USD/ha	−272.29	−137.08	−262.75	−223.28	−43.94	−128.63	−7.13	171.27	366.73	−157.34	200.23	305.99

Notes: VC: variable costs, TVC: total variable costs, CP: conventionally ploughed control treatment, Ripper = rip-line seeded CA treatment, DSeeder = direct seeded maize treatment, Partial budgets are only made from the maize crops in the particular seasons. There was an increase in labour costs from 3 US$·d^{-1} in November 2010 to 4 USD·d^{-1} in December 2011; adapted from [30]. The labour data is an aggregate from 7 farmers in Zimuto.

3.4. Farmer Perceived Challenges

Focus group discussions during field days, study tours and evaluation meetings revealed a clear set of challenges that affected the farmers in various ways. These can be clustered in three groups: (a) technical and biophysical challenges; (b) operational challenges and (c) institutional challenges (Table 7). Besides the often stated challenges considered as major impediments to the adoption of CA systems, such as limited amounts of crop residues to retain on the soil surface [5,20,21] and increased weed abundance as a result of CA [24,26,27], farmers were very particular about other limitations of CA systems in the different sites. CA was often considered as a system that works well with maize and some legumes but would not be suitable for tobacco and root crops (e.g., sweet potatoes and cassava). The main reason by farmers was that tobacco needs a sterilized seedbed (which would require burning of residues). Furthermore, to avoid waterlogging, tobacco could not be grow on the flat. This is despite large areas under tobacco in Brazil [46,47] and highlights the need for cite-specific adaptation. Farmers did not think that root crops could perform under CA as they would disturb the soil too much during harvesting and would make the harvesting process too laborious. Examples from Latin America clearly show that cassava can be planted under minimum tillage with good success [48].

The choice of crops, especially in Malawi, was also determined by the small landholding size because of the dependence on maize for food security. In some cases, an increase of some pests and diseases was noted by farmers as a constraint in the application of CA systems. The most frequently mentioned pests were termites, white grubs and wire worms. Fungal diseases, carried over to next seasons on crop residues, were also mentioned by farmers.

On the operational and institutional level, farmers complained about the unavailability and/or cost of inputs such as seed, herbicides and seeding equipment (e.g., direct seeders in Zimuto) as well as the lack of credit to purchase inputs. In Zimuto, the lack of clear communal grazing rights led to free roaming cattle and grazing of crop residues intended for soil cover. This was not a problem in Zidyana, due to the low numbers of livestock in the area. Finally it was overwhelmingly accepted that both extension officers and farmers lacked knowledge and capacity to embrace the full concept of CA, indicating the need for more training and the production of up-to date extension materials to provide a solid foundation to promote CA.

Table 7. Some of the major challenges of implementing conservation agriculture mentioned during focus group discussions in Zidyana, Malawi and Zimuto, Zimbabwe.

Technical Challenges	Operational Challenges	Institutional Challenges
Inadequate amounts of crop residues Low crop productivity Habitual burning Livestock grazing	Management intensity Often CA is more demanding than farmers' conventional practice	Unstable input/output markets Increases in prices for inputs Decreases in prices for outputs
Greater weed pressure No-till lead to more weed densities initially Limited effectiveness of herbicides on sandy soils	Labour shortage Initial labour needed to match the larger management intensity	Unavailability of good quality legume seed Legume seeds often recycled for many years Limited variety of legume crops

Table 7. *Cont.*

Technical Challenges	Operational Challenges	Institutional Challenges
Crop choice Root crops under CA	Herbicides Not available and affordable locally. Inadequate herbicides use experience Limited effectiveness with some weeds	Unavailability of credit for inputs No funds to purchase fertilisers, improved seed and herbicides
Termites attack On yield at physiological maturity on crop residues	Equipment Direct seeder is very expensive Not available locally	Knowledge and capacity Farmers lack the knowledge on new management steps Extension officers are trained on outdated technical knowledge
Pest and diseases At some sites, the incidence of white grubs was observed Fungal diseases may be carried over through residues		Land constraints How to introduce diversified crop rotations when the land holding size of farmers is too small to ensure food security with non-cereal crops

Note: Table adapted from [10].

4. Discussion

4.1. Effects of CA on Maize Productivity and Soil Relations

Results from the high potential area of Zidyana in Malawi, showed higher yields and water infiltration with hand-seeded CA treatments over time compared with conventional systems. However, a clear trend was achieved only after five cropping seasons, which highlights the need for continued technical support for farmers to appreciate the change in benefits in the medium to longer term. This was previously reported by [9] and [40] who concluded that CA systems are more productive than conventional ridge and furrow systems but need a few years to show their (tangible) benefits. This contrasts with [49] who found no yield increases in a worldwide meta-analysis of no-tillage systems. The perceived reasons for a delay in yield benefits have been highlighted previously in various publications [1,10]. Farmers in target communities need to learn how to plant under CA, which is different from the usual ridge and furrow system. Retention of residues on the soil surface with minimum tillage may also lead to nitrogen lock-up in the initial cropping cycles, which may lower maize yields in the initial years. CA systems also tend to have more weeds in the early years [24]. This has often led to challenges to control weeds, which may affect maize yields if weeding is delayed [27]. The switch to minimum tillage, residue retention and crop diversification has effects on the soil life with time of adaptation. Some parameters of soil quality change fast (e.g., improved pore systems and infiltration) while others take longer (e.g., soil carbon). In the case of Zidyana, the soils are considered relatively fertile which means that it will take many years to see a significant differences in soil properties after switching to CA from conventional ridge tillage.

At Zimuto, CA treatments seeded with an animal drawn direct seeder consistently outyielded the conventional ploughed system from the second cropping season onwards (Figure 2). It is often the marginal environments with frequent in-season dry-spells and poorer soils where CA shows a clear advantage over the conventional control [42]. In the study reported here, the conventional control remained lowest throughout the experimental period. However, overall yield levels in Zimuto remained small and rarely exceeded 2.5 t·ha^{-1}. Given a maize grain to stover ratio of approximately 1:1, the biomass of crop residues is insufficient to maintain a minimal groundcover of 30%, which would equal to 2.5–3 t·ha^{-1} of maize stover that ideally should be retained annually. Nevertheless, in our dataset, soil quality indicators such as carbon and infiltration improved over time as has been previously reported by [42]. This highlights that even under marginal environments, CA will provide some benefits with good management. However, yield increases of more than 300%, as sometimes reported from southern Zimbabwe, are rather unlikely and are almost certainly a result of comparing well managed and fertilized CA systems with unfertilized farmer practices. In Zimuto, higher water infiltration and soil carbon were clearly measured. Although the beneficial effects of CA on water infiltration has been documented by others [6,9,50], there are conflicting results on soil carbon [9,51–53]. Clearly, more research is needed to establish a true causal relationship between CA and the increase in soil carbon under sub-humid and semi-arid environments.

4.2. Socio-economic Evaluation and Farmer Perceptions

Research from Zidyana and Zimuto showed clear economic benefits of CA systems for smallholders in southern Africa. While significant labour reductions have been reported on land preparation and weeding when comparing direct seeding using dibble sticks with conventional ridge tillage in Malawi [9], this was not the case in Zimbabwe, where farmers use the mouldboard plough for land preparation without herbicides. In Zidyana, CA systems saved 34–42 labour days·ha^{-1} which offers a significant benefit for farmers if they use the time for other productive activities such as expanding or diversifying their farming, working off-farm or undertaking various income generating activities. However, farmers often do not value their own family labour, which has implications on their perceptions about the labour-intensive task of constructing ridges and the purchase of “expensive labour-saving inputs” such as herbicides. Based on these results, the net benefits in Zidyana support the claims that CA is more viable and economical than the conventional farmers’ practice.

Despite the perceived challenges by farmers, the socio-economic assessment in the target area showed that it was conducive to adopt CA. Central Malawi where Zidyana is located, is characterized by low crop-livestock interaction and strong private and governmental extension support. Farmers use and have in principle access to critical inputs such as fertilizers and herbicides. Adoption has therefore increased in the target area from 12 farmers in 2005 to more than 15,000 farmers in 2013, as has been reported by [54] and [55], and this trend is steadily increasing. The reduced risk of crop failure in Zidyana has also encouraged farmers to move away from maize monocropping and successful maize-groundnut rotations under CA have started to thrive. This will not only increase the level of food security but also the financial income and nutrition for farm families in the longer term. A range of challenges still persist and farmers highlighted these in focus group discussions during field and study tours, as well as during evaluation meetings. Some of them were very specific to CA such as challenges with weed control, retention of residues and/or pest and diseases. Some challenges were more institutional in scope such as the quality and scale of extension services, trained personnel, and access to input and output markets.

In Zimuto, positive net benefits were achieved with CA systems in two out of the four cropping seasons. In seasons of low productivity, due to erratic and unevenly distributed rainfall, no positive gross margins were observed with any of the three cropping systems, although in any case, the gross margins were more favourable for CA systems. The number of farmers adopting CA also remained static due to an unfavourable socio-economic environment with less than 70 farmers in the target community and approximately 1000 farmers in the surrounding wards. Most of these farmers were supported by projects implemented by CARE and OXFAM. Farmers in Zimuto mainly live off remittances, lack the capacity and opportunity to purchase critical inputs and are guided by weak extension services. Additionally the economic melt-down in Zimbabwe and periodic droughts since the 2000s have made farmers more dependent on food aid.

Despite the huge potential of CA to improve the adaptation to climate variability and change, the perceived risk of crop failure in this area is a serious concern for farmers when considering a change to a different way of farming. A remarkable point is that the gross margin analysis revealed no positive benefit from the conventional practice, indicating that it may be more beneficial to farmers to stop growing crops in favour of extensive cattle production and/or game ranching [30].

5. Conclusions

A long-term study was carried out in two contrasting areas of Malawi and Zimbabwe in high potential and low potential areas. The study showed that CA is a viable and adaptable system in contrasting environments due to its biophysical and economic benefits. Maize grain yields were generally higher under CA systems and increased with years of practice. In the high potential area of Zidyana, a clear trend in yield benefits from CA was not evident until the fifth cropping season. In the low potential area of Zimuto, yield benefits were evident after the second season onwards with an increasing trend over time. Greater infiltration was recorded at both sites but increased soil carbon levels on CA systems were recorded only at Zimuto.

Economic benefits were mostly evident in Zidyana where labour reductions of 34–42 labour days·ha^{-1} were recorded on CA systems compared with the conventional control. Greater yields and reduced labour costs led to increased net benefits on CA systems in the Zidyana area of Central Malawi. In Zimuto, CA systems led to greater net benefits despite limited labour savings. However, maize production on CA systems in Zimuto was only profitable in two out of four cropping seasons due to negative gross margins in seasons of low rainfall.

The adoption of CA is guided by socio-economic conditions and farmers' perceptions towards this improved cropping system. Governmental support should focus on providing access to critical inputs, suitable farm equipment and viable extension services as they proved to trigger large scale experimentation and adoption. Investments in knowledge and capacity were also considered to be important preconditions for farmers to adopt CA. In areas where CA is at the margin, any crop production be it conventional or CA may not be a sound option as too many times farmers will lose out economically. Zimuto is a clear example where CA could potentially work but the socio-economic circumstances are serious bottlenecks for large-scale CA adoption [30]. Alternative livelihood strategies such as extensive cattle production or game ranching may be more profitable for smallholder farmers and the land dedicated to annual crops should be drastically reduced in these areas to create more grazing areas for livestock.

Different manual and animal traction CA systems have been tried and tested in two contrasting agro-ecologies of Malawi and Zimbabwe. For both areas, CA showed benefits both on the biophysical and socio-economic side. However, farmers should be aware when trying CA that some basic prerequisites are required to successfully implement this promising cropping system in southern Africa. There is need for adequate rainfalls, which we believe is >500 $mm \cdot a^{-1}$ in this region. The soils have to be reasonably fertile and not completely degraded to produce enough biomass. Farmers need to have access to the necessary support services such as markets for seed, fertilizer, herbicides and equipment as well as reliable extension. We believe that under such circumstances CA can effectively reduce food insecurity and poverty in the medium to long term.

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Author Contributions

Christian Thierfelder had the original idea of the study and with all co-authors carried out the study. He also wrote the first draft of the paper. William Trent Bunderson led the field work in Malawi while Christian Thierfelder and Walter Mupangwa were responsible for the study in Zimuto. All authors read and agreed to the final draft.

Conflicts of Interest

The authors declare no conflict of interest.

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