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Review

Maize productivity and profitability in Conservation Agriculture systems across agro-ecological regions in Zimbabwe: A review of knowledge and practice

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A B S T R A C T

Conservation agriculture (CA) is increasingly promoted in southern Africa as a strategy to improve food security and reverse soil degradation in the face of climate change. However, the performance of CA under different environments and its ability to improve ecosystem services is still unclear. The effects of the CA options; direct seeding, rip-line seeding, and seeding into planting basins on maize grain yield, soil health and profitability across agro-ecological regions in Zimbabwe were evaluated through a review of literature in combination with meta-analysis. Overall, CA improved maize yield over conventional agriculture. Compared to conventional agriculture, direct seeding, rip-line seeding, and seeding into planting basins increased yield by 445, 258 and 241 kg ha^{-1}, respectively. However, there was an initial yield decline in the first two years. CA practices reduced soil erosion and bulk density, and increased soil water content in most studies. Under high levels of residue retention (6 Mg ha^{-1}), CA systems exhibited greater macro fauna abundance and diversity than conventional agriculture, particularly termites. Weed pressure tended to increase labour requirement for hand-hoe weeding under CA compared to conventional agriculture. However, the use of herbicides reduced weeding labour demand during the early season. The benefits of CA are tied to the farmers' management intensity including: time of planting, weeding, fertiliser and herbicide application, and adequate training on equipment use. Economic analysis results showed that on average, a farmer incurs losses for switching from conventional agriculture to CA in the main maize growing regions of Zimbabwe. Based on the six seasons' data, the losses were least with the ripper in drier areas and worst with the direct seeder in wetter areas. Incorporation of chemical herbicides worsens the economic returns of CA tillage options in all the agro-ecological zones. Overall, the study showed that the rip-line seeding is more attractive in the drier areas than direct seeding. Although not costed in this study, critical is the cumulative reversal of soil degradation associated with consistent CA practice which can sustain agriculture. Results from this review suggest that the benefits of CA depend largely on the type and context of CA being practised. It is thus imperative to profile the technology, the farmer socio-economic circumstances and the bio-physical environment in which the farmer operates for proper geographical and beneficiary targeting to achieve greater impact. More longer-term studies are required to fully elucidate the benefits and context of CA options and practice.

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Contents

1. Introduction

Increasing population pressure and competing global demands for food and feed, and in recent years, renewable energy, warrant the need for options that optimise crop production per unit area in the face of the changing climate (e.g. Lobell, 2014). This is particularly important in Sub-Saharan Africa (SSA) and the rest of the developing world, where an increasing demand for food has been worsened by a variable and changing climate (Challinor et al., 2007). Conservation agriculture (CA) has been promoted in SSA in recent years as an alternative to conventional agriculture because of its ability to reduce soil degradation, enhance soil health, improve resource use efficiency and sustain long-term crop productivity (Gwenzi et al., 2009; Vanlauwe et al., 2014). CA is based on three principles: (i) continuous minimum mechanical disturbance of the soil through no-till, (ii) maintenance of a permanent organic cover using crop residues, and (iii) diversification of crop species grown in sequences e.g. cereal-legume rotations (Kassam et al., 2009; FAO, 2011). CA has been promoted in southern Africa, a region which is vulnerable to climate change and variability impacts that frequently result in low crop yields and sometimes total crop failure (Hobbs, 2007; Wall, 2007).

Research on CA in Zimbabwe can be traced back to as far as the 1920s, with the original focus mainly on minimum or reduced tillage. High costs of diesel and spare parts as a result of economic sanctions applied on the then colonial government accelerated the development of minimum tillage equipment and practices. It is estimated that at independence in 1980, 30% of commercial farmers in Zimbabwe were using reduced tillage systems (Smith, 1988). From 1996 to 1998, a collaborative project between the Department of Agricultural Technical and Extension Services and the German Technical Cooperation Agency was implemented focusing on reduced tillage for sustainable crop production in smallholder farming systems. The major objective of that project was to develop a number of tillage technologies to address problems of soil loss, runoff and erosion and declining crop yields (Nyagumbo, 2002). In that project, mulch ripping, clean ripping and tied ridges were tested against a conventional control treatment, i.e. moldboard ploughing or hand-hoeing. Mulch ripping involved the use of a tine ripper to rip (~25 cm depth) between planting rows with crop residues being left on the surface whereas crop residues were removed under clean ripping. Tied ridges were permanent ridges with ties in the furrows approximately every 50 cm, creating a basin-like system with crops planted on the ridges. After several seasons of on-farm and on-station research, it was concluded that mulch ripping with its high water use efficiency was the most viable conservation tillage practice in the semi-arid regions of Zimbabwe (Nyagumbo, 2002). However, there was limited uptake of reduced tillage practices by smallholder farmers during and after the project. This was largely due to the institutional framework of the project and lack of appropriate equipment (Johansen et al., 2012).

In 2003, there was renewed interest to promote CA in Zimbabwe with its three main principles of no-till, mulch cover and crop rotations or diversification, mainly driven by substantial donor funding targeting food security for vulnerable households with no draught power to facilitate early planting and increased crop yields (Mashingaidze et al., 2006). A consortium of organizations including Food and Agriculture Organization of the United Nations (FAO), Department for International Development (DFID), European Union, International Crop Research Institute for the Semi-arid Tropics (ICRISAT), International Maize and Wheat Improvement Centre (CIMMYT), University of Zimbabwe, various non-governmental organizations (NGOs) and extension services were involved in research and promotion of CA technologies throughout the country. The CA technologies promoted were primarily seeding into hand-hoe basins, animal traction rip-line and animal traction direct seeding. Tractor powered seeding systems were left out because most donor funds were meant to target only those communities considered vulnerable due to lack of draught power, labour and chronic illnesses such as HIV/AIDS (Nyamangara et al., 2014). The basin/mulch package represented a disconnection with earlier science based experimentation with reduced tillage practices that were previously tested in Zimbabwe. Of late, the focus of promotion in Zimbabwe by the Department of Agricultural and Extension Services has shifted to mechanized systems (Marongwe et al., 2011).

While the common goal is to improve crop productivity, the term CA means different things to different stakeholders e.g. farmers, NGOs, media, policy makers, among others. Terms such CA, conservation tillage, no-tillage, conservation farming, precision conservation agriculture, resource conserving technologies and minimum tillage practices are commonly used in CA nomenclature (Table 1). Hence CA in smallholder farming systems in Zimbabwe is a set of principles where reduced tillage is applied in different ways according to farmer circumstances.

Crop productivity on many smallholder farms in Zimbabwe and much of Africa is constrained by a combination of interrelated factors, e.g. low soil fertility, insufficient and inappropriate fertiliser application, erratic rainfall, lack of improved cultivars, labour constraints, and in some situations inappropriate tillage practices. Due to this, many farmers are trapped in abject poverty, experience food insecurity and poor nutrition (Sanginga and Woomer, 2009). CA has been promoted to address these constraints (FAO, 2002; Wall, 2007), with approximately 903,000 ha of land under CA in southern Africa (Friedrich et al., 2012). The components of CA; no-till, mulching with living or dead plants and crop rotation and diversification affect processes such as organic matter decomposition (Chivenge et al., 2007; Gwenzi et al., 2009), rainfall infiltration, soil moisture, soil erosion (Yimer et al., 2008; Thierfelder and Wall, 2009), and ultimately crop productivity (Stevenson et al., 2014). CA can potentially make a difference in situations of erratic rainfall distribution and seasonal dry spells where higher moisture conservation during critical crop phases may increase crop yields at harvest or at least reduce the risk of crop failure (Thierfelder and Wall, 2010; Rusinamhodzi et al., 2012). This suggests that CA has potential to improve crop productivity in the semi-arid areas, and will become especially important in Zimbabwe and southern Africa where drought occurrence is projected to increase as the climate changes. CA also improves soil fertility, associated with the build-up of organic carbon in the soil, although the amount and the time needed to reach appreciable amounts of soil organic carbon vary greatly between sites and cropping systems (Govaerts et al., 2009; Thierfelder and Wall, 2012). The climatic and edaphic conditions in southern Africa vary greatly within short distances due to relief and soil parent material (Lewis and Berry, 1988), and it is not sufficient to draw lessons from few localities.

Table 1
Typologies of conservation agriculture in smallholder farming systems in Zimbabwe.

Technology/practice used	Characteristics
Conventional tillage	Intensive tillage using ploughs, discs, harrows and rippers No residues left on the surface
Minimum till/tillage	• Minimum soil manipulation, this causes a lot confusion
Strip till	Uses minimum tillage, leaves some crop residues
Conservation tillage	Objective to reduce soil erosion and 30% cover with crop residue
No till/no tillage/zero tillage	Growing crops year to year without soil disturbance
Direct seeding/mulch based cropping systems	• Minimum soil disturbance • Soil cover through cover crops in rotation with the main crop
Conservation farming	Using a basin and mulch
Planting basins	Using pits smaller than the Zai pits
Zai systems	Originated from West Africa • Harvesting water • Applying organic inputs • No mulch is used
Conservation agriculture (CA)	3 principles • Minimum soil disturbance • At least 30% cover • Crop rotation
Precision CA	Fertiliser application • Application of fertiliser in basin • No mulch used

In the smallholder farming systems of Zimbabwe land preparation has largely been ox-power based, but with the decline in livestock numbers as a result of droughts and economic challenges, there have been notable increases in manual planting. The CA options available in manual systems are: use of the dibble stick, jab planter, hoe planter and planting basins, whereas animal-traction rippers and direct seeders are the more mechanized systems accessible to smallholder farmers. The planting basin, ripper and the direct seeder are the most practiced CA options in the country at present. The benefits of CA are diverse and depend to a large extent on the nature of the agro-ecosystem in question and how well CA technologies are adapted to the local environmental and, socioeconomic and cultural conditions. Most studies show that CA has yield advantage over the conventional agriculture in most agro-ecological zones (Marongwe et al., 2011). Most studies also show that labour requirement with some of the CA options also increases (Siziba, 2007; Mazvimavi and Twomlow, 2009; Thierfelder et al., 2013), mostly due to increased weed pressure, if no herbicides are used. Perennial weeds become difficult to control when soil is not tilled. Although the labour demand for land preparation and crop seeding are substantially reduced with the ripper and direct seeder, basins are in fact, more laborious as they are dug manually with hand-hoes. To a farmer the decision to switch from the conventional plough to the CA options largely depends on trade-offs between gains in crop yield and the opportunity cost of additional labour. With the ripper and direct seeder, implementation costs are additionally considered. If herbicides are used, the trade-off is between the cost of the chemical and the reduction in labour needed for manual weeding.

A review of CA practices in Zimbabwe was conducted with three main objectives. The first objective was to quantitatively synthesise the yield advantages of practising CA over conventional agriculture in the maize-based smallholder farming systems across agro-ecological environments in Zimbabwe using published data. The second was to evaluate the impact of CA practices on soil health. The third objective was to evaluate the economic benefits (profitability) of switching to CA options for farmers. Current estimates suggest a total of over 300,000 smallholder farmers implementing some components of CA (mostly no-tillage planting basins) over an area just above 100,000 hectares (Nyamangara et al., 2014). However, the estimates were not based on the strict definition suggested by FAO (2011). Thus, in order to retain enough data to be able to conduct the analysis, CA systems including those not complying with the strict definition were used in this synthesis. Maize was used as the main test crop as it accounts for 50-90% of the population's caloric intake (Dowswell et al., 1996). Yield advantages were analysed by computing the mean difference between CA and conventional agriculture. As an incentive for farmers to adopt a new production system short-term benefits especially in the form of yield gains or other economic benefits are important. Finally, the study analysed how the biophysical, socio-economic and institutional conditions in the selected sites can support and sustain the benefits realised under CA.

2. Materials and methods

For the purposes of this study, CA systems evaluated were with the following no-till practices; ripper tines, direct seeders and jab planters. Residues were left on the surface under no-till.

2.1. Data sources

Maize grain yield data were obtained from tillage and crop residue management studies established under rain-fed conditions in Zimbabwe. Treatments had to be from randomised plots with at least three replicates. Studies were obtained from refereed journals, book chapters or peer reviewed conference proceedings (see Appendix A) through online searches in OvidSP, Scopus, Google Scholar and Web of Science as well as personal communication with key experts and researchers who are working on CA. The online search was comprehensive, using the following keywords and their combinations: conservation agriculture; reduced tillage; no-tillage; maize yield; rain-fed; Zimbabwe. The data included in the analyses had to satisfy the following minimum requirements:

(a) The studies were established under rain-fed conditions in three agro-ecological zones (II, III and IV), locally known as natural regions[1] in Zimbabwe,
(b) The treatments included a conventional tillage (control) and no-till,
(c) The experimental design was randomised and treatments replicated at least three times,
(d) The test crop was maize and the same variety was applied to all treatments under comparison, and
(e) Nutrient management was the same across treatments.

2.2. Site descriptions

Most soils in the study sites had a loamy to sandy loam texture, dominated by *Lixisols* and *Arenosols* while some sites were characterised by *Luvisols.* In all the sites, maize is the major food crop while sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br.) are important cereals. Grain legume crops such as groundnuts (*Arachis hypogaea* L.), cowpea (*Vigna unguiculata* (L.) Walp), dry beans (Phaseolus vulgaris L.) are often grown in rotation or association with the cereal crops. The large parts of Zimbabwe smallholder farming systems are characterised by a greater integration of crop and livestock production. Most smallholder farmers use cattle for draught power and mostly use the mouldboard plough for land preparation and also cultivators for weed control (Riches et al., 1997). During cultivation, the plough cuts, breaks, loosens, inverts the soil and buries weeds, crop residues and manure.

2.3. Summary of field experiments

The tillage experiments were established as follows:

Conventional tillage (i.e. control treatment) without residue retention, achieved using a mouldboard plough at shallow soil depth (10–15 cm) and planting into furrows created by the plough. Remaining crop stubbles and weeds were incorporated by the plough,

Rip-line seeding (Ripper) using an animal traction ripper (Magoye ripper) with residue retention. Maize was planted in rip-lines of 5–10 cm depth at seeding. Crop residues were retained *in situ* after harvest,

(a) Animal drawn direct seeder where maize was fertilised at planting, crop residues were retained *in situ* after harvest, and
(b) Planting basins dug using a hand-hoe, each basin was 15 cm (length), 15 cm (width) and 15 cm (depth), and spaced at 90 cm between rows and 60 cm within rows.

Weed control on conventional agriculture was manual through hand-hoes, and on ripper and direct seeder, chemical herbicides were used, mainly glyphosate applied at planting.

2.4. Data analyses

2.4.1. Crop productivity

A meta-analysis was performed using the ‘meta’ package in R to assess the yield benefits of CA over conventional tillage practices across sites and seasons. The effect size was obtained by computing the weighted mean difference (WMD) using the random-effects model (DerSimonian and Laird, 1986; Egger et al., 1997; Borenstein et al., 2009). We used the mean difference in yield between the treatment and control because of its ease of interpretation and the relevance for comparing potential gains (Ried, 2006; Sileshi et al., 2008). In the random effects model, it is assumed that the true effect of CA on crop yield varied from site to site and from season to season, thus contributions of each study to the overall effect size was considered to be independent. Weight (w_i) assigned to each study was calculated as the inverse of the variance ($1/v_i$) where v_i is the within study variance for study (i). The weighted mean is calculated as the product of mean and weight divided by the overall weight. The overall weight is the inverse of variance of the whole study (Eqs. (1.1)–(1.5)).

$$\text{Mean difference(MD)} = \text{mean}_{\text{treated}} - \text{mean}_{\text{control}} \tag{1.1}$$

$$\text{weight}_i = \frac{1}{\text{variance}_i} = \frac{1}{\text{SD}_i^2} \tag{1.2}$$

$$\text{Weighted mean difference (WMD)}_{\text{overall}} = \frac{\sum_{i=1}^{i=n}(\text{weight}_i \times \text{MD})}{\sum_{i=1}^{i=n}\text{weight}_i} \tag{1.3}$$

$$\text{CI}_{95\%} = \text{mean}_{\text{overall}} \pm (1.96 \times (\text{variance}_{\text{overall}})^{0.5}) \tag{1.4}$$

$$\text{Variance}_{\text{overall}} = \frac{1}{\sum_{i=1}^{i=n}\text{weight}_i} \tag{1.5}$$

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[1] Natural regions are agro-ecological zones classified mainly on the basis of amount of rainfall and temporal distribution. There are six main zones and the others are I (≥1000 mm; most of which falls throughout the year; good soils), IIa (750–1000 mm; good temporal distribution; generally good soils), IIb (same as IIa but less reliable); III (500–750 mm; subject to severe mid-season drought); IV (450–650 mm; Severe dry spells during the rainy season, and frequent seasonal droughts; normally considered unsuitable for dryland crop production); V (<450 mm; Highly erratic rainfall; poor soils normally considered unsuitable for crop production [Adapted from: Vincent and Thomas, 1960; Department of the Surveyor General, 1984].

Studies (seasons and sites) with lower variance contributed more weight to the overall effect. The analysis included how these mean differences were affected by soil type and the amount of rainfall received in a season. All the data were derived from studies established in Natural Regions II, III and IV as described under Section 2.1. Nitrogen input was not considered because it did not vary much across the experiments used for the meta-analysis.

2.4.2. Economics of switching to CA

Literature shows that economic incentive (profitability) is central to sustainable uptake of a new technology (Cary and Wilkinson, 1997; Pannell, 1999). A partial budget approach (CIMMYT, 1988) was adopted in evaluating the net economic effect of switching from the conventional plough to prospective CA options. The focus was on the economic implications of making the switch for each CA option. The financial benefits and costs associated with each option were evaluated against an average resourced smallholder farmer in Zimbabwe mostly cultivating maize on a one hectare plot, using the traditional ox-drawn plough and family labour. It was assumed that the input use (fertilisers and seeds) levels between CA and the conventional systems were the same—necessary for a fair comparison. In this context, switching to CA implied possible changes in the following parameters: a change in maize yield (gains are expected), change in labour demand (an increase—due to extra weeding or decrease—due to reduced tillage can occur), and equipment costs of new implements. If herbicides were used their cost was incorporated. In the analysis we attached values to these costs and benefits to compute the net economic effect of switching to CA for farmers. Our prices were based on the 2013/14 season.

Incremental maize gain, the major expected benefit of CA was evaluated using the 2013/14 maize price of US$ 375 per metric ton. The annuity method was used to spread the investment costs of equipment over the analysis period of six years. For all equipment, annual maintenance costs were computed as 5% of the purchase value of the equipment. Costing labour in the smallholder sector in Zimbabwe is not easy because most farmers use family labour, and also the labour market is not fully developed. The Government of Zimbabwe gazetted wage rate of US$3 per day was used to attach value to the opportunity cost of family labour. However, the authors were cognisant of the fact that the wage rates can fluctuate across the season tending to be high during peak periods. Under herbicide use, a mixture of glyphosate, atrazine and metolachlor; identified as the most effective under CA (Muoni et al., 2013) was assumed. Again market prices were used in costing this herbicide regime. The economic effect is the net difference of the value of benefits and value of costs associated with each CA option. The net economic effect for the six years a farmer adopt CA was computed. This allows the capture of the dynamic effects of CA yields over time. The Net Present Value (NPV) was used to summarise the economic effect over the six years of switching from the conventional plough tillage to CA options of direct seeding or ripping. The NPV is a summation of the discounted net economic effects over the six years. An interest rate of 14%, the prevailing real interest rate at the time, was used to discount the stream of net economic effects.

Breakeven yields and labour savings required for the switch from the conventional plough to CA were also derived. These are the values of labour savings and maize yield gains required to make the NPV equal to zero. This is the situation when CA and conventional ploughing would give the same economic returns, a threshold for the switch. For example, a farmer considering uptake of the direct seeder without use of herbicides will have to purchase the direct seeder and incur investment and maintenance cost of the new equipment. Since the farmer already owns a plough which also suffers the same kind of costs, the net equipment cost would be the difference in the cost of the two equipment. Since the direct seeder at US$550 is more expensive than the plough (US$ 125) the farmer incurs higher equipment cost for the switch. Assuming that overall labour use does not change, then the incremental equipment cost should be off-set by the value of additional maize yield for the farmer to switch to the direct seeder. The minimum maize grain yield gain required to off-set the incremental equipment cost is the breakeven yield gain. Alternatively, assuming no yield change, the minimum labour reduction necessary to off-set the incremental equipment cost could be computed—the breakeven labour savings. Incorporation of chemical herbicides in CA options, potentially reduces labour demand, but also adds cost to farmers. Herbicide use costs include the cost of the herbicide chemicals and, the investment and maintenance costs of the knapsack sprayer. Currently, few farmers use herbicides, even with CA systems. Exploring the economic implications of herbicide use are limited by the lack of studies that examined the labour dynamics when herbicides are used. The trade-off between the additional costs of the herbicide chemicals and the extent to which weeding labour is reduced determines the net economic effect. Muoni et al. (2013) explored weed control strategies in CA systems. It is the only available published material tracking labour use changes under different herbicide regimes in Zimbabwe. From this work, it was derived that the best herbicide control regime (a mixture of glyphosate, atrazine and metolachlor) can reduce manual weeding labour in CA by as much as 8 days ha^{-1}. Below are the economic effect and NPV equations used in the analyses:

i) The economic effect equation

$$\mathrm{EE} = \Delta Y \times P + \Delta \mathrm{EC} + \Delta L \times W + \Delta \mathrm{HC} \tag{1.6}$$

where EE is the net economic effect of the switch (US$); ΔEC is change in equipment cost (US$); ΔL is change in labour use (days ha^{-1}); W is the wage rate (US$ day^{-1}); ΔY = change in maize yield (kg ha^{-1}); P is the maize grain price (US$ kg^{-1}); and ΔHC is change in cost of herbicides (US$ ha^{-1})

$$\text{ii)}\mathrm{NPV} = \sum_{t=0}^{5} \frac{\mathrm{EE}_t}{(1+r)^t} \tag{1.7}$$

where NPV is the net present value (US$); EE is the economic effect in each subsequent year of CA adoption; t is the time period (0 in the first year of adoption and 5 for the 6th year); r is the real interest rate (0.14).

The minimum maize yield gains and labour savings that would be necessary for farmers to at least find the CA tillage options as profitable as the ox-plough tillage were explored. To do this all else was held constant and only the parameter of interest (labour or maize yield gain) changed and the point at which the NPV was equal to zero observed; a situation when farmers would be indifferent between choosing the CA tillage option and the ox-plough tillage. This analysis was not done for herbicide incorporation because of the poor economic performance.

3. Results and discussion

3.1. Yield benefits of CA over conventional tillage

Overall, the direct seeder treatment was not different from the ripper (sub-soiler) but out-yielded conventional tillage by almost 300 kg ha^{-1} (Fig. 1). Large yield benefits of CA were observed in favourable growing conditions of Natural Region II with the direct seeder whereas the ripper was superior in the driest region, i.e. in Natural Region IV (Fig. 2). Basins and jab-planter treatments were excluded from the box-plot due to limited sample sizes from the available data (Fig. 1). However, similar analyses have shown that

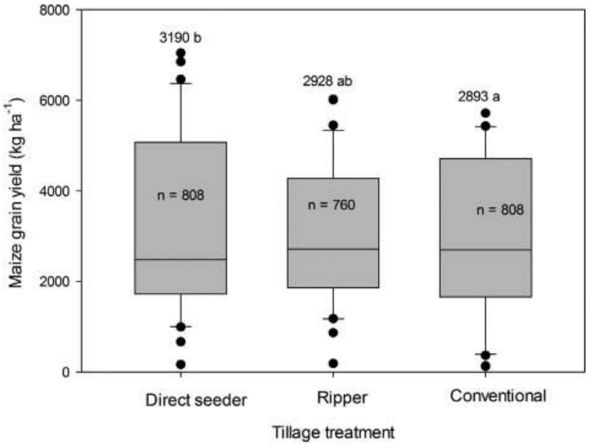

Fig. 1. Summary statistics for maize grain yield data from the tillage treatments used in the meta-analysis. Values above the plots are the means for each treatment. Mean yields followed by a different letter are significantly different at $p < 0.05$. The box plot represents the standard five number summary: minimum (lower whisker), first quartile, median, third quartile, and maximum (upper whisker). The points below or above the minimum and maximum respectively are outliers.

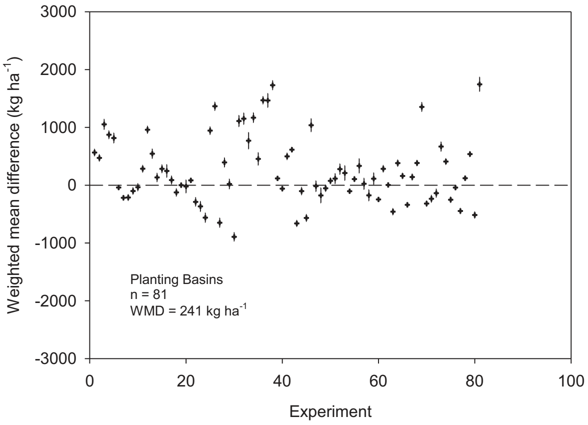

Fig. 3. The weighted mean difference (WMD) in yield between planting basins and conventional tillage for the drier southern part of Zimbabwe. The vertical bars respresent standard deviation. Figure originally reported by Nyamangara et al. (2013b).

basins out yielded conventional tillage in 64% of the cases considered in the semi-arid regions of Zimbabwe (Fig. 3), and the ripper was only superior to conventional tillage in 8% of the cases under those conditions (Nyamangara et al., 2013a).

The weighted mean difference showed that direct seeding out-yielded conventional tillage by 445 kg ha^{-1} overall (Fig. 2a). However, yield advantages across the agro-ecological regions tended to vary; the yield difference tended to be largest in the favourable growing conditions of Natural Region II, but were significant in Natural Region IV. The 95% confidence interval for weighted mean difference in Natural Regions II and III extended into the negative indicating no significant differences between direct seeder and conventional tillage in these regions.

The overall yield advantage of ripper over conventional tillage was 284 kg ha^{-1}, much less than that of the direct seeder (Fig. 2b). There were no significant differences between the ripper and conventional tillage in Natural Regions II and III, but in Natural Region IV, characterised by lower rainfall, the yield advantage of the ripper was 400 kg ha^{-1}. This is because the ripper allows deeper water infiltration and greater moisture capture and conservation than conventional tillage, which is beneficial under dry environments and within-season dry-spells (Rao et al., 1998; Fan et al., 2013).

Large yield benefits of CA were observed in Natural Region II with the direct seeder (though there are chances of low yields) whereas, it was with the ripper in the drier regions. The results suggest that the high rainfall in Natural Region II is favourable to the direct seeder where seeds are planted in fairly shallow planting holes and is likely to offset the devastating effects of long dry spells. The high yield potential in this region also suggests an increasing likelihood of providing sufficient biomass for mulch. It should also be noted that a significant proportion of the data showed negative effect of direct seeding on yield. This could suggest the effects of waterlogging due to excessive rainfall (Griffith et al., 1986).

In the drier Natural Region IV, the sub-soiling impact of the ripper could be an important factor in increasing infiltration and storage of rainwater, and thus water use efficiency. In Natural Region IV, there was no negative weighted mean difference in both the direct seeder and ripper suggesting the positive effect of these tillage treatments on the water balance (Nyamangara et al., 2013a). This is in support of the view that CA improves crop yields relative to conventional agriculture in dry areas because of greater moisture conservation leading to enhanced crop water productivity (Farooq et al., 2011). A recent global meta-analysis, showed that although the overall result suggest that CA reduces crop yields, in

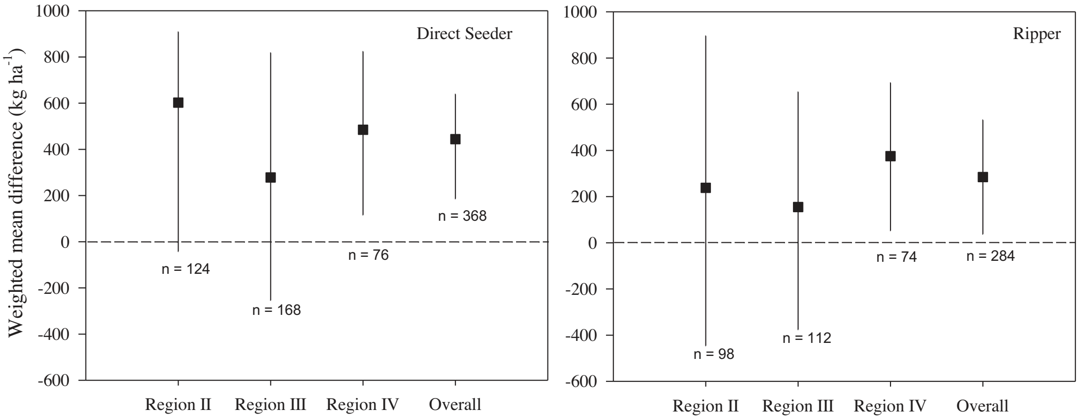

Fig. 2. Pooled and natural region-specific weighted mean differences (WMD) in yield a between direct seeder and conventional tillage, and b between ripper and conventional tillage, in Zimbabwe. Region II, III and IV represent three of the six natural agro-ecological regions of Zimbabwe1. The vertical bars represent the 95% confidence intervals.

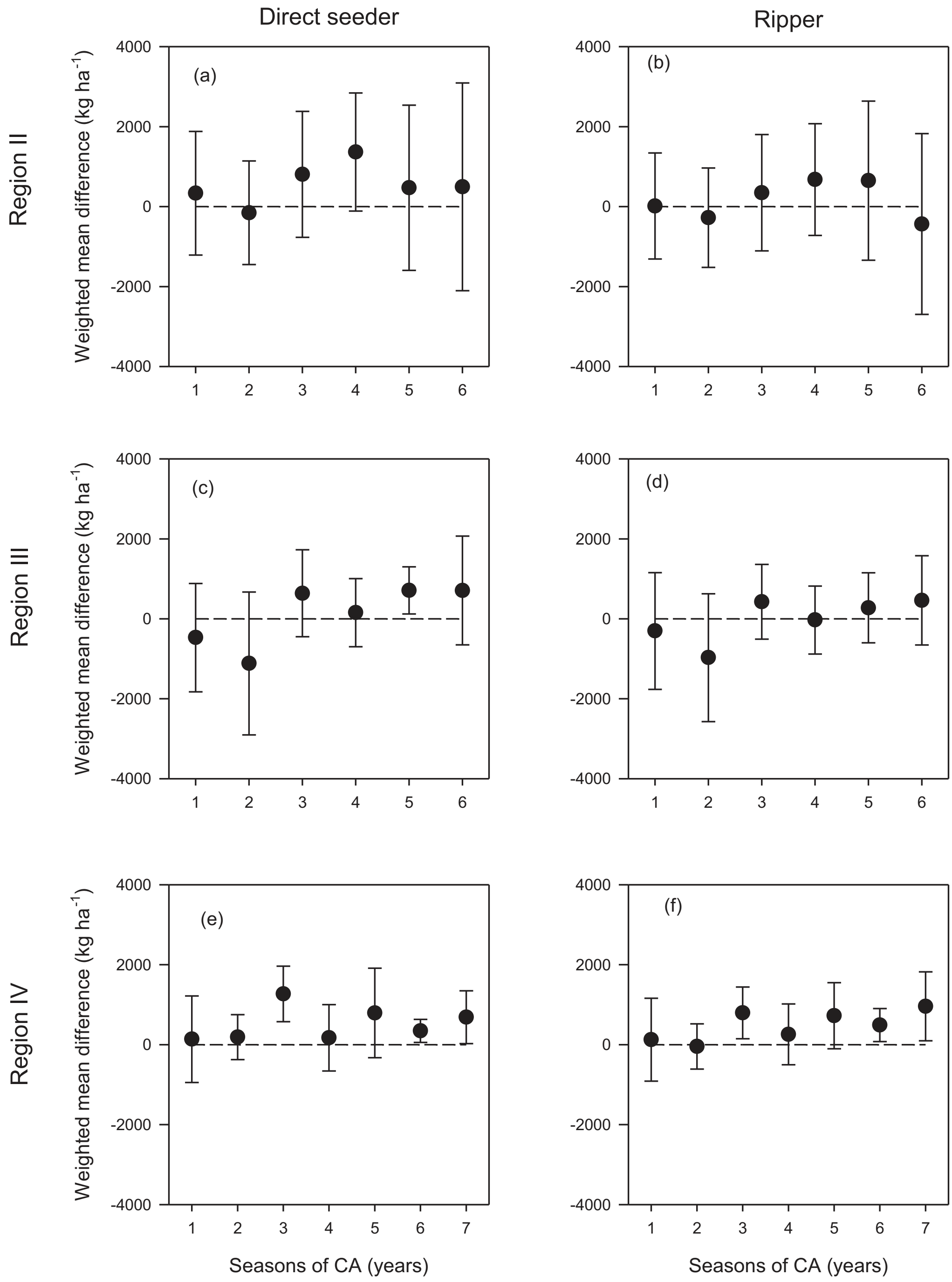

Fig. 4. Weighted mean differences in yield between direct seeder and conventional tillage on the left; and ripper and conventional tillage on the right in time across natural regions in Zimbabwe. The comparisons between the direct seeder and conventional tillage are shown in (a), (c), and (e) for Regions II, III and IV, respectively. The comparions between the ripper and conventional tillage are shown in (b), (d), and (f) for Regions II, III and IV, respectively. The vertical bars represent the 95% confidence intervals.

drier regions CA increases crop yields, due to the greater benefit derived through improved moisture conservation (Pittelkow et al., 2014), depending on the type of CA systems and soil types. This has important implications on the potential of CA to improve crop productivity and its sustainability in Zimbabwe given that the southern Africa region is projected to get drier with more erratic rainfall and heat stress (Challinor et al., 2007; Cairns et al., 2012; Cairns et al., 2013;).

Negative weighted mean differences were recorded in the first two years of the experiments in both direct seeder and ripper treatments in both Natural Region II and III, and increased thereafter but diminished after year five in Natural Region II but maintained in Natural Region III and IV (Fig. 4). The initial years of shifting to CA are fraught with challenges including: inadequate amounts of crop residues, poor management skills by farmers, weed pressure in the absence of herbicides and or insufficient labour for optimum weed control can depress yield (Muoni et al., 2013; Muoni et al., 2014; Stevenson et al., 2014; Thierfelder et al., 2015a). In the medium term, yields can improve due to the likely improvement in soil quality, e.g. soil organic matter over time

(Chivenge et al., 2007; Thierfelder and Wall, 2012; Thierfelder et al., 2015b). The depressed yields in later years could be due to the negative monoculture effects on maize productivity previously observed in a similar study (Rusinamhodzi et al., 2011).

After a similar meta-analysis of ICRISAT data from tillage and crop residue management "CA" trials between 2004 and 2010, Nyamangara et al. (2013b) observed that: planting basin CA has a greater chance of increasing maize yield above conventional agriculture due to precision application of nutrients and water collection in the basins. Planting basins were superior to conventional tillage in 59% of the experiments. The overall reported weighted mean difference for planting basins was 241 kg ha^{-1} (Fig. 3). However, firstly, this yield advantage was reported to decrease to 95 kg ha^{-1} if rainfall was in the range of 500–830 mm per season. Secondly, CA does not stabilise yield under conditions of poor rainfall distribution and should be implemented in combination with other drought mitigation technologies and the use of drought-tolerant varieties (Cairns et al., 2013). Thirdly, the performance of CA under semi-arid conditions is enhanced by the addition of small amounts of mineral N fertiliser and cattle manure but is depressed by surface mulching with crop residues of high C:N ratios. Nutrient management is important for improving crop production under CA (Rusinamhodzi, 2015b). Lastly, basins should be recommended for sandy soils with good drainage. The data showing this evidence were not included in the current review but the findings are relevant as they covered most of the semi-arid regions (Nyamangara et al., 2014). The general conclusion from the meta-analysis was that yield performance under CA is influenced by soil type, rainfall amount and distribution, inorganic fertiliser and manure application. These findings are further supported by another global meta-analysis of maize yield data under rain-fed conditions (Rusinamhodzi et al., 2011) (Fig. 5).

3.2. Conservation agriculture and soil health in Zimbabwe

The basis for yield increases in CA systems is increased water use efficiency and improved nutrient cycling. These derive from soil surface cover, increased micro and macrofauna, and in some instances, accumulation of soil organic carbon (Brouder and Gomez-Macpherson, 2014) that improve soil physical and biological properties. In the following sections, the effect of CA on the soil biological, physical, and chemical properties in Zimbabwe are explored.

3.2.1. Soil biological properties

Soil fauna are important regulators of decomposition, nutrient cycling, soil organic matter dynamics and improvement of soil physical properties. CA using planting basins combined with mulching have a significant effect on soil fauna diversity and abundance (Table 2) (Nhamo, 2007; Mutema et al., 2014). Mutema et al. (2014) observed high fauna population (termites, ants, centipedes and beetle larvae) in CA systems compared to conventional practices in studies conducted on multiple sites in Natural Region III and IV in Zimbabwe. In that study, termites were the most dominant fauna group across all sites with the CA treatment having at least 1600% greater numbers of termites than conventional agriculture (Table 2). Similarly, Nhamo (2007) observed at least 120% more termites under direct seeder and ripper based CA than the conventional practice. The abundance of

Table 2
A synthesis of the effects of conservation agriculture on soil properties.

Property	Units	Conventional	CA	% difference	Tillage	Time under CA (years)	Soil texture	Source
Biological	Number/monolith							
Termites	number m^{-2}	750	12925	1623	Basin	2	Loam	Mutema et al. (2013)[a]
	number m^{-2}	50	110	120	Direct seeder	2	Sandy loam	Nhamo (2007)
	number m^{-2}	50	140	180	Ripper	2	Sandy loam	Nhamo (2007)
Ants	number m^{-2}	95	350	268	Basin	2	Loam	Mutema et al. (2013)
Centipede	number m^{-2}	0	290		Basin	2	Loam	Mutema et al. (2013)
Beetle larvae	number m^{-2}	100	685	585	Basin	2	Loam	Mutema et al. (2013)
	number m^{-2}	10	20	100	Direct seeder	2	Sandy loam	Nhamo (2007)
	number m^{-2}	10	22	120	Ripper	2	Sandy loam	Nhamo (2007)
Earthworms	number m^{-2}	5	8	60	Direct seeder	2	Sandy loam	Nhamo (2007)
	number m^{-2}	5	10	100	Ripper	2	Sandy loam	Nhamo (2007)
Physical								
Bulk density	g cm^{-3} (0–5 cm)	1.45	1.35	−7	Basin	5	Sandy	Nyamangara et al. (2014)
	g cm^{-3} (0–5 cm)	1.25	1.15	−8	Basin	5	Clay loam	Nyamangara et al. (2014)
Infiltration	mm	25.3	78.2	209	Direct seeder	6	Sandy soil	Thierfelder and Wall (2012)
Pore volume	% (0–5 cm)	7	16	128	Basin	5	Sandy	Nyamangara et al. (2014)
	% (0–5 cm)	11	19	73	Basin	5	Clay loam	Nyamangara et al. (2014)
Soil moisture	mm	66.6	80.7	21	Direct seeder	3	Sandy	Thierfelder and Wall, (2009)
Erosion	t ha^{-1}	68.9	29.9	−130	Direct seeder	8	Sandy	Thierfelder et al. (2012a,b)[b]
Run-off	mm	361	165	−119	Direct seeder	3	Sandy	Thierfelder and Wall (2009)
	mm	1.7	1.5	−12	Ripper	1	Sandy	Mupangwa et al. (2008)[c]
	mm	1.7	1.0	−41	Basin	1	Sandy	Mupangwa et al. (2008)
Chemical								
pH	H_2O (0–20 cm)	4.6	5.1	10	Basin	9	Sandy	Nyamangara et al. (2013)[d]
Organic C	t ha^{-1} (0–30 cm)	6.9	13.3	93	Direct seeder	4	Sandy	Thierfelder and Wall (2012)
	g kg^{-1} (0–20 cm)	5.9	6.8	15	Basin	9	Sandy	Nyamangara et al. (2013)
	t ha^{-1} (0–15 cm)	9.4	15.9	69	Basin	5	Sandy	Nyamangara et al. (2014)
	t ha^{-1} (0–15 cm)	20.5	28.4	38	Basin	5	Clay loam	Nyamangara et al. (2014)
Total P	g kg^{-1} (0–20 cm)	0.17	0.19	12	Basin	9	Sandy	Nyamangara et al. (2013)

[a] Averaged across five sites for the CA treatment where 2 t ha^{-1} residues were added.
[b] Cummulative erosion load over 8 years.
[c] Basin based CA averaged across 450 farms in 15 districts.
[d] Averaged across four sites.

termites confirms farmers' belief that retention of crop residues will increase prevalence of termites, which may subsequently damage crops. Mutema et al. (2013) observed an increase in fauna abundance with increasing amounts of crop residues applied under CA, in the order of $6\,t\,ha^{-1} > 4\,t\,ha^{-1} > 2\,t\,ha^{-1} > 0\,t\,ha^{-1}$. However, results showed limited occurrence of millipedes and earthworms. In contrast, Nhamo (2007) observed 60% and 100% more earthworms under CA than conventional agriculture. Additionally, there were greater abundances of beetle larvae under CA than conventional agriculture and in all cases the ripper had more fauna than the direct seeder. The increased abundance of soil fauna under CA improved soil physical properties such as infiltration, porosity, aggregate stability and hydrological properties.

3.2.2. Soil physical properties

Increased rainfall infiltration and soil water storage appear to be the most obvious and immediate benefits associated with CA provided that there is sufficient soil cover (Thierfelder et al., 2014). Thierfelder and Wall (2012) observed up to 209% greater infiltration under direct seeded CA treatments with surface residues retention compared with conventional tillage treatments with residue removal (Table 2) in a study conducted from 2005-2010 with a mini-rainfall simulator at Henderson Research Station in Zimbabwe. This supports other studies from Malawi, Zambia and Mozambique where increased infiltration has been shown to be desirable when mid-season dry-spells are common (Ngwira et al., 2013; Thierfelder and Wall, 2010; Thierfelder et al., 2013), otherwise waterlogging can arise leading to depressed yields (Thierfelder and Wall, 2010).

In conventional agricultural systems, soil losses of the order of $50\ Mg\ ha^{-1}$ per year through soil erosion and losses of 30% of received rainfall has been reported in Zimbabwe (Elwell and Stocking, 1988). In contrast, CA reduces soil erosion and was initially introduced to regulate both wind and water erosion (Rosenstock et al., 2014). Many trials have shown the positive effect of CA on water productivity, higher infiltration rates and water content. In addition, reduced soil loss and run-off were recorded in CA systems compared to conventional tillage systems (Table 2; Thierfelder and Wall, 2009). Greater infiltration rate under CA compared to conventional agriculture was observed already after the second year of continuous treatment (Thierfelder and Wall, 2009). The abundance of macro fauna in CA systems also contributes to improving soil physical properties. Increased infiltration was either a result of aggregate stability (Thierfelder et al., 2014), greater biological activity and reduced bulk density (Table 2; Nyamangara et al., 2014).

Similarly, CA has been shown to improve soil quality through the improvement of soil physical properties in four natural regions in Zimbabwe, but with greater benefits in high clay soils (Brouder and Gomez-Macpherson, 2014). In contrast, however, there was no significant correlation between improved bulk density and infiltration with maize grain yields in a study conducted in Murehwa district, Zimbabwe (Rusinamhodzi et al., 2013). This may imply that soil physical properties may not be the major limitation to maize grain yields but nutrient supply and availability instead (Nyamangara et al., 2013a).

3.2.3. Soil chemical properties

Globally, the impact of CA practices on soil organic carbon is inconclusive (cf. Govaerts et al., 2009). In Zimbabwe, Nyamangara et al. (2013a) rejected the hypothesis that CA increases soil organic carbon after a study based on soil samples collected from about 450 farms in 15 districts across the country (Table 2). Similarly, Chivenge et al. (2007) after assessing organic carbon in soil derived from a 9-year tillage experiment concluded that soil organic carbon is hardly affected by tillage practices in sandy soils and decisions to enhance organic carbon in these soils should focus more on managing organic inputs. Lack of sufficient carbon inputs in the form of mulch which is often the case on most smallholder farms can lead to no or very slow soil organic carbon increase (Nyamangara et al., 2013a). This observation is particularly important given that smallholder farmers in Zimbabwe occupy mostly the poor sandy soils. Where positive effects of CA on soil organic carbon are reported, the magnitude of change are often very small or insignificant (Thierfelder et al., 2012a,b; Pannell et al., 2014). Nyamadzawo et al. (2009) reported greater soil organic carbon sequestration in no-till systems because of improved aggregation which protected carbon from mineralization compared to conventional tillage although the system was different because continuous maize was compared with maize-legume fallows. It appears biomass production during the fallow period was the major driver of SOC increases in the maize-fallow systems under no-till (Nyamadzawo et al., 2008).

There were no significant differences in soil pH and phosphorus between CA and conventional systems (Supplementary Fig. 4; Nyamangara et al., 2013a). This could be attributed to application of low amounts of mulch with high C:N ratios, which could potentially lead to immobilization of mineral nutrients and low crop yields. However, these results were obtained from short-term research projects. There is a need to invest in long-term experiments (beyond 10 years) to monitor changes in soil properties and relate these to crop productivity.

3.3. Weed dynamics in CA systems

Although CA systems improve crop yields for smallholder farmers, challenges with weed management in the early years of adoption has been cited as a major reason for low adoption of these systems on small plots by farmers (Mazvimavi and Twomlow, 2009). Increased weed growth has been reported to be problematic in the first few years but will decline and become easier to control with time in CA systems (Wall, 2007). In support of these earlier claims, Muoni et al. (2014) recently found that weed population declined exponentially in four cropping seasons on a sandy soil site at Domboshawa Training Centre, Zimbabwe. Other studies have shown increased weed pressure after six years of practising CA and related reduced tillage systems (Nyamangara et al., 2013b). Long-term studies by Mashingaidze et al. (2012) showed that CA systems had higher earlier weed growth compared to conventional tillage (Supplementary Fig. 3). This would imply the need for early and more frequent weeding in CA systems compared to conventional tillage systems and thus increase the labour demand. Mabasa et al. (1998) showed that the seedbed under the mouldboard plough was weed-free for up to four weeks after a ploughing operation and reduced the need for early weed control. Most of the weeds observed in CA systems were perennial, which grow rapidly with the first rains due to the deep root system and their perennial growth habit that enabled them to tolerate long dry seasons (Mashingaidze et al., 2012). Perennial weeds regenerate rapidly after hand-hoe weeding under wet conditions, suggesting more labour is needed for weeding in CA systems if no herbicides are used (Mashingaidze et al., 2012).

Weed control methods used by most smallholder farmers rely on hand-hoe weeding and to a lesser extent mulching. The need for early and frequent weeding in CA system will result in competition for labour for ploughing and planting operations at the beginning of the season. Hence, there is a need to evaluate less-labour-demanding weed control measures. Mulching with crop residues has been shown to be an appropriate practice to reduce early weed growth. Mulching with maize residues at $4\,Mg\,ha^{-1}$ reduced weed growth (Mashingaidze et al., 2013). Weed suppression through mulching may reduce labour demand in the early season. However, the majority of the smallholder farmers may not be able to mulch at 4 Mg ha^{-1} because of mulch scarcity. The amount of mulch available to smallholder farmers is limited by low biomass production in semi-arid conditions under poor soils. The little crop residues available is also used for livestock feeding during the dry season, hence there is little mulch which remains for sufficient mulching to eliminate the need for early weeding in CA systems as suggested previously (e.g. Valbuena et al., 2012; Rashid et al., 2013).

Labour constraints and mulch limitations for weed control in CA systems dictate that alternative weed control systems be evaluated and promoted. Weed control using a hand-hoe in CA system is inadequate due to high weed pressure and diversity (Arslan et al., 2014). Several authors have suggested the use of herbicides for weed control in CA systems (Mashingaidze et al., 2012; Muoni et al., 2013). Pre-emergence herbicides such as atrazine, cynazine and alachlor have been used to control weeds effectively in conventional tillage systems. Until recently (Muoni et al., 2014), herbicide effectiveness in CA systems with higher weed density and diversity has not been well-documented in Zimbabwe. There were significant lower weed densities under pre-emergence herbicides compared to hand-hoeing at three weeks after crop emergence (Supplementary Fig. 4; Arslan et al. (2014)).

The effective weed suppression by pre-emergence herbicide during the first six weeks after crop emergence has helped to reduce labour required for early weeding in CA systems. Mixtures of two pre-emergence herbicides or three effectively controlled weeds compared to individual herbicides application (Muoni et al., 2013; Arslan et al., 2014). Application of mixtures of herbicides effectively controlled both grass and broad leaved weeds and also changed weed community structure by reducing weed diversity indices. This has significant implications for weed management strategies. Although application of herbicides can save labour for weed control in CA systems, use of herbicides by smallholders is problematic. Earlier studies have shown that only 2% of smallholder farmers use herbicides in Zimbabwe (Vogel, 1994) although this has increased in the 2000s. This is mainly because farmers in low productivity areas lack the capital to purchase herbicides and associated equipment. Herbicide technology is also knowledge-intensive and thus requires substantial capacity development of smallholder farmers on the correct herbicide application equipment, rate, techniques, timing and as well as safe use of the chemicals (Siziba, 2007). More research is needed that focusses on alternative weed control strategies to reduce costs.

3.4. Economic profitability of CA options

3.4.1. Economic returns of CA options

Table 3 illustrates the details of how NPV was computed using the case of Natural Region II and Table 4 gives the summarised results for all natural regions. The net present values (NPVs) were negative for both CA tillage options in all the three natural regions (Table 4). Thus the value of yield gains in the six years was outweighed by the additional costs of equipment and labour associated with switching to CA options. The profitability of CA tillage options was further reduced by the incorporation of herbicides. This means that the evaluated herbicide option (mixture of glyphosate, atrazine, and metolachlor) adds more costs than the benefits to farmers. Herbicides are supposed to

Table 3

Net economic effects of switching to CA options and net present values (NPV) over six years—computation example in NRII.

	Year						
	1	2	3	4	5	6	NPV
Ripper no herbicide							
Grain (kg)	16.38	−276.93	348.78	678.05	650.86	−433.97	
Grain value ($)	6.14	−103.85	130.80	254.27	244.07	−162.74	
Labour cost ($)	−72.00	−72.00	−72.00	−72.00	−72.00	−72.00	
Equipment cost ($)	3.19	3.19	3.19	3.19	3.19	3.19	
Net economic effect($)	−62.67	−172.66	61.98	185.46	175.26	−231.55	−$4.92
Direct seeder no herbicide							
Grain (kg)	336.00	−152.84	808.35	1365.30	473.02	497.11	
Grain value ($)	126.00	−57.31	303.13	511.99	177.38	186.42	
Labour cost ($)	−171.00	−171.00	−171.00	−171.00	−171.00	−171.00	
Equipment cost ($)	−90.44	−90.44	−90.44	−90.44	−90.44	−90.44	
Net economic effect($)	−135.44	−318.75	41.69	250.55	−84.06	−75.02	−$10.43
Ripper with herbicide	1	2	3	4	5	6	
Grain value ($)	6.14	−103.85	130.79	254.27	244.07	−162.74	
Labour cost ($)	−48.00	48.00	48.00	48.00	48.00	48.00	
Equipment cost ($)	−3.62	−3.62	−3.62	−3.62	−3.62	−3.62	
Herbicide cost ($)	−63.95	−63.95	−63.95	−63.95	−63.95	−63.95	
Net economic effect ($)	−109.43	−219.42	15.22	138.70	128.50	−278.31	−$8.26
Direct seeder with herbicide							
Grain value ($)	126.00	−57.31	303.13	511.99	177.38	186.42	
Labour cost ($)	−147.00		147.00		147.00	−147.00	
Equipment cost ($)	−97.25	−97.25	−97.25	−97.25	−97.25	−97.25	
Herbicide cost ($)	−63.95	−63.95	−63.95	−63.95	−63.95	−63.95	
Net economic effect ($)	−182.20	−365.51	−5.07	203.79	−130.82	−121.78	-$13.77

Assumptions and notes:
All equipment have a useful life span of 15 years.
The annuities methods was used to compute the annual cost of all equipment using an interest rate of 14%.
Hire rate for draught power is US$ 50 per ha.
Wage rate is US$3 per man day and a man day is 8 h long.
Maize price is US$0.375 per kg.
Equipment purchase prices: plough = US$125; ripper = US$ 110; direct seeder = US$550.
NPV computed using a real interest rate of 14%.

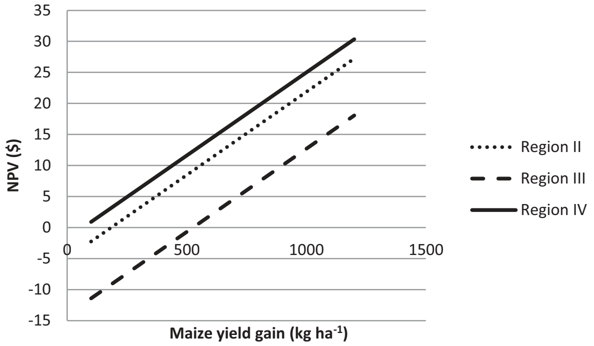

Fig. 5. Ripper breakeven maize yield gains across natural regions II, III, and IV in Zimbabwe. NPV = net present value.

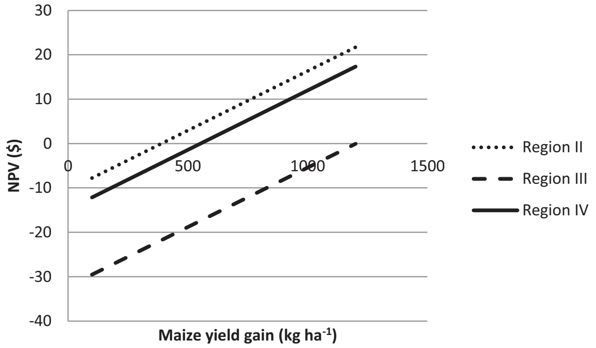

Fig. 6. Direct seeder breakeven maize yield gain across natural regions II, III and IV in Zimbabwe. NPV = net present value.

substitute for the laborious hand weeding. The value of displaced labour, was therefore less than the direct cost of purchasing the herbicides plus the indirect cost of acquiring the knapsack sprayer at the prevailing market prices of all these inputs. Thus given the prevailing yield responses, maize grain prices, equipment costs, labour prices and interest rate, farmers would make economic losses by switching from the conventional system to the CA option (direct seeder and ripper) in the three Natural Regions (II, III, and IV). The ripper option fared better in all the natural regions compared to the direct seeder because of its lower equipment cost. The best performance for the ripper without herbicides was in Natural Region IV (NPV = $ − 1.79) and largely driven by relatively higher maize yield gains over the ox-plough tillage realised in the region. In the relatively dry Natural Region IV, use of the ripper triggered substantial maize yield gains that nearly equalled the cost of additional weeding labour and the relatively lower equipment cost. The relatively equipment cost heavy direct seeder performed best in the wetter Natural Region II.

3.4.2. Breakeven maize yield gains

Generally, less maize yield gains are required with the ripper than with the direct seeder in all natural regions to make CA tillage match ox-plough tillage returns (Fig. 5 Vs Fig. 6). For example, in Natural Region IV, an additional maize yield gain of 125 kg is required in each of the six years with the ripper. An additional yield gain of as much as 1000 kg per year is required for the direct seeder to give equal economic returns as the ox-plough in Natural Region III (Fig. 6). Generally, the additional yield gains, ranging 125–1000 kg, seem relatively high. This is because in addition to covering the cost of labour and equipment, there is need to compensate for the observed negative yield gains that occur in the second year of CA adoption and in some cases even beyond the second year.

Table 4
Net present values (NPV) for switching from conventional tillage to CA tillage options.

	Natural region		
CA tillage option	II	III NPV	IV
No herbicide			
Ripper	−$4.92	−$14.09	−$1.79
Direct seeder	−$10.43	−$32.21	−$14.82
With herbicide			
Ripper	−$8.26	−$17.43	−$5.13
Direct seeder	−$13.77	−$35.55	−$18.16

3.4.3. Breakeven labour savings

Literature shows that labour use increases by 24 mandays ha^{-1} and 57 mandays ha^{-1} for the ripper and direct seeder respectively (Siziba, 2007). Fig. 7 depict labour savings needed to for CA tillage options to realise equal economic returns as the ox-plough at the observed maize yield gains. The less costly ripper generally required less labour savings than the direct seeder in all natural regions. An increment in labour of up to 16 labourdays ha^{-1} was allowable to make the ripper as profitable as the ox-plough in Natural Region IV; in Natural Region II the critical point was zero; and in Natural Region III a labour saving of 30 mandays ha^{-1} was required. For the direct seeder, the Natural Region II had the lowest labour savings requirement (−27 mandays ha^{-1}); this was followed by Natural Region IV (−10 mandays ha^{-1}); and in Natural Region III a positive labour saving (60 mandays ha^{-1}) was necessary. It is noteworthy that the breakeven labour savings for both CA tillage options are lower than actual margins observed in literature, except in Natural Region III.

3.4.4. Overall profitability of CA

At current average CA yield responses and market prices in Zimbabwe, the CA options do not present economic incentives for farmers to adopt. The ripper fared better, because of the lower equipment cost. The labour requirement increases, largely for weeding, present a huge opportunity cost of farmers' labour. Although, this is an implicit cost, it is important because even if farmers do nothing but rest, the opportunity cost of their labour is

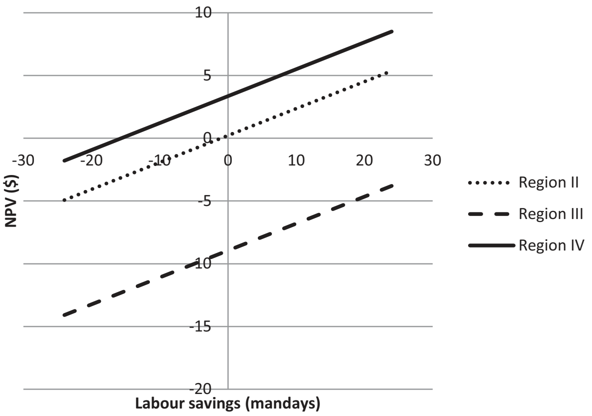

Fig. 7. Ripper breakeven labour savings across natural regions II, III and IV in Zimbabwe. NPV = net present value.

not zero as people attach some value to leisure time (CIMMYT, 1988). The four critical parameters that drive net economic effects of switching to CA are the yield gain advantage, and the cost elements of equipment, herbicides and labour. While we are confident of the yield impact estimate because of the considerable number of studies that quantified CA yield responses, and the relatively large samples and wider geographic coverage (different rainfall, soil type), data on the accompanying labour changes is scanty. The paucity of labour use data could be due to the difficulty of measuring labour. In the current paper, a single study by Siziba (2007), which is based on only seven on-farm trials within one locality in one district, was relied on for labour data. However, through the breakeven curves, the analysis allows evaluation of economic effects under different yield and labour response levels. Though at the averages of the economic effect equation parameters (maize yield responses, prices, and labour use changes) the returns were negative, there are still conditions under which returns could be positive. These would generally be cases where yield responses are maximised and labour increases minimised. The yield gains may be increased by good farmer management or where soils are fertile but moisture is very limiting such in Natural Region IV. Labour increase can be minimised under biophysical environments where weed pressure is naturally low. There are many farmers who may be able to enjoy this niche and realise positive returns. Such prospects are more likely with the ripper in Natural Region IV where best NPVs were realised.

3.5. CA in the broader farming system

In-situ crop harvest residue management is one of the pillars of conservation agriculture (CA) but also the most pronounced barrier to its widespread practice especially on smallholder farms in the tropics (Rusinamhodzi, 2015a). This is because crop and livestock production are closely integrated (Thornton and Herrero, 2001; Rufino et al., 2011) i.e. crop residues are needed to provide livestock feed during the dry season where feed is severely limited while manure is strongly needed for crop production (Rufino et al., 2011; Rusinamhodzi et al., 2013). Due to the communal open-grazing system in the dry season, non-cattle owners need to either invest in fencing or carry their crop residues for protection and bring them back at the start of cropping incurring significant labour costs in the process. Thus the absence of alternative grazing in the dry season due to degraded communal rangelands characterized by poor quality fodder (Rufino et al., 2011), coupled with rejection of potential fodder grass and tree species by farmers (Giller, 2001) means smallholder farmers at present cannot achieve sufficient mulch cover to successfully practice CA (Giller et al., 2009).

3.6. Government policy

Implementation of CA in southern African countries is at different stages, driven by significant policy shifts in some countries and indifference in others. The NGO community plays a major role through advocacy as well as strategic lobbying for external funding for the technology. The government policies around CA are still fragmented. The conditional technical performance of CA often reported have not done much to influence agricultural policy in southern Africa. In Zimbabwe, the government has adopted CA as one of the sustainable technologies that can increase productivity and production and a CA up-scaling framework which targets at least 500,000 farmers practising CA on at least 250,000 ha by the end of 2015 with an average yield of 1.5 t ha^{-1} on CA field (AMID, 2011). CA is not exclusively promoted at policy level thus suggest limited mechanisms to encourage its widespread practice.

3.7. Future research needs

The CA initiatives and experiences in Zimbabwe are largely focussed on the technology and less on the users. Much data are primarily on biophysical impacts, and little effort is committed to understanding and describing the technology user or the “farmer”. In addition, private sector engagement models have been limited. Based on these scenarios, the following aspects were identified as important to shape the future research and promotional efforts on CA in Zimbabwe:

- There is need for studies on farmers’ knowledge, attitude and perceptions on CA on different soil types and agro-ecological zones in order to develop appropriate locally adapted technologies
- There is need to develop and evaluate machinery to ease labour demands experienced especially in the initial stages of CA.
- Public-Private Partnerships, including local level CA land preparation services that provide sustainable access to CA equipment by smallholder farmers, need to be explored and promoted.
- Need more information on cost-effectiveness of herbicide use under different circumstances.
- Research is needed to explore various options to generate sufficient plant biomass for effective cover in CA systems. As most smallholder farms are mixed crop-livestock, more research is needed to better understand the trade-offs between livestock and crop production with specifics on how to make CA fit in systems with high demands for crop residues.
- Because CA is not a maize-only cropping system, research efforts should target adaptation of CA systems to other crops (e.g. cassava, sweet potatoes, tobacco, cotton, small grains etc.)
- Soil health indicators in CA based systems on soil biological, chemical and physical properties should be developed and downscaled for easier understanding by field practitioners, development agents and farmers
- Long-term studies on the impact of CA systems on soil biological, chemical and physical properties are needed to understand the sustainability of the systems
- There is need to establish comprehensive and well-designed studies on the biophysical and socioeconomic boundary conditions for CA adoption.
- Alternative land-use practices need to be explored where CA is not adequate or not possible due to biophysical and socio-economic constraints.
- There is need for more farm-level studies to track the actual yield gains and labour use changes realised by farmers to enable empirical evaluation of CA profitability.
- The niche for CA in the current farming systems could be increased if better farm planning procedures were applied and implemented by farmers.
- The potential effects of CA on climate adaptation and mitigation need to be better understood and quantification of future effects could be assessed through modelling
- Research on policy and institutional studies to support CA adoption on a wide scale is needed.
- Adoption and dis-adoption studies on CA systems on temporal and spatial scales are urgently needed.
- The occurrence and role of termites in mulched land needs further investigation.

4. Conclusions

In Zimbabwe, well-designed long-term CA experiments based on sound agronomic management practices are still scarce. Field-based results show that CA has greater potential to increase yields in some areas more than in others. The results also show that ripline seeding is a more attractive option than direct-seeding in the drier areas. Soil quality assessments show a general increase in biological activity in CA systems but due to the limited studies that have addressed the subject, results are not conclusive. The relative profitability of CA is small, largely because of increased labour costs for weed control. The returns of CA depend on specific yield gains and labour increases per farm, which are influenced by the interactions between the biophysical conditions and the farmer's management. However, data on labour demand in CA systems is very scanty. Prospects of improving profitability are there, especially if labour demand is reduced. The success of CA implementation will largely depend on addressing the challenges together with farmers to find local solutions and to adapt CA system to local conditions. Results from this review suggested that the benefits of CA depend largely on the type of CA being practiced, where, when and by whom. It is thus imperative to profile the technology, the end users (farmers) and the bio-physical environment in which they operate for proper targeting and greater impact. The evidence presented in this study suggests that more longer-term studies beyond ten years are required to fully elucidate the benefits and context of CA practice.

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Appendix A. Studies used in the meta-analysis.

Study	Source	Treatments
Mashingaidze et al. (2012)	Soil and Tillage Research	CP, NT
Mavunganidze et al. (2014)	Crop Protection	CP, NT
Nyamangara et al. (2013a,b)	Agriculture, Ecosystems and Environment	CP, NT
Muoni et al. (2013)	Crop Protection	CP, NT
Thierfelder (2006)	14th International Soil Conservation Organisation Conference—Morocco.	CP,NT
Thierfelder et al. (2006)	CPWD International Forum on Water and Food	CP,NT
Wall and Thierfelder (2008)	SSSA Annual Meeting, Houston, 2008	CP,NT
Thierfelder and Wall (2009)	Soil and Tillage Research	CP, NT
Wall and Thierfelder (2009)	Challenge Program on Water and Food, 2008.	CP, NT
Thierfelder and Wall (2010)	Journal of Crop Improvement	CP, NT, NTR
Thierfelder and Wall (2010)	Experimental Agriculture	CP, NT, NTR
Thierfelder and Wall (2012)	Innovations key for the Green Revolution in Africa	CP, NT, NTR
Marongwe et al. (2011)	International Journal of Agricultural Sustainability	CP, NT
Thierfelder et al. (2012a,b)	International Journal of Agricultural Sustainability	CP, NT, NTR
Thierfelder et al. (2012a,b)	Field Crops Research	CP, NT
Thierfelder et al. (2012a,b)	Soil Use and Management	CP, NT, NTR
Thierfelder et al. (2013)	Field Crops Research	CP, NT, NTR
Thierfelder et al. (2013)	Soil and Tillage Research	CP, NT, NTR
Thierfelder et al. (2013)	International Journal of Agricultural Sustainability	CP, NT
Mupangwa et al. (2007)	Physics and Chemistry of the Earth	CP, NT, NTR
Mupangwa et al. (2012)	Field Crops Research	CP, NT, NTR

CP = conventional ploughing; NT = no tillage, NTR = no tillage with legume rotation.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.01.017.

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