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Where is the limit? lessons learned from long-term conservation agriculture research in Zimuto Communal Area, Zimbabwe

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Abstract Smallholder farming in Zimbabwe is increasingly affected by dwindling maize (*Zea mays* L.) yields due to declining soil fertility and the negative effects of climate variability and change. A long-term on-farm study was established between 2004 and 2013 at the Zimuto Communal Area near Masvingo, Southern Zimbabwe to test the feasibility and viability of conservation agriculture (CA) systems under the circumstances of low fertility and erratic rainfall. CA seeding systems based on animal traction excelled and significantly increased maize productivity by up to 235% (1761 kg ha^{-1}) and legume productivity by 173% (265 kg ha^{-1}) as compared to the conventional control treatment. Soil quality indicators such as infiltration and soil carbon improved 64-96% and 29-97 %, respectively, over time. However, a direct link between increased infiltration and grain yield could not be established. Increased plant population, because of greater precision and moisture conservation during direct seeding as well as an improved response to fertilizer application due to gradually increasing soil carbon could be the reasons why yields on CA systems outyielded the conventional control. CA systems were more economically viable than planting crops under the normal conventional practice with mouldboard ploughs and removal of crop residues. Farmers generally rated important crop characteristics of maize planted under CA as high but weed control was rated as low, due to the lack of an appropriate herbicide under the prevailing environment. The results of this study show that CA is a potential option even in areas of climate risk and low soil fertility. However, the adoption of CA was low amongst members of the rural farming community due to the perceived risk of crop failure, lack of appropriate and accessible inputs and markets for farm produce, and lack of appropriate information and knowledge about alternative agricultural methods. This highlights the need for better resource and input availability as well as more vibrant and efficient extension services. Successful CA promotion requires that the systems are adapted to farmers' circumstances. However, CA cannot expand where farmers depend on remittances, are donor dependent, and where crop production in general is doubtful. Land uses such as extensive livestock production or game ranching may be better and more profitable alternatives for farmers in these situations.

Keywords Sustainable land management · Soil fertility · No-tillage · Residue retention · Climate variability · Profitability · Farmer perception

Introduction

Continuous soil degradation and potential future threats of climate variability and change have affected sub-Saharan Africa in recent years. Yields in many areas are declining, the highest average yield in the last decade (1128 kg ha^{-1}) being less than the lowest yields (1202 kg ha^{-1}) in the 1970s (Fig. 1), and farmers are confronted with increased frequencies of drought, crop failure and food insecurity (Cairns et al. 2012; Sanginga and Woomer 2009; Lobell et al. 2008).

These conditions are particularly prevalent in southern Zimbabwe. Farming in this area is characterized by mixed crop-livestock systems. Farmers preferentially grow maize (*Zea mays* L.) (Nyamangara et al. 2013) instead of the more

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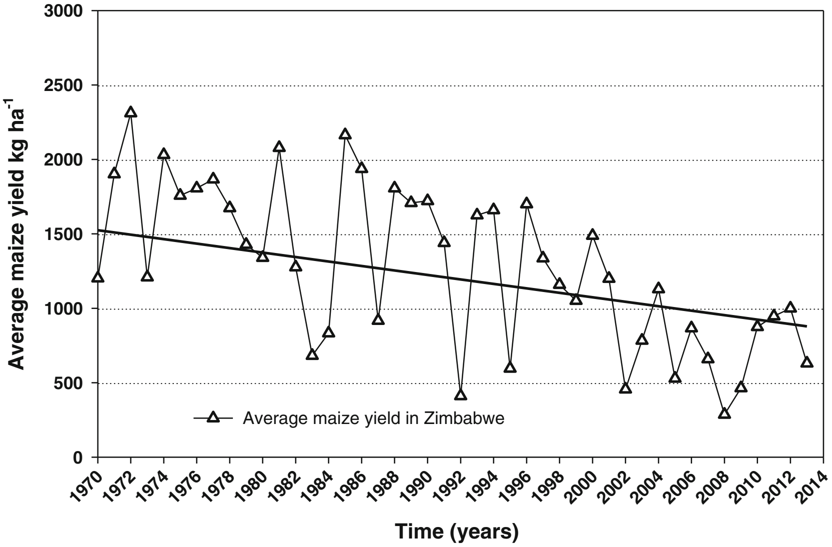


Fig. 1 Average maize grain yield in Zimbabwe 1970–2013 (FAOSTAT 2013)

climate resilient sorghum (*Sorghum bicolor* L.) or millet (*Pennisetum glaucum* L.) (Blum and Sullivan 1986; Muchow 1989) due to better yields when rains are conducive and the preferred taste of maize porridge as a staple food.

The soils in this area are largely characterized by granitic parent material, have a mostly sandy texture with soil organic matter (SOM) levels of around 0.5 % and poor inherent soil fertility (Nyamapfene 1991). Drought is a common event, affecting rain-fed maize production over large areas. While there is some uncertainty around precipitation projections, the frequency of drought events is expected to increase (Cairns et al. 2013). Climate projections for 2050 for this drought-prone region suggest temperatures will increase by 2.6 °C, while the length of the rainy season will be reduced (Lobell et al. 2008; Cairns et al. 2012). Southern Africa has been identified as one of the two regions most vulnerable to the potential impacts of climate change (Lobell et al. 2008). Without sufficient adaptation measures, food insecurity will continue to increase. This questions the suitability of the drier areas of Zimbabwe and southern Zambia for crop production and suggests that alternative land management strategies, such as converting available land resources into rangeland. These are being discussed.

Increased numbers of crop failures in southern Zimbabwe in recent years has led to a major push for the promotion of conservation agriculture (CA) systems in this area, originally supported by the Department of International Development (DFID)-funded Protracted Relieve Program (PRP), which lasted from 2004 to 2010 (Mashingaidze et al. 2006). Since then, many development agencies (e.g. Care International, World Vision, Catholic Relief Service, Concern Worldwide, Foundation for Farming, German Agro Action amongst others) have started promoting CA in their development portfolios. CA has previously been defined as a crop management system based on three general principles: a) minimum soil disturbance, b) crop residue retention and c) increased diversification through rotation and/or intercropping of different crop species (Kassam et al. 2009; FAO 2002). Traditionally, the land in these areas is ploughed by animal traction mouldboard ploughs or cultivated by hand hoes before planting any crop (Thierfelder and Wall 2012). Crop residues are grazed, burned or removed and maize is the dominant food security crop. Besides maize, farmers grow sorghum, finger millet (*Eleusine coracana* L.), groundnuts (*Arachis hypogaea* L.) and cowpeas (*Vigna unguiculata* (Walp)). Common crops around homesteads are sweet potatoes (*Ipomoea batatas* L.) and sunflower (*Helianthus annus* L.).

Moving away from the traditional crop management systems to CA involves changes to the overall cropping systems at the field and farm level, which might lead to biophysical and socio-economic challenges. These need to be addressed at different scales and at different intensities. However, CA is not a completely new way of agriculture as it only tries to replace the unsustainable parts of the current systems: excessive tillage is replaced with minimum soil disturbance, residue removal or burning with surface retention and monocropping with diversified crop rotations (Wall et al. 2013).

CA improves a number of soil quality parameters, which could help to overcome the negative effects of fertility decline as well as drought and heat stress. Results from the region show that CA has immediate biophysical and socio-economic benefits: 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 through infiltration from the ponding effect of the residues (Thierfelder and Wall 2010a, b; Munyati 1997). Reduced evaporation of soil moisture occurs as the crop residues protect the surface from solar radiation (Lal 1974), leading to an improved crop water balance (Thierfelder and Wall 2009; Shaxson 2003) and less frequent and intense moisture stress because of increased infiltration and reduced evaporation (Mupangwa et al. 2008; Thierfelder and Wall 2010a). Soil carbon can be stabilized and in some cases increased (Thierfelder et al. 2013b; Thierfelder and Wall 2012), with aggregate stability being greater on CA than conventionally treated control plots. Improved biological activity, manifesting itself in greater numbers of earthworms was found in CA fields in Zambia (Thierfelder and Wall 2010b). Reduced traction and labour requirements for land preparation and for weeding have been reported if herbicides are used (Muoni et al. 2013; Mashingaidze et al. 2012; Vogel 1994, 1995), hence saving costs of manual labour, animal draft and fuel, depending on the farming system (Ngwira et al. 2012a, b; Johansen et al. 2012; Mazvimavi et al. 2008). Increased longer term productivity and economic viability in the smallholder farming context have been shown for southern Africa (Ngwira et al. 2012b; Thierfelder et al. 2013a).

Nevertheless, constraints to the adoption of CA systems in southern Africa have also been highlighted (Andersson and D'Souza 2013; Arslan et al. 2013; Giller et al. 2009). These challenges include keeping enough crop residues for mulching in mixed crop-livestock systems (Valbuena et al. 2012; Erenstein et al. 2012), weed control if no herbicides are used (Muoni et al. 2013), access to markets for critical inputs and machinery (Sims et al. 2012; Thierfelder et al. 2014), knowledge and capacity about this relatively new cropping system (Wall 2007) and the mindset of farmers that agriculture production is only possible if the land is tilled (Wall 2007; Wall et al. 2013).

CA research, especially if focussed on biophysical aspects alone, has often left out farmers' perceptions of new technologies, which are important for better understanding of the technology and its adoption, and also for the design process of appropriate technology and diffusion strategies. If farmers perceive technologies as useful innovations they will start experimenting with them, whereas farmers' negative perceptions of innovations have been used to explain low and slow adoption of some technologies derived from on-station research (Becker et al. 1995). Farmers' perceptions of the usefulness of CA technologies depend on many factors, some reflecting on the utility and efficiency of the technology. According to Wossink et al. (1997) a decision-maker's attitude towards an innovation depends on his valuation of a set of characteristics of that innovation. Adoption or rejection of CA technologies by farmers often reflect rational decisions on the basis of the technology's characteristics. Farmers may reject CA components that are not relevant to their needs, not suited to their agro-ecological environment or which may conflict with other activities that are considered to be important within their farming systems (Chamala et al. 1987). Empirical evidence has shown that sources of information available to a potential adopter, such as those from extension agents, have an important role in the development of perceptions of innovations (Kulshreshtha and Brown 1993; Guerin 1999).

Little evidence is available about where CA would work, where it should not be pursued, and where CA would be of marginal benefit. The aim of this paper is to summarize the results from long-term research in Zimuto Communal Area, Zimbabwe and highlight the key lessons learned throughout nine cropping seasons. The paper highlights a) the performance and viability of the CA system in Zimuto Communal Area, b) farmers' perceptions of CA and c) local constraints, with the aim of answering the basic questions: can CA work in a marginal area, such as Zimuto Communal Area, and what are the conditions required for CA to be successful in such an environment.

Material and methods

Locations

Validation trials comparing two CA options with a conventionally ploughed control treatment were carried out in southern Zimbabwe in the area around Chikato village in the Zimuto Communal Area of Masvingo Province (19.85 S; 30.88 E; altitude 1223 m.a.s.l). The mean annual rainfall is approximately 620 mm. Dominant soils at Zimuto are *Arenosols* developed from granitic sands of low inherent fertility. Sand and organic matter content are around 94–95% and 0.2–0.4%, respectively (Table 1). The site lies in Natural Region IV (Vincent and Thomas 1961), which is

Table 1 Soil properties (depth 0–20 cm) of Chikato, Zimuto Communal Area, Masvingo Province, Zimbabwe

Parameter	Unit (method)	Chikato
Depth	cm	0–20
Clay	%	3 (±0.6)
Silt	%	3 (±1.2)
Sand	%	94 (±1.6)
Texture		coarse sand
Bulk density	g cm^{-3}	1.40 (±0.05)
Rooting depth	cm	77.4 (±28.5)
Corg	g kg^{-1}	0.26 (±0.2)
pH	($CaCl_2$)	4.6 (±0.5)
Available P	mg kg^{-1} (Bray II)	15.3 (±12.8)
K	cmol kg^{-1}	0.10 (±0.1)
Ca	cmol kg^{-1}	0.30 (±0.2)
Mg	cmol kg^{-1}	0.14 (±0.1)
Na	cmol kg^{-1}	0.08 (±0.1)
CEC	cmol kg^{-1}	2.51 (±1.2)

Note: values show means across sites and the standard deviation characterized by 450–650 mm of rainfall per annum (Table 2). Rainfall was recorded throughout the trial period from 2004 to 2013 with rain gauges in farmers' fields (Fig. 2).

The research area is characterized by four distinct land-use types, locally labelled as vleis, vlei margins, topland soils and homestead fields (Vaughan and Shamudzarira 2000). Land-use types differ in their hydrology: vleis are wet and swampy areas; vlei margins are periodically waterlogged in years of heavy rainfall; and topland soils and homestead fields are normally cropland areas that have greater distances from the underlying water table. In Zimuto communal area, topland fields are used for growing crops during the summer season (November–April) while vleis are also used for crop production during both the dry (June–October) and summer seasons. Crops grown on topland fields include maize and small grains such as finger millet and sorghum, and these are often intercropped with grain legumes and minor crops such as pumpkins (*Cucurbita maxima* L.) and sweet potatoes (*Ipomoea batatas* L.). In the vleis farmers grow maize and rice (*Oryza sativa* L.) during the summer while horticultural crops dominate cropping in the dry season. Livestock manure and mineral fertilizer are the main sources of nutrients applied to different crops grown on top lands and vleis. Land preparation on toplands and vleis is often done by conventional mouldboard ploughing at the onset of the summer and whenever a new crop is being planted in the vleis. The trials under this study were planted mostly on topland fields and on a few vlei margins.

Analysis of climate risk

An analysis of climate risk was done for Zimbabwe and the probability of a failed season (PFS) was determined using predetermined clusters of probabilities. PFS measures the probability of growing season failure due to insufficient availability of soil water (Kassie et al. 2012), which is based on a too-short growing season or a too-severe level of water stress within the growing period (Thornton et al. 2006). The PFS shows the exposure to drought that results in crop failures (Kassie et al. 2012).

Trial description

Seven replications of a trial with three treatments were initiated in Chikato, Zimuto Communal Area in 2004, each farmer being a replicate in the trial. The initial trial replicates were established on abandoned fields as farmers selected those sites in a participatory process to be given to the project. These initial fields were characterized by poor soil fertility and infestations with problematic weeds (e.g. *Cynodon dactylon* L. and *Richardia scabra* L.).

The experimental design of these trials has been previously described in Thierfelder and Wall (2012). Numbers of farmer replicates increased and decreased over time because some fields had to be replaced due to farmers' deaths. Each selected farmer owned a span of draught animals, which was used for land preparation and seeding throughout the trial period. The trial ended in 2013 after nine consecutive cropping seasons (2004/05-2012/13). Plot size at each farmer location was 3000 m^2 divided into 3 equal portions of 1000 m^2 each. The treatments at Chikato were as follows:

a) A conventional control plot (CP) in which soil tillage was carried out with animal traction using a mouldboard plough at shallow depth (10–15 cm). Residues were mainly grazed or removed and the remaining stubble incorporated with the plough.
b) The first CA treatment was planted in rip-lines spaced at 90 cm created by an animal drawn subsoiler at 25 cm soil depth (Palabana subsoiler) and manual seed and fertilizer

Table 2 General characteristics of the five agro-ecological regions of Zimbabwe

Natural region	Annual rainfall (mm)	Soil types	Farming systems
I	>1000, rain in all months of year, relatively low temperatures	*Acrisols, Ferralsols*	Suitable for maize and fruit production, horticulture and floriculture, coffee and tea, dairy farming, forestry, beef cattle
II	750–1000, rainfall occurs in summer (November–April), relatively low temperatures	*Arenosols, Cambisols, Luvisols*	Suitable for maize, cotton, tobacco, wheat, grain legumes, sorghum, livestock production (pig, poultry, dairy)
III	500–800, experiences mid-season dry spells, high temperatures	*Arenosols, Leptosols, Lixisols*	Crops are maize and cotton, grain legumes, sunflower, sorghum, pearl millet
IV	450–650, severe dry spells, frequent droughts	*Arenosols, Luvisols*	Crops are maize, sorghum, pearl millet, finger millet, grain legumes (groundnuts, cowpea, bambaranuts), livestock production
V	<450, erratic rainfall, frequent droughts	*Leptosols, Luvisols, Vertisols*	Crops grown include sorghum, pearl millet, maize, cotton, cattle and goat production

Sources: Adapted from Vincent and Thomas (1961)

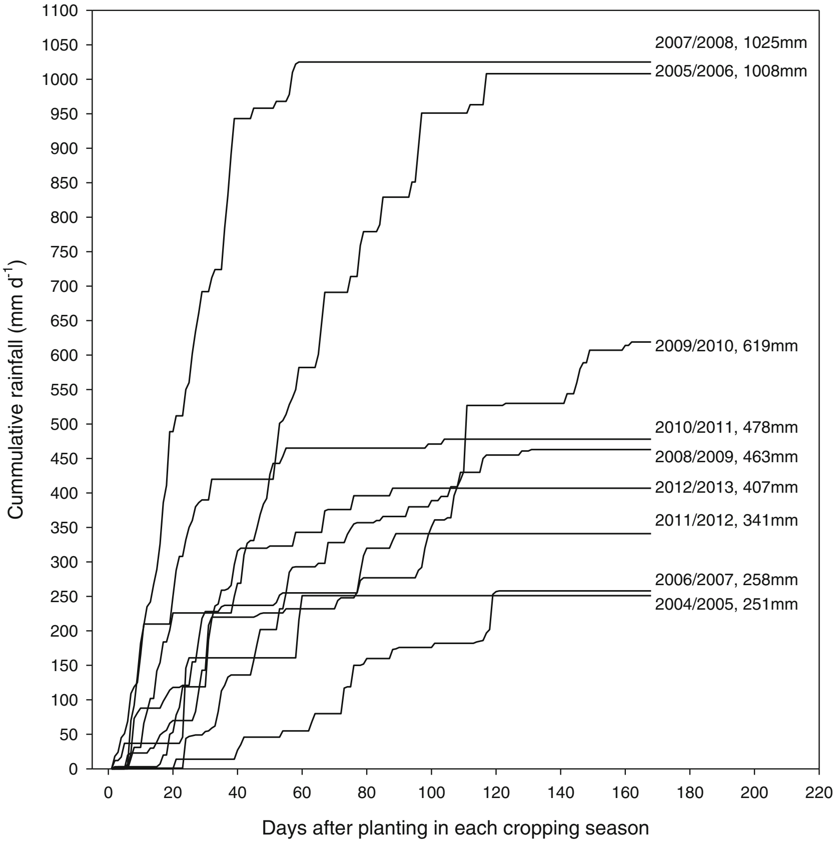


Fig. 2 Cumulative rainfall after planting at Zimuto Communal Area, NR IVb, Southern Zimbabwe, 2004–2013

placement at 5 cm soil depth in the furrow. In subsequent seasons, a Magoye chisel-tine opener was used (GART 2002) for rip-line creation at 10–12 cm soil depth and hand-seeding at 5 cm soil depth. Residues were retained on the soil surface, initially using thatching grass at a rate of 2.5–3 t ha^{-1} in both CA options due to lack of sufficient amounts of maize stover in the first cropping season. After the first season all residues were retained either on the field or stored after harvest next to the demonstration plots and spread on the fields to achieve sufficient ground cover at the onset of the cropping season. Locally growing grass species (H*yparrhenia* spp.) were used to supplement the crop residues to achieve at least 30% ground cover each season.

c) The second CA treatment was planted with an animal traction direct seeder (DS) (Irmãos Fitarelli, Brazil, model #12), which enables simultaneous seeding and fertilization into the mulch (Johansen et al. 2012). As in the first CA treatment, residues were retained at 2.5–3 t ha^{-1} (30% ground cover).

All treatments were fertilized at planting and top-dressed at 4 weeks after crop emergence. The total amount of nutrients applied was 11 kg ha^{-1} N:10 kg ha^{-1} P:10 kg ha^{-1} K as a basal dressing followed by a top-dressing of 35 kg ha^{-1} N (at four weeks after crop emergence) in 2004/2005 and 69 kg ha^{-1} N in all succeeding years as ammonium nitrate (34.5% N). This was necessary, as the initial fertilizer dose was by far too little to achieve any meaningful production. The maize varieties sown were ZM521 in 2004/05, ZM423 in 2008/09 and 2009/10 (OPVs), SC513 in 2005/06 and SC403 (hybrids) in 2006/07, 2010/11, 2012/13 at 37,000 plants ha^{-1} (90 cm rows, 60 cm in-row spacing and 2 plants per planting station) on all plots in a particular year. Seeding usually started in the last week of November up to mid-December in each year. The choice of maize variety was a result of a participatory process in the target community and the variety selection on plots was decided by the farmers' majority vote. Cowpeas (CBC 2 variety) were intercropped at 37,000 plants ha^{-1} (90 cm between rows and 30 cm in-row spacing, one plant per station) into the maize from the fourth season onwards and fully rotated at some sites in 2010/11 and 2011/12.

Herbicides were not used for weed control due to the very sandy soil texture at Zimuto Communal Area and all weeding was done with hand hoes at shallow depth ("scratching"). The number of weeding activities varied between 3 and 4 times per-season depending on the seasonal rainfall pattern, with farmers weeding more in wetter seasons compared with relatively dry seasons. Each host farmer decided when to weed and farmers were encouraged to control weeds before they reached 10 cm in height or in circumference.

Biophysical measurements

Maize and legume harvest

Maize was harvested at physiological maturity, taking 10 samples of 2 rows x 5 m length each from each treatment (harvest area 10×9 m^2 per treatment). Sub-samples of maize cobs and above-ground biomass (stalks and leaves) were dried and maize cobs shelled, after which the grain yield and grain moisture were determined. Maize grain was corrected for moisture and calculated at 12.5% moisture content on a per hectare basis. Biomass subsamples were measured fresh and dry and the total amount of dry biomass calculated on a per hectare basis. Cowpea grain and biomass yields followed the same principles. Ten samples (of 9 m^2) were taken from each treatment and pods and above-ground biomass weighed. Pods were dried and shelled and final grain and biomass yields were recorded.

Soil carbon and infiltration measurements

For soil carbon, a composite soil sample from each research plot was taken at Zimuto in October 2004, October 2008 and October 2011. The sample depth was 0-20 cm. Total carbon was measured through a CE Elantech Flash EA1112 dry combustion analyser. Soil carbon (in t ha^{-1}) was calculated from the carbon concentration, thicknesses and bulk densities of the horizons (Ellert and Bettany 1995):

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

where:

M element	element mass per unit area (t ha^{-1})
conc	element concentration (kg $t^{-1)}$
p_b	field bulk density (t m^{-3})
T	thickness of soil layer (m)

Infiltration was measured through a proxy method called “time-to-pond” (Thierfelder and Wall 2012; Verhulst et al. 2011) that has been previously tested and calibrated for monitoring soil quality. A ring 50 cm in diameter made from metal wire is placed on the soil surface and water from a watering can, with a rose nozzle, applied to the centre. The time taken from the start of application to when the water spreads beyond the ring and the volume applied are recorded. Six measurements were taken for each plot of each treatment in each replication at Zimuto in four consecutive seasons. The measurements were done in March/April of each cropping season, just before harvest of the maize crops.

Socio-economic assessment

a) Farmers’ perception

The data set used in this study was obtained from a case study analysis carried out in Chikato village in 2012. Structured interviews were conducted with 18 farmers who were aware of and/or practising some form of CA (8 dis-adopters, 4 non-adopters and 6 partial adopters of at least two principles). Data were also gathered from 45 plots owned by these households. The small sample size enabled the researchers to carry out in-depth analysis about the constraints to CA adoption as the community was characterized by high dis-adoption rates. Questions focusing on farmers’ perception of the different CA technologies were developed. They consisted of a number of subthemes that investigated farmers’ perception of the technology efficacy: these consisted of constraints to adoption and incentives that motivate farmers to adopt different components of CA technology. Risk bearing incentives were included, based on empirical evidence that risk aversion is one of the main contributing factors to agricultural technology non–adoption and/or dis-adoption (Wall 2007; Derpsch et al. 2010). The questionnaire used a ten-point Likert scale to rank the technology efficacy and constraints conditioning adoption (from 10 representing the most important and 1 least important).

Farmers (non-adopters, dis-adopters and partial adopters) also evaluated the maize crop grown under different tillage systems to assess its performance at different physiological stages of growth. Focus group discussions with key informants in the community complemented the structured surveys.

The intensity of CA technology adoption was assessed so that the different adoption groups could be distinguished. Survey enumerators evaluated CA principles and agronomic practices applied on every maize plot operated by each farmer and determined the land area of each plot that was managed based on CA recommendations. CA adoption intensity was calculated for each surveyed household by adding up all maize areas under CA technology components and weighting it by the total maize area cultivated by the household. Data was collected on key variables such as household demographics, assets, income and expenditure, land use, input use, crop harvests, the CA components adopted, livestock ownership, distances to local markets, access to extension services and labour use. Finally, three groups were defined: a) partial adopters, who have been trying at least two or more principles of CA; b) dis-adopters who tried CA but abandoned it and c) non-adopters, who never tried CA.

b) Economic analysis

The data used for the economic analysis was from four planting seasons, 2009/10-2012/13. The gross margin analysis was done by recording the total variable costs (TVC), which were all labour and input costs in USD ha^{-1}, and subtracting this value from the gross receipts. Gross margin analysis was used to assess the potential net benefits of planting maize under conservation agriculture, using different seeding systems. In this analysis, labour and financial capital were considered to be the most limiting factors of production. Returns to labour for the different technologies were therefore calculated as gross receipts less the other material costs rather than just dividing labour by the labour cost:

$$Returns\ to\ labour\ (USD) = Gross\ receipts - (TVC - labour) \Big/ labour \qquad (2)$$

Similarly, the return to every dollar invested was calculated by dividing the gross margin by the total variable cost

$$Returns\ to\ TVC\ (\%) = Gross\ margin \Big/ TVC\ x\ 100 \qquad (3)$$

Statistical methods

Results from all biophysical measurements were subjected to a test of normality and homogeneity of variance and subjected to an analysis of variance (ANOVAs), using a 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.

Results

Rainfall and climate risk

Zimuto Communal Area, located in Natural Region IV of Zimbabwe with a defined rainfall pattern of 450–600 mm is characterized by a highly variable climate (Fig. 2). Rainfall varied greatly in the different cropping seasons ranging from extreme drought years (2004/05) to seasons with excessive rainfall (2005/06 and 2007/08). The amounts available for crop production after planting ranged between 251 mm per annum in 2004/05 and 1025 mm per annum in 2007/08. Climate risk analysis showed that the risk of crop failure ranged between 31 and 40% (Fig. 3), indicating that farmers in Zimuto Communal Area face a high probability of crop failure mainly due to a too–short growing season or a too–severe level of water stress within the growing period.

Long-term effects on productivity

The three cropping systems, receiving the same fertilizer level and planted with the maize varieties previously stated (see *Trial Description*) at Zimuto Communal Area, were compared from cropping season 2004/05 to 2012/13 (Table 3). In the analysis three different growth strategies were separated: maize treatments with continuous maize cropping, with maize-cowpea intercropping and maize planted in full rotation with cowpea. Grain yields ranged from very low yields (121 kg ha^{-1}) in the drought year 2004/05 to the largest yields (3389 kg ha^{-1}) in season 2008/2009 (Table 3).

Direct seeded treatments significantly outyielded the conventional control from the second season onwards and thereafter in most of the cropping seasons and most growth strategies except 2007/2008, 2009/2010 (apart from continuous sole maize cropping) and 2010/2011 in the maize cowpea intercropping treatment (Table 3). Ripline seeded treatments were, in most cases, lower than the direct seeded treatment (except 2007/08, 2009/10 and 2010/11 in the maize-cowpea intercropping strategy) and not significantly different from the conventional treatment in 2004/05, 2005/06 and 2006/07 in the continuous sole cropping strategy and in 2008/09 and 2011/12 in the maize-cowpea intercropping strategy (Table 3). In summary, in most of the cropping seasons, CA treatments outyielded the conventional control leading to yield benefits of up to 235% (1761 kg ha^{-1}) between a direct seeded and a conventionally seeded maize treatment in rotation with cowpea (e.g. in 2011/12).

A graphical comparative analysis of the different treatments from 2004 to 2013 confirmed that in the majority of cases CA treatments had greater yields than the conventional treatment (Fig. 4). Hence, most of the rip-line and direct seeded treatments were at or above the 1:1 line. In some cases, the yield benefit exceeded the 1: 2 line, indicating that CA treatments had more than double the yield than had been achieved on conventional control plots.

The low productivity environment in Zimuto led to very low above-ground maize biomass yields, ranging between 95 kg ha^{-1} and 2708 kg ha^{-1} in different years and under different management practices (Table 3). As with grain yield, the biomass weights in CA treatments outyielded the conventional control treatment in most years, with few exceptions.

A clear relationship between maize grain yield to increasing levels of annual rainfall could not be established (Fig. 5), however, results showed that the grain yield response on CA treatments was greater in

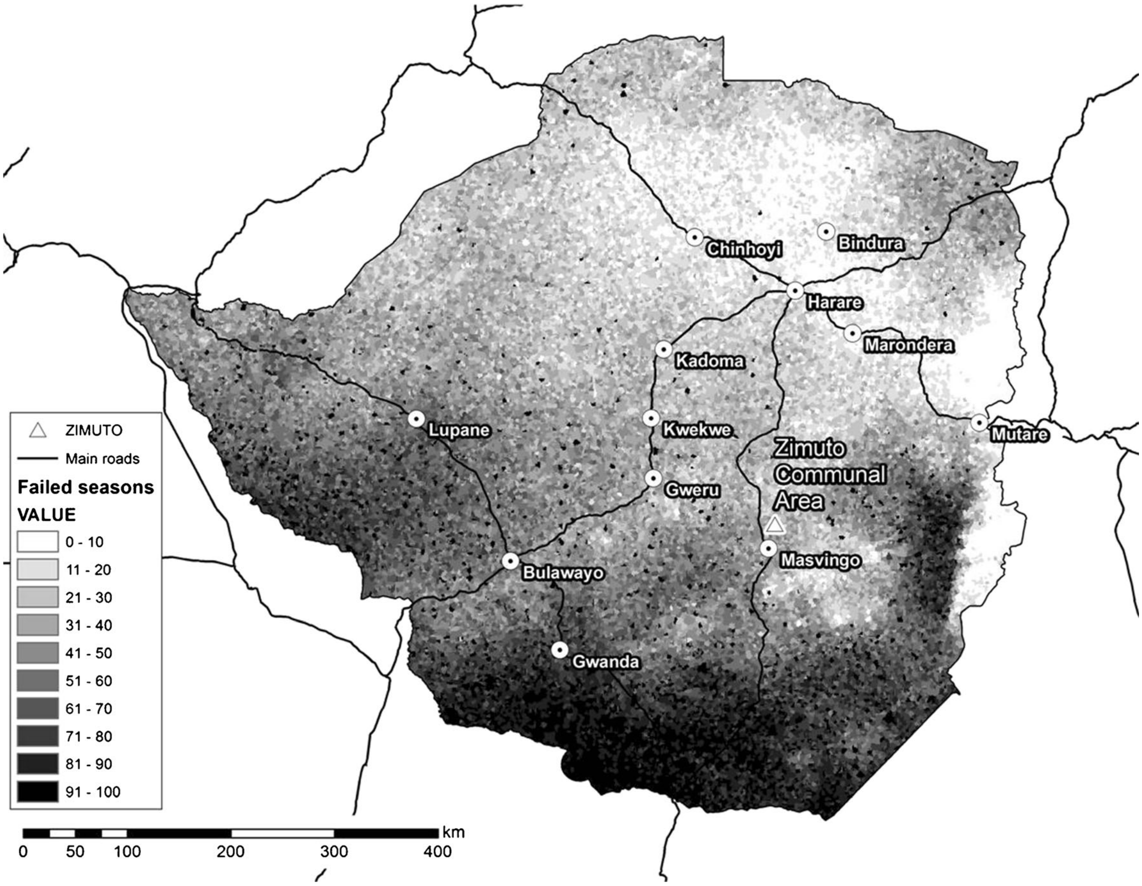


Fig. 3 Probability of a failed season in Zimbabwe (adapted from Thornton et al. (2006))

almost all cases as compared to the conventional control treatment, except for the first drought year.

Plant populations ranged from 15,027-39,657 plants ha^{-1} in the conventional control; 20,677-53,288 plants ha^{-1} in rip-line seeding and 17,437-50,180 plants ha^{-1} in direct seeding, with mean values of 26,758 plants ha^{-1}, 37,455 plants ha^{-1} and 35,128 plants ha^{-1} in the three treatments, respectively. An increased plant population significantly increased maize grain yield (Fig. 6) although the r^2 only showed a low correlation (r^2=0.24) in the heterogeneous dataset.

Cowpea yields from intercropped and rotation treatments were low and did not respond as clearly to tillage treatment as maize (Table 4). Nevertheless, significantly greater yields (up to 173% or 265 kg ha^{-1}) were recorded in 2008/09 and 2009/10 between both CA treatments and the conventional control treatment in full maize-cowpea rotation and in the intercropping treatment in 2009/10. In 2012/13, only the direct seeded treatment was different from the control treatment (Table 4).

Soil indicators

No-tillage and surface residue retention in both CA treatments had significantly greater infiltration, measured by the "time-to-pond" method, as compared to the conventionally ploughed system in all investigated seasons (Fig. 7). Both CA treatments had equally high infiltration rates and no significant difference was recorded. In year 2008, the time to pond was comparably higher than in other seasons (11.5 and 10.9 s on rip-line seeding and direct seeding respectively as compared to 6.6 s on conventional tillage). In all other seasons, time to pond ranged between 5.1 and 6.2 s in both CA treatments while it was between 3.0 and 3.2 s in the conventional control treatment (Fig. 7).

Soil carbon showed no significant differences among all treatments at research inception (2004) (Table 5). Soil carbon values significantly increased in CA treatments until October 2008 and remained at a low level in the conventional treatment after four cropping seasons. In 2008, the direct seeding treatment had 93% more soil carbon than plots that were conventionally ploughed. Similar increases in soil carbon values (97%) with the direct seeding method compared with conventional ploughing were recorded in 2011, the last date on which data were available (Table 5).

Economic assessment

The results of the gross margin analysis showed that mechanized CA, using animal traction, direct seeding and rip-line

Table 3 Maize grain yields at Chikato School as influenced by tillage treatment, Zimuto Communal Area, Zimbabwe, 2005–2013

		Continuous sole maize cropping		Maize-cowpea intercropping		Maize-cowpea rotation	
		Maize grain yield kg ha^{-1}	Biomass yield	Maize grain yield kg ha^{-1}	Biomass yield	Maize grain yield kg ha^{-1}	Biomass yield
2004/05	Conventional control	121 a	95 a				
	Rip-line seeding	183 a	151 a				
	Direct seeding	164 a	150 a				
	LSD	105	85				
	N	7	7				
2005/06	Conventional control	1112 b	1192 b				
	Rip-line seeding	1116 b	1196 b				
	Direct seeding	1681 a	1802 a				
	LSD	327	351				
	N	8	8				
2006/07	Conventional control	1566 b	1414 b				
	Rip-line seeding	1962 ab	1974 ab				
	Direct seeding	2482 a	2703 a				
	LSD	826	983				
	N	8	8				
2007/08	Conventional control			1108 b	1074 a		
	Rip-line seeding			1463 a	1178 a		
	Direct seeding			1331 ab	1048 a		
	LSD			244	296		
	N			6	6		
2008/09	Conventional control	1477 b	1016 b	1958 b	1435 b		
	Rip-line seeding	2381 a	1741 ab	3042 ab	2394 ab		
	Direct seeding	2680 a	1930 a	3389 a	2708 a		
	LSD	726	770	1426	1199		
	N	4	4	4	4		
2009/10	Conventional control	420 b	500 a	305 b	360 b		
	Rip-line seeding	741 a	507 a	987 a	666 a		
	Direct seeding	726 a	440 a	602 b	510 ab		
	LSD	222	221	382	259		
	N	4	4	4	4		
2010/11	Conventional control			436 b	354 a	537 b	576 b
	Rip-line seeding			1199 a	729 a	1160 a	1225 a
	Direct seeding			863 ab	648 a	1070 a	1149 a
	LSD			691	380	448	489
	N			3	3	5	5
2011/12	Conventional control			1185 b	1251 b	749 b	892 b
	Rip-line seeding			1765 ab	1891 ab	2188 a	2346 a
	Direct seeding			2358 a	2528 a	2510 a	2691 a
	LSD			1085	1176	605	757
	N			4	4	3	3
2012/13	Conventional control			676 b	688 b		
	Rip-line seeding			1689 a	1794 a		
	Direct seeding			1913 a	2025 a		
	LSD			583	636		
	N			7	7		

Note: means followed by the same letter in each particular year are not significantly different at $P \leq 0.05$; Biomass is the total non-cob, above ground biomass

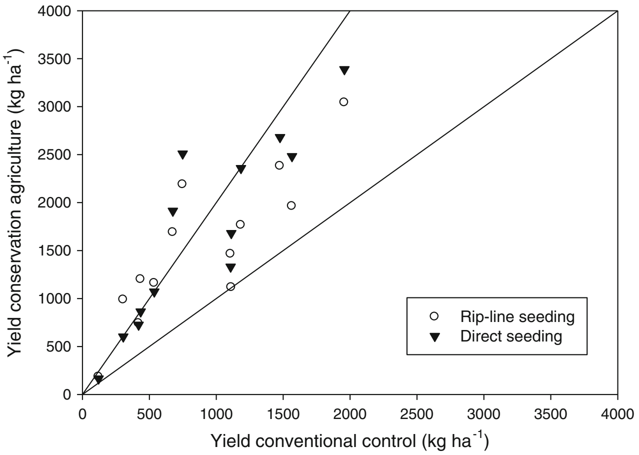


Fig. 4 Graphical comparison of two CA seeding systems (Rip-line seeding and direct seeding) with a conventionally ploughed control plot, Zimuto Communal Area, 2004–2013

seeding had higher gross margins per hectare in 2011/12 and 2012/13, with direct seeding performing better than rip-line seeding. In contrast, the conventional control treatments ran at a loss in 2009/10 and 2010/11 (Table 6). In the first two seasons analysed (2009/10 and 2010/11) and in all treatments no positive net returns that were significant were recorded due to erratic and unevenly distributed rainfall and relatively low yields (see also Table 2). The direct seeder had significantly higher gross margins for the last 2 seasons of $395.03 and $352.60 compared to $192.45 and $243.25 for the ripper, respectively. The CA systems had higher Total Variable Costs (TVC) compared to the conventional system except in 2011/12 where the difference between the conventional system and the direct seeding treatment was not significant.

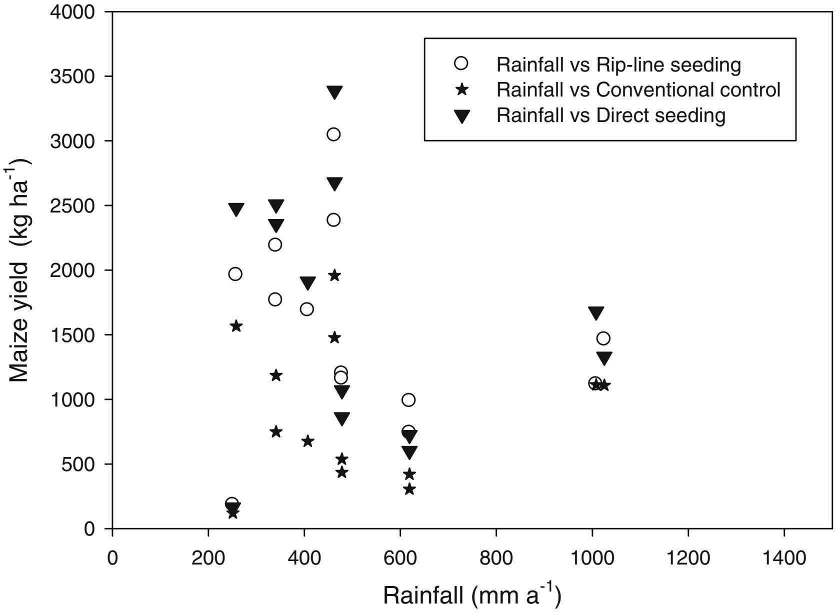
From 2010/11 onwards, the rip-line seeded treatment had the highest labour demand (115.32–145.2 USD ha^{-1}) as compared to other treatments. It is important to highlight that the costs for labour increased from 2011/12 to 2012/13 from a daily casual wage of 3 USD to 4 USD d^{-1}, which reduced the potential gross margins in later years. Greater returns to labour were recorded on both CA treatments, which was already positive in 2010/11 for the ripline-seeded treatment and for both CA treatments in all subsequent years (Table 6). For all dollars invested into this farming enterprise, the highest return to TVC was recorded from the direct seeded treatments in 2011/12 and 2012/13.

Farmer perception

During participatory technology evaluation, direct seeding followed by rip-line seeding were the most preferred systems because they had the best plant establishment, cob filling, cob numbers and final grain and stover yields (Fig. 8). Maize plots under the conventional control treatment were, however, rated high on weed control due to the possibility of using a plough and/or cultivator for weed control in this treatment. Weed control on CA plots was rated lower mainly due to the unavailability of an appropriate herbicide to be used on CA fields and increased labour burdens for manual weeding. This was further confirmed in focus group discussions. Farmers reiterated that it was mechanized weed management that attracted them to keep some of their land under conventional agriculture.

Furthermore, despite the visible benefits of conservation agriculture, farmers cited a number of other reasons for not adopting these practices (Fig. 9). These included lack of

Fig. 5 Yield response to increasing levels of annual rainfall in two CA treatments (Rip-line seeding and direct seeding) and conventionally ploughed control plot. Zimuto Communal Area, 2004–2013



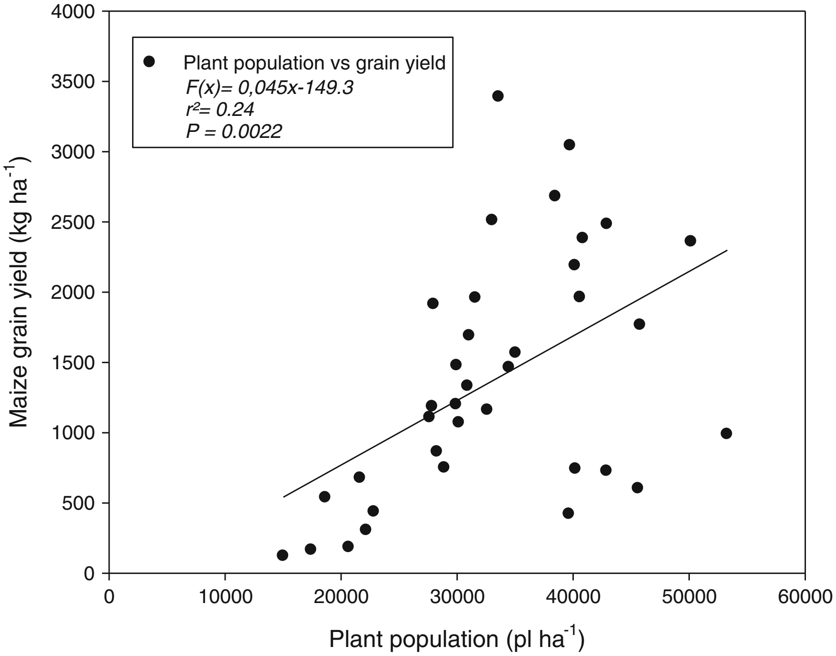


Fig. 6 Relationship between maize grain yield and final plant population at Zimuto Communal Area, 2004-2013

information on the technology and technical support, perceived risk of crop failure and conflicts with other economic activities. Partial adopters were more concerned about the short supply or unavailability of adapted CA equipment on the market and incompatible herbicides on the very sandy soils in Zimuto. In focus group discussion it was also evident that the availability of residues as well as lack of and access to functional input and output markets and lack of available cash were considered major constraints. The surveyed farmers were asked to rank the main constraints to CA adoption. Lack of information and technical assistance, risk aversion and time conflicts with other economic activities were rated as the most binding constraints by the farmers surveyed (Fig. 9).

Discussion

Biophysical assessment

The analysis of climatic conditions at Zimuto Communal Area shows that farmers are confronted with high risk. Farmers have failed seasons either because of too much water (waterlogging) or too little water (drought or seasonal dry spells) to successfully grow a crop. Furthermore, the seasonal cumulative rainfall shows that the rainfall distribution was very variable and, in some years, high rainfall may have led to negative side effects (e.g. leaching of fertilizer, waterlogging, surface run-off, erosion). To reduce the risk at household level, the Dwala granite dominated areas of Zimuto offer the opportunity to shift from topsoil to vlei areas and successfully grow crops. However, the data from this study showed that only in some years were sites prone to complete drought, which questions the high probability of risk of crop failure shown in Fig. 3 and results previously reported by Nyamangara et al. (2013).

The results from nine years of research on CA systems at Zimuto Communal Area show that there are advantages of moving to CA for farmers, even in this marginal environment. Farmers had in most cases greater maize and cowpea yields, with a few exceptions, indicating greater productivity and water-use-efficiency than the conventional treatment. Increased precision and moisture conservation on treatments seeded with the direct seeder or a ripper tine led to comparably higher plant populations and final plant stand. A relationship between increasing maize grain yield and increases in plant population explains some of the yield advantages of CA systems. This concurs with previous results from the Zimuto region, which showed that CA outperforms conventional systems after 3–5 cropping seasons with the exception of marginal environments where the yield advantage manifests itself faster (Thierfelder and Wall 2012; Ngwira et al. 2012a, b; Thierfelder et al. 2013a, b). Nevertheless, a stipulated ground cover of 2.5–3 t ha^{-1}, sufficient to cover around 30% of the soil surface was rarely achieved and only under favourable rainfall conditions, which might limit the overall potential to increase soil fertility and production and to reduce risk over time (Baudron et al. 2013). To achieve sufficient ground cover, thatching grass, which is available in sufficient quantities, could be used to increase the mulch cover. However, this also has environmental and social consequences for farmers as it is

Table 4 Cowpea grain yield at Chikato School as influenced by tillage treatment, Zimuto Communal Area, Zimbabwe, 2005–2013

		Intercropping		Rotation	
		Yield (kg ha^{-1})		Yield (kg ha^{-1})	
		Grain	Biomass	Grain	Biomass
2009	Conventional			153 b	163 a
	Rip-line seeding			266 a	212 a
	Direct seeding			237 a	253 a
	LSD			83.2	140.7
	N			4	4
2010	Conventional	190 b	N/A	153 b	N/A
	Rip-line seeding	240 a	N/A	398 a	N/A
	Direct seeding	253 a	N/A	418 a	N/A
	LSD	49.5		212.1	
	N	4		4	
2011	Conventional	35 a	42 a	37 a	225 a
	Rip-line seeding	95 a	75 a	244 a	884 a
	Direct seeding	92 a	69 a	293 a	774 a
	LSD	71.4	39.9	271.7	865.5
	N	3	3	4	4
2012	Conventional	359 a	551 a	N/A	N/A
	Rip-line seeding	287 a	524 ab	N/A	N/A
	Direct seeding	246 a	396 b	N/A	N/A
	LSD	204.5	151.1	N/A	N/A
	N	5	5		
2013	Conventional	134 b	187 a		
	Rip-line seeding	203 ab	150 a		
	Direct seeding	215 a	209 a		
	LSD	79.0	74.6		
	N	7	7		

*Note: means followed by the same letter in each particular year are not significantly different at P ≤0.05)

an additional labour burden and might limit the attractiveness of CA.

Increased infiltration is a direct result of no-tillage and surface residue retention, which encourages the formation of a continuous soil pore system and reduces soil crusts (Thierfelder and Wall 2009). It also activates biological soil fertility organisms leading to greater earthworm abundance, which in turn increases the number of soil macropores (Kladviko et al. 1986). The results of this study show a clear advantage of CA systems in water infiltration. Nevertheless, to conclude that greater infiltration automatically leads to increased maize yield would be premature as the season quality and the amount of water infiltrating play crucial roles in the overall performance of cropping systems as the sandy soils of Zimuto tend to accumulate too much water leading to waterlogging (Thierfelder and Wall 2012).

Economic assessment

The results from the gross margin analysis show that although CA treatments had slightly increased TVCs, overall it was more economical to practise CA except in years of erratic rainfall and/or drought. The largest contributing factors to the TVC for the CA system were labour for manual weeding and mulching on both CA treatments and planting on the rip-line seeded treatment. The sandy soils in Zimuto were incompatible with available herbicides such as glyphosate, which can only be used as a pre-emergence herbicide on loamy and clay soils where the product is rapidly deactivated without further harm to the maize seedlings. Farmers clearly expressed their favour in mechanically controlling weeds. This could not be balanced through labour savings on planting. Challenges regarding weed control are therefore one of the major limitations for the adoption of CA, at least in the first years of conversion (Mwale 2009; Muoni et al. 2013).

Although the results showed that the conventional tillage system was less labour intensive when compared to the other seeding systems, the yield was also significantly lower, making the system economically unviable. The conventional system also had the least return to labour and to TVC compared to the CA systems. These results are consistent with other findings in the region where yield gains of 50 to 300% after adoption of CA were reported in Zimbabwe and Zambia (Ngwira et al. 2012b; Twomlow et al. 2006; Umar et al. 2011)

Adopting any of the mechanized CA technologies is therefore more profitable. However, it is more beneficial to adopt the direct seeder than the ripper, depending on the farmers' ability to purchase the machinery and the availability of equipment on the market.

Feasibility of CA in Zimuto Communal Area

The fact that dis-adopters and non-adopters cited lack of information as a major limiting factor to CA adoption shows that technical support and guidance is very important for farmers to continue using the technology, particularly in early years of adoption when the results may not fulfil initial high expectations (Wall 2007; Davis et al. 2008). Government extension officers were the main sources of agricultural information and advice in the district and the lack of a more vibrant non-governmental extension service may explain the perceived lack of access to information. These results are also consistent with other findings asserting weak extension programs and institutions as the main factors for low adoption of agricultural innovations in southern Africa (Wall et al. 2013; Erenstein et al. 2012). Governmental investments in increasing knowledge and capacity of smallholder farmers would have a great impact on farmer awareness and of alternative and maybe more sustainable agriculture methods.

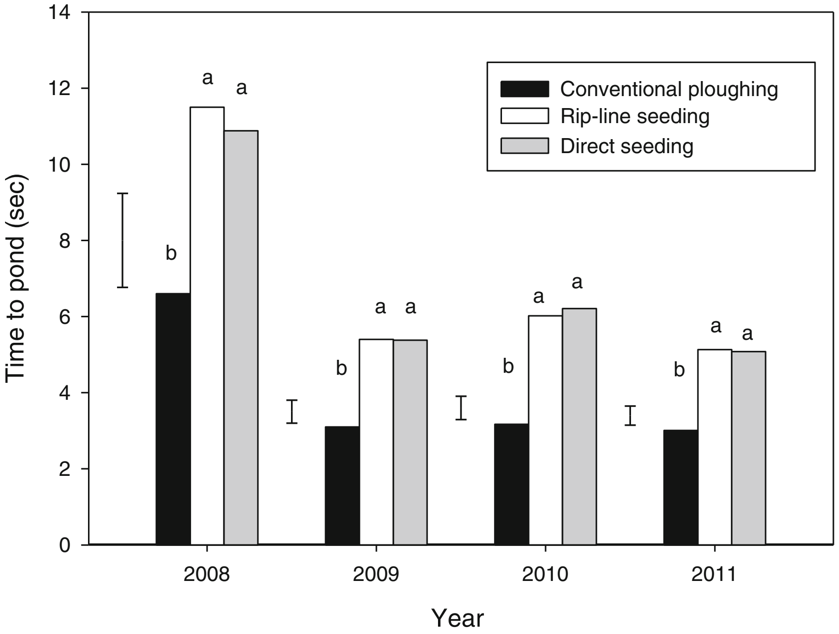


Fig. 7 Infiltration measured with the time to pond method on farmers' fields in Zimuto Communal Area, Zimbabwe in March/April 2008–2011; the measurement was carried out in the period 90–135 days after planting

Unavailability of equipment, particularly the direct seeder, and herbicide incompatibility with soil type were other important reasons for low adoption rates cited by partial adopters of the technology. Eighty-three percent of the farmers in the district were pensioners, depending on market gardening and remittances for their livelihood. Crop production was not the main economic activity or primary interest of farmers because the area is prone to droughts. This probably explains why risk aversion was cited as one of the key constraint to CA adoption.

The conversion of seemingly unproductive land to CA might be possible as has been shown by the long-term data. However, the large numbers of old and retired farmers make it rather unlikely. Due to the projected future biophysical limits in this area, alternative land uses should be explored that are more profitable and viable in such an environment.

Table 5 Changes in total soil carbon (t ha^{-1}) in 2004, 2008 and 2011 in two conservation agricultural and one conventional treatment at Chikato

	Depth cm	Total carbon t ha^{-1}	Total carbon t ha^{-1}	Total carbon t ha^{-1}
Chikato		2004	2008	2011
Conventional ploughing	0–20	8.3 a	6.9 b	6.5 b
Rip-line seeding	0–20	5.4 a	9.5 ab	8.4 b
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 within the columns are not significantly different at $P \leq 0.05$ (LSD-test); Samples were all taken in October of each respective year before the cropping season. Samples were corrected for bulk density and calculated to t ha^{-1} (adapted partially from Thierfelder and Wall 2012)

Conclusion

The long-term research at Zimuto Communal Area has clearly shown that CA is a productive system, which is economically viable in normal years. Yields of both maize and cowpeas increased significantly as compared to the conventional control treatment under the prevailing conditions of low soil fertility, sandy soils and extremely erratic and unpredictable rainfall. Improved plant stand can be considered as one of the contributing factors to higher yields on CA plots as direct seeding techniques disturb the soil less, leading to more available moisture for seed germination and plant development. Increased soil fertility, although marginal, greater nutrient use efficiency and better response to fertilizer application could have further contributed to increased yields on CA plots in comparison to the conventional control treatment, especially in the longer term. Although cereal and leguminous biomass yields were often not enough to achieve the stipulated yields of at least 2.5–3 t ha^{-1}, residues could be supplemented by thatching grass or leaf litter to achieve sufficient ground cover. However, this could also be a major impediment to widespread adoption as collecting grass for mulching is an additional labour burden for smallholder farmers.

Farmers' perceptions of maize production under CA were generally seen as very positive. Plants under CA were therefore rated high on crop establishment and all yield-related indicators (cob size, cob numbers and grain filling) but not

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

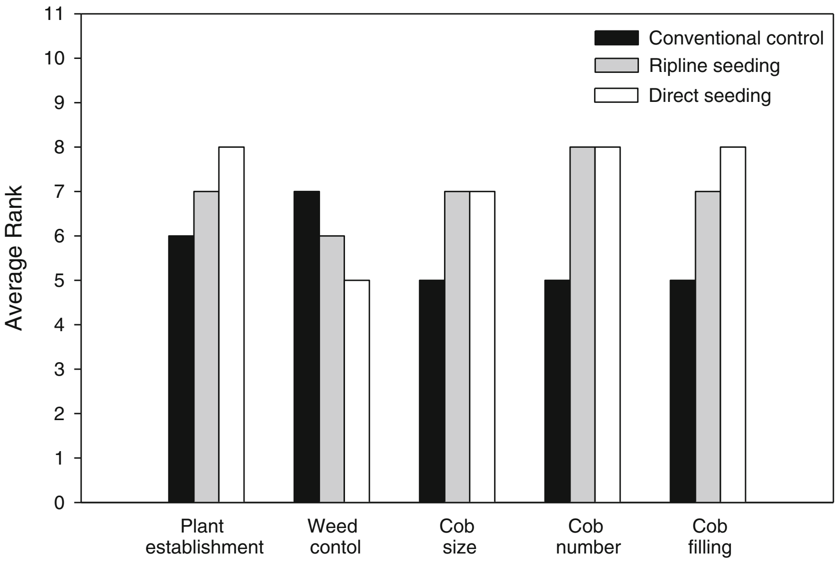
	2009/10			2010/11			2011/12			2012/13		
	CP	Ripper	DSeeder	CP	Ripper	DSeeder	CP	Ripper	DSeeder	CP	Ripper	DSeeder
Gross receipts	97.30	289.92	182.02	141.96	378.17	278.36	376.58	562.28	751.27	271.00	680.85	770.80
Variable costs (VC)												
Seed	66.00	66.00	66.00	76.00	76.00	76.00	60.00	60.00	60.00	76.00	76.00	76.00
Fertiliser	243.50	243.50	243.50	216.40	216.40	216.40	215.00	215.00	215.00	216.40	216.40	216.40
Labor days												
Pre-season weeding	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	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 application	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	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	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	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	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	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	0.00	7.00	7.00	0.00	7.00	7.00	0.00	7.00	7.03	0.00	4.00	4.00
Total labour days	18.81	35.22	42.68	22.54	38.44	34.74	31.50	31.61	27.08	31.28	36.30	31.45
Labour unit price	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	56.43	105.66	128.05	67.61	115.32	104.23	94.49	94.83	81.24	125.12	145.20	125.80
Total VC	365.93	415.16	437.55	360.01	407.72	396.63	369.49	369.83	356.24	417.52	437.60	418.20
Gross margin	-268.63	-125.24	-255.53	-218.05	-29.56	-118.27	7.09	192.45	395.03	-146.52	243.25	352.60
Returns to labour	-3.76	-0.19	-1.00	-2.23	0.81	-0.14	1.07	3.03	5.86	-0.17	2.92	4.06
Return to TVC (%)	-73	-30	-58	-61	-7	-30	2	52	111	-35	56	84

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, Returns to labour=Gross receipts-(TVC-Labour)/Labour; Returns to TVC=Gross margin/Total VC

There was an increase in labour costs from 3 US\$ d^{-1} in 2010/11 to 4 USD d^{-1} in 2011/12

on weed control as farmers preferred controlling weeds with a plough or cultivator, which is not possible on residue covered CA fields. The lack of an appropriate herbicide on the very sandy soils of Zimuto added to increased manual labour on CA fields, which was not balanced by reduced labour time spent on seeding.

Fig. 8 Farmers' rating of different maize crop attributes for on farm trials in Zimuto Communal Area, Zimbabwe



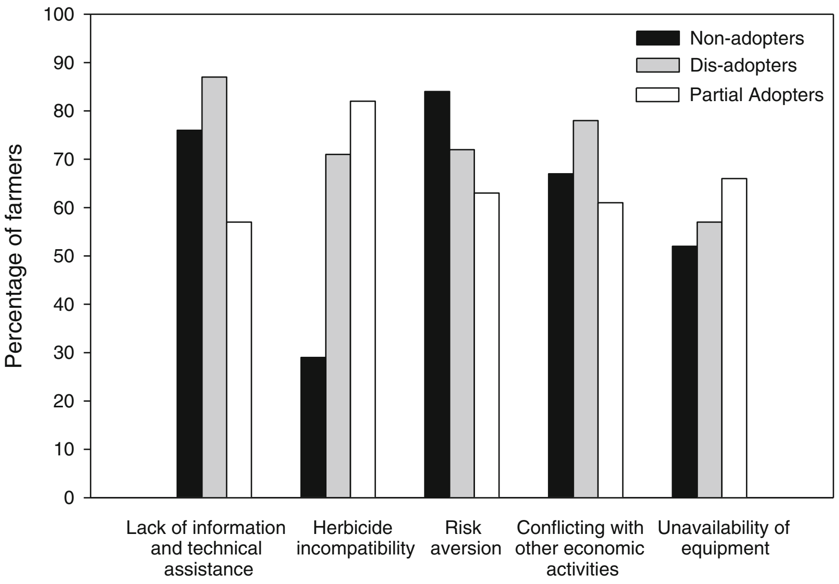


Fig. 9 Farmers' perception of constraints to CA adoption at Zimuto Communal Area, Zimbabwe. Farmer groups were subdivided into farmers that had never tried CA (Non-adopters), farmers that had tried and stopped practising (Dis-adopters), and farmers that had adopted at least two principles of CA (Partial adopters)

However, positive biophysical results of CA on farmers' fields did not lead to widespread adoption of the technology, which highlights the limits and critical needs for successful CA outscaling. Farmers gave many reasons why it was difficult for them to adopt CA. Lack of information, conflicts with other economic activities, lack of access and unavailability of important inputs, such as appropriate equipment, herbicides or mineral fertilizers as well as the purchasing power of smallholder farmers were highlighted.

The perceived risk of crop failure has limited farmers' willingness to "experiment" with new forms of agriculture, although some are convinced that the current way of agriculture is too extractive and leads to soil degradation. Farmers in this area are often retired and live off remittances, which makes any viable crop production questionable.

The authors therefore conclude that CA, although biophysically and economically viable may have its limitations in Zimuto Communal Area due to socio-economic constraints: the high risks associated with crop production and a lack of technical information and financial capacity. However, this not only applies to CA but also to general crop production. Alternative land uses should be explored and CA could be restricted to small fields near homesteads whereas other areas should be converted into more appropriate land uses such as rangeland for extensive livestock holding or game ranching.

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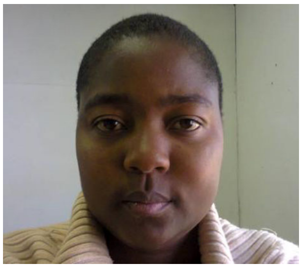

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