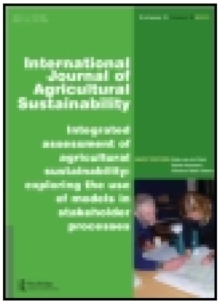

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Integration of conservation agriculture in smallholder farming systems of southern Africa: identification of key entry points

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A component-omission experiment based on the principle of conservation agriculture (CA) was established on smallholder farms for three seasons in Murehwa and Hwedza districts, Zimbabwe; Barue district in Mozambique; Balaka district and Chitedze Research Station in Malawi, and Monze district in Zambia to identify strategies for improving crop productivity and livelihoods for smallholder farmers. The objective of the experiment was to evaluate the effect of tillage, residue retention, fertiliser application and weed control on maize yield. In addition, the study analysed possible combinations of these factors that could provide a sustainable entry point for intensification through CA. Results showed that fertilisation had the strongest effect on crop yield in both tillage systems; adequate fertilisation is therefore key to success in CA. Retention of crop harvest residues increased yield in no-tillage systems; no-tillage without residues depressed yield by 50% when compared with yields of conventional tillage. A step-wise integration of CA into the smallholder farming systems is proposed as a possible strategy to avoid new constraints on smallholder farms. If resources are limiting, farmers may apply all principles on small areas to overcome the initial demand in resources (labour, fertiliser and residues), and once productivity is raised, they can expand.

Keywords: maize yield; no-tillage; residue retention; smallholder farming systems; step-wise integration; sustainable agriculture

1. Introduction

Smallholder agriculture in southern Africa is constrained in many areas by low soil fertility, frequent droughts or excessive water, water run-off and soil erosion, inappropriate and often dysfunctional input–output markets and weak extension systems. As a result, many rural households in the region are malnourished, cannot improve their livelihoods and are food insecure (Dixon *et al*. 2001, Vanlauwe *et al*. 2010). Yields are declining with the current agriculture systems (Figure 1), and land pressure prevents farmers from shifting to more fertile virgin land, and therefore more inputs are required to stem soil fertility decline (Smaling *et al*. 1997).

Maintenance of soil organic matter over time is important for restoration of soil fertility and sustainability of agriculture systems (Bayer *et al*. 2000, Bessam and Mrabet 2003, Wall 2007). Unless farmers can maintain or increase the level of organic matter in their soils, the agricultural production systems cannot be environmentally sustainable, and lead to physical, chemical and biological soil degradation in the long term (Thierfelder and Wall 2011). Among the sustainable options to restore soil fertility and improve crop productivity is conservation agriculture (CA) (Wall 2007, Kassam *et al*. 2009, Thierfelder and Wall 2009). CA is based on minimum soil disturbance, surface crop residue retention (mulching) from previous crops or cover crops, and

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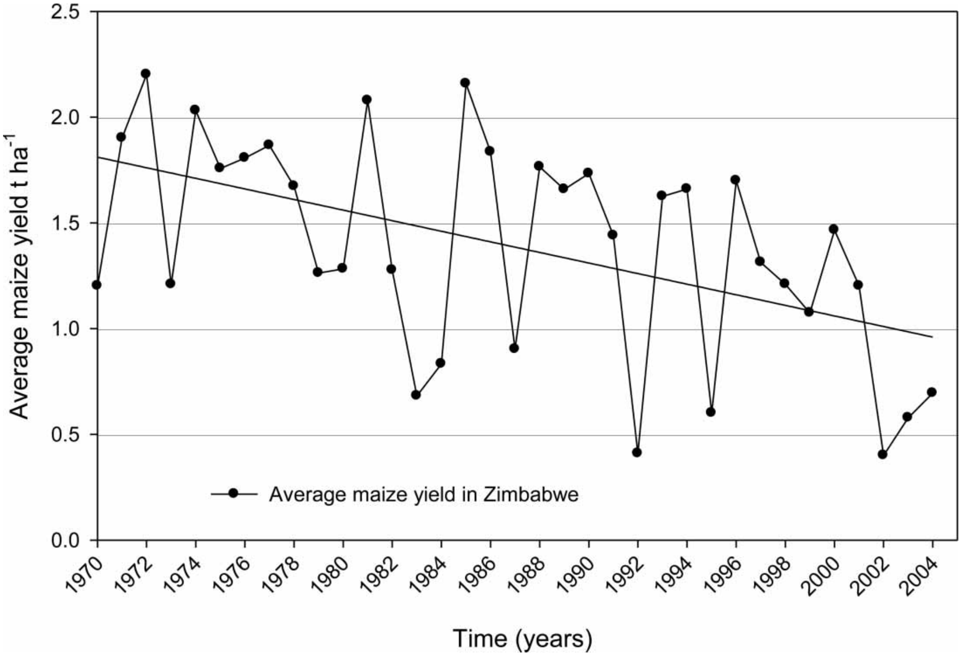

Figure 1. Average maize yield in Zimbabwe (in t ha^{-1}) from 1970–2004 (CSO, 1987; CSO, 1984–1989; FAOSTAT, 2004).

diversified crop rotations or associations (FAO 2002). CA was developed in the America and Australia mostly on large-scale farms and has shown tremendous success in these environments (Bolliger *et al*. 2006). However, the feasibility of CA for smallholder farmers in southern Africa is constrained by biophysical and socio-economic challenges (Giller *et al*. 2009). CA requires increased knowledge of the system and adaptation to the site and farmer circumstances (Wall 2007, Erenstein *et al*. 2012). A special set of cultural practices that are different from traditional plough-based systems need to be acquired (Lal *et al*. 2000). Adaptation to new seeding techniques and fertilisation strategies, new residue management and weed control options, different harvest and crop management procedures is important for the successful implementation of CA (Thierfelder and Wall 2011). Providing evidence that crop production is possible without tilling the soil is the most important stage in encouraging a shift in mindset among farmers so they can move away from the traditional mouldboard plough (Wall 2007).

The integration of CA into smallholder farming systems has to address the prevailing constraints without creating new complex ones. Unlike a new seed variety or a new type of fertiliser, CA involves many simultaneous changes to the farming system, which can lead to complexity (Thierfelder and Wall 2011). However, higher and stable yields are often obtained when all components of CA are implemented. The benefits of CA cannot be realised when soils are depleted of plant nutrients; the soils will not support the production of enough biomass needed for crop residue retention. The obvious and widely accepted strategy to address these constraints would be the use of mineral fertilisers. However, the use of fertiliser among smallholder farmers in southern Africa remains low due to limited market access and high prohibitive cost – i.e. fertiliser costs are between two and six times the cost in America, Europe and Asia (Smaling *et al*. 1997, Sanchez 2002). Some soils do not respond to added chemical fertiliser due to extremely small concentrations of soil organic matter (Tittonell *et al*. 2007). Depending on the farming system, an integrated approach to restore soil nutrients should be pursued along with the practice of CA. Among the possible solutions to overcome soil nutrient limitations are inorganic fertilisers, grain legumes, animal manures, compost, integrated nutrient management and agroforestry (Mafongoya *et al*. 2006, Gilbert 2012).

Research results from Latin America show the importance of crop residues in managing CA systems (Wall 1999, Govaerts *et al*. 2006, Verhulst *et al*. 2010) and most of the benefits in CA are linked to crop residue retention (Erenstein 2002). In southern Africa, smallholder farmers manage mixed crop–livestock systems where animals are used for draught power, produce manure for crop production, contribute to income and risk reduction and document the status of wealth in a community (Valbuena *et al*. 2012). Competing uses of crop residues for soil surface cover and for livestock feed create conflicts and there are strong trade-offs for their efficient allocation (Mueller *et al*. 2001, Thierfelder and Wall 2012).

Another critical factor in the integration of CA is provision of sufficient knowledge to farmers and extension agents on the effects of each component of the CA system on crop productivity. Farmers understand the effect of fertilisation on crop yield, but the effects of reduced tillage and/or residue retention and the combination of these are relatively unknown and little understood. The contributions of each component of the system are also difficult to separate as most of the benefits of the CA systems arise when several components are integrated with each other.

The objective of this study was therefore to analyse the effect of CA component-omission on crop yield in multi-locational trials in Malawi, Mozambique, Zambia and Zimbabwe. The factors tested were tillage, residue retention, fertilisation and weed control. However, one of the three principles of CA – crop rotations and/or associations – was not included. The analysis was also intended to identify a sustainable pathway for the integration of CA into the smallholder farming systems of southern Africa.

2. Materials and methods

2.1. *Sites description*

The trials were carried out in Balaka District (14.99 S; 34.97 E, altitude: 622 m a.s.l.), Malawi in five intervention villages (Ntonya, Zammimba, Njereka, Chifodya and Chimkwezule) and at the Chitedze Research Station (13.97 S; 33.65 E, altitude 1,144 m.a.s.l), Malawi; in Barue District, Mozambique (18.11 S; 33.19 E, altitude: 590 m a.s.l.) in four intervention villages (Mussianharu, Munene, Mvilamiti, Nyamuka), five villages (Wagoneka, Samunderu Nyamutsika Chidhora Nhukarume) in Hwedza (18.37 S; 31.35 E altitude 1,427 m.a.s.l) and four intervention villages (Bruces, Springdale, Kournine, Twin Rivers) in Murehwa Districts (17.74 S: 31.57 E altitude 1,280 m.a.s.l), Zimbabwe and the Malende Agriculture Camp in Monze District (16.24 S; 27.44 E; altitude: 1,103 m a.s.l.), Zambia (Figure 2).

Harvest data were available for three cropping seasons (2008/2009–2010/2011) in Balaka and Barue, two cropping seasons (2009/2010 and 2010/2011) in Chitedze and Hwedza and each one cropping season in Murehwa (2009/2010) and Monze (2010/2011).

All target areas were dominated by maize (*Zea mays* L) production with the highest intensity of this crop being found in Malawi. The sites in Zimbabwe and Zambia are characterised by higher integration between crop and livestock components where crop residues are fed to livestock and manure used for crop production. In Mozambique and Malawi, the level of integration diminishes; most of the sites in Malawi are crop-based farming systems. Rotations with other crops were not widespread in Malawi due to land constraints and relatively small land holdings (World Bank 2007). Groundnuts (*Arachis hypogea*) and tobacco (*Nicotiana tabacum*) and sometimes cassava (*Manihot esculenta*) and tomatoes (*Lycopersicon esculentum*) are common

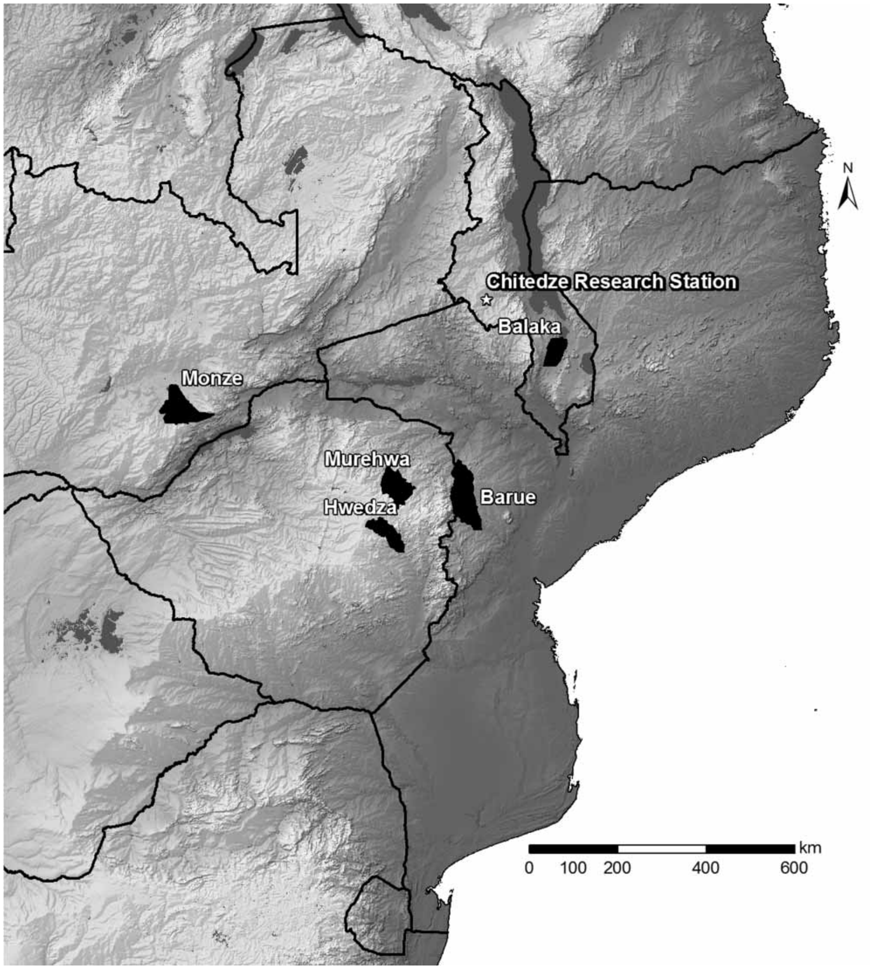

Figure 2. Map of the regional trials in Balaka District and Chitedze Research Station of Malawi, Barwe District of Mozambique, Hwedza and Murehwa District of Zimbabwe and Monze District of Zambia.

rotational crops in Balaka and around Chitedze. In Mozambique farmers grow sorghum (*Sorghum bicolour* L.) besides maize or intercrop maize with pigeonpea (*Cajanus cajan* L.). Common beans (*Phaseolus vulgaris*) and sunflower (*Helianthus annuus*) were grown as cash crops. In Zimbabwe, maize is the main food crop followed by sorghum and groundnuts. Farmers grow beans, sweet potatoes (*Ipomoea batatas*), finger millet (*Eleusine coracana*) and sunflower in rotation or on homestead fields.

The experiments in Balaka, Malawi were established on soils with a sandy-to-sandy loam surface soil texture and average rainfall of about 855 mm per season; at Chitedze Research Station, soils have mainly sandy clay loam texture and the average rainfall is around 960 mm. The sites in Mozambique were mainly on clay loams and the average rainfall of about 1,000 mm per season. The sites in Murehwa, Zimbabwe had mainly sandy loam soils and an average rainfall of 850 mm per season. In Hwedza, soils were sandy and the sites received the lowest average rainfall of 600 mm per season. At Malende, Zambia the soils are sandy clay loams with the average rainfall of 748 mm per season.

2.2. *Experimental design*

The experiment called ‘step trials’ was established in all sites in 2008. It was designed around a series of increasing management steps from a very basic conventional system to a high-input intensive CA system (Table 1). All sites had no previous history of no-tillage and were established on farmers’ fields previously under conventional tillage practices. The treatments consisted of (1) a farmer’s practice with conventional tillage and no fertiliser (CP); (2) conventional tillage and mineral fertiliser (CP+F); (3) a no-tillage system with no fertiliser and no residue retention (NT); (4) no-tillage, with no fertiliser but residue retention (NT+R); (5) no-tillage treatment with no residue retention but fertiliser (NT+F); (6) no-tillage with fertiliser and residue retention (NT+F+R); and (7) a no-tillage treatment with fertiliser, residue retention and chemical herbicide use (NT+F+R+H). Treatment 3 was not applied on all the sites in the 2008/2009 cropping season. The treatments are replicated four times at each location and randomized in a completely randomized block design.

The seven common treatments were slightly different at each site due to different land preparation techniques and local fertiliser application rates. In Malawi the hand hoe was used to make ridges and furrows in the conventional systems and residues were removed. The CA systems were planted with a pointed stick (dibble stick) and residues applied at a rate of 2.5–3 t ha^{-1} if treatments had residues. The population density followed the Sassakawa Global 2000 recommendation of 53,000 plants per hectare, planted in 75 cm rows and 25 cm in-row spacing (Ito *et al*. 2007). Plots were fertilised at 69N:21P_2O_5:4S if treatments had fertiliser, supplied in a basal and top dressing at about 4 weeks after planting. Weed control in treatment 7 was a mixture of 2.5 l ha^{-1} glyphosate (*N*-(phosphono-methyl)glycine) and 6 l ha^{-1} of Bullet® (25.4% Alachlor (2-chloro-*N*-(2,6-diethylphenyl)-*N*-(methoxymethyl) acetamide) and 14.5% atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine) which was applied as a pre-emergence herbicide after planting. All treatments were additionally weeded with a hand hoe when weeds were 10 cm high or 10 cm in circumference. Weeding on all no-tillage treatments was shallow to avoid soil disturbance as much as possible.

In Mozambique, land preparation was manual using hand hoes in the conventional practices. Residues in treatments 1 and 2 were burned *in situ*. In the CA treatment with residues they were retained and a manual jab-planter was used for planting. Fertiliser was applied at a rate of 58N:24P_2O_5:12 K_2O as a basal dressing and one topdressing at 5 weeks after planting if treatments had fertiliser. Weed control was done manually with hand hoes except for treatment 7 in which glyphosate was applied at a rate of 2.5 l ha^{-1} followed by manual weeding.

In Hwedza and Murehwa, Zimbabwe, treatments 1 and 2 were seeded into the soil prepared by the mouldboard plough and into planting basins in treatments 3–7. All residues were removed in the conventional tillage treatments whereas they were retained *in situ* on the CA plots if residues

Table 1. Trial design of the multi-locational ‘step-trial’ in Malawi, Mozambique, Zambia and Zimbabwe.

Treatments	Description	Tillage	Fertiliser	Residues	Herbicides
1	Control, +T, −F	✓	○	○	○
2	Control, +T +F	✓	✓	○	○
3	No-till, −F, −R	○	○	○	○
4	No-till, −F, +R	○	○	✓	○
5	No-till, +F, −R	○	✓	○	○
6	No-till, +F, +R	○	✓	✓	○
7	No-till, +F, +R, +H	○	✓	✓	✓

Notes: Treatment 3 was tested in the 2009/2010 season only.
✓ – yes; ○ – no; T – tillage; F – fertiliser; R – residues; H – herbicides.

were used in the treatments. Fertiliser was applied in fertilised treatments at a rate of $81N:24P_2O_5:12K_2O$ as a basal and top dressing. Weed control in treatment 7 was achieved with glyphosate at a rate of 2.5 l ha^{-1} and manual weeding. All other treatments were weeded with hand hoes four times during each season to reduce weed pressure on crop productivity.

The site in Malende, Zambia followed the same land preparation and management practices as in Hwedza and Murehwa but fertilization was slightly higher at a rate of $109N:34P_2O_5:17K_2O$. For weed control, only glyphosate at a rate of 2.5 l ha^{-1} and manual weeding was applied. All other treatments were weeded with hand hoes as necessary.

2.3. *Yield measurement*

At physiological maturity, maize was harvested from four rows by 5 m from each plot. The harvest area of the net plots was used to extrapolate yields to a hectare basis. A sub-sample of cobs per plot was dried and shelled to calculate grain yield at 12.5% moisture. All maize stalks were weighed at harvest without harvest produce (grain or cobs) and recorded as biomass; one biomass subsample per plot was air dried for at least 4 weeks before final dry weights were taken and biomass was calculated to an area basis.

Harvest data were available for three cropping seasons (2008/2009–2010/2011) in Balaka and Barue, two cropping seasons (2009/2010 and 2010/2011) in Chitedze and Hwedza and each one cropping season in Murehwa (2009/2010) and Monze (2010/2011).

2.4. *Statistics*

Statistical analyses were carried out using Statistix 9 for Windows (Statistix 2008). Yield data were tested for normality and subjected to an analysis of variance using completely randomized block design. Where the *F*-test was significant a least significant difference (LSD) test was used at $p < 0.05$ for mean separation. Binary recursive portioning was used for constructing classification trees by splitting the data into homogeneous binary subgroups or nodes based on the factors tested in this experiment. Node splitting was based on the Gini splitting rule:

$$\mathrm{Gini}(t) = 1 - \Sigma_i p_i^2$$

where p_i is the probability of class i in t (Apté and Weiss 1997). The Gini splitting procedure finds the largest homogeneous category within the dataset and separates it from the remainder of the data; subsequent nodes are then identified the same way until further divisions are not possible (Buntine 1992).

3. Results

3.1. *Crop yield trends*

Results showed that yield benefits were not universal (Table 2); in Balaka, yield ranges were 777–2,675 kg ha^{-1} in the 2008/2009 season, 1,774–5,180 kg ha^{-1} in the 2009/2010 season and 1,281–3,269 kg ha^{-1} in the 2010/2011 season. At the Chitedze Research Station yield ranged from 1,667 to 4,321 kg ha^{-1} in the 2009/2012 season and 1,942–5,524 kg ha^{-1} in the 2010/2011 season. In Barue, yield ranges were 894–1,409 kg ha^{-1} in the 2008/2009 season, 1,974–4,099 kg ha^{-1} in the 2009/2010 season and 1,272–4,168 kg ha^{-1} in the 2010/2011 season. In Hwedza, yields ranged between 866 and 2,486 kg ha^{-1} in the 2009/2010 season and then 307–975 kg ha^{-1} in the 2010/2011 season. In Murehwa, yields ranged between

Table 2. Crop yield as affected by tillage, mulch, fertiliser and weed control across six districts and three seasons in southern Africa.

Site	Treatment	Year		
		2008/2009	2009/2010	2010/2011
Balaka, Malawi	Conventional tillage	777	2,032	1,281
	Conventional tillage + F	2,203	3,724	2,606
	No-till	n.a.	1,774	1,819
	No-till + R	832	2,291	2,070
	No-till + F	2,675	3,104	2,150
	No-till + R + F	2,161	4,901	2,654
	No-till + R + F + H	2,314	5,180	3,269
Chitedze, Malawi	Conventional tillage		2,420	2,522
	Conventional tillage + F		4,199	4,990
	No-till		1,667	1,942
	No-till + R		2,379	2,648
	No-till + F		3,372	4,828
	No-till + R + F		4,314	5,079
	No-till + R + F + H		4,321	5,524
Barue, Mozambique	Conventional tillage	1,001	2,937	2,630
	Conventional tillage + F	1,247	4,099	4,057
	No-till	n.a.	1,974	1,272
	No-till + R	894	2,283	1,774
	No-till + F	1,153	3,411	2,910
	No-till + R + F	1,409	3,328	4,168
	No-till + R + F + H	1,029	3,808	4,057
Hwedza, Zimbabwe	Conventional tillage		866	370
	Conventional tillage + F		1,769	879
	No-till		867	307
	No-till + R		1,157	355
	No-till + F		1,930	681
	No-till + R + F		2,166	975
	No-till + R + F + H		2,486	663
Murehwa, Zimbabwe	Conventional tillage		1,463	n.a.**
	Conventional tillage + F		2,957	n.a.
	No-till		1,223	n.a.
	No-till + R		1,543	n.a.
	No-till + F		2,509	n.a.
	No-till + R + F		2,699	n.a.
	No-till + R + F + H		3,114	n.a.
Monze, Zambia	Conventional tillage			3,577
	Conventional tillage + F			5,843
	No-till			3,087
	No-till + R			3,002
	No-till + F			5,842
	No-till + R + F			5,904
	No-till + R + F + H			4,828
SED		113	272	415

Note: Means per site in each country are based on five locations in Balaka and Hwedza, and four locations in Barue and Murehwa; at each location, the experiment is replicated four times. **Sites in Murehwa did not harvest anything due to a prolonged dry spell. R = residues; F = fertiliser; H = herbicides.

1,223 and 3,114 kg ha^{-1} in the 2009/2010 season. In 2010/2011, the site was hit by drought and no crop was harvested. In Monze, yield ranges were 3,002–5,904 kg ha^{-1} in 2010/2011.

Across sites, yields were depressed in the 2008/2009 season but increased significantly in the following two seasons. In the absence of crop residue cover, conventional tillage resulted in

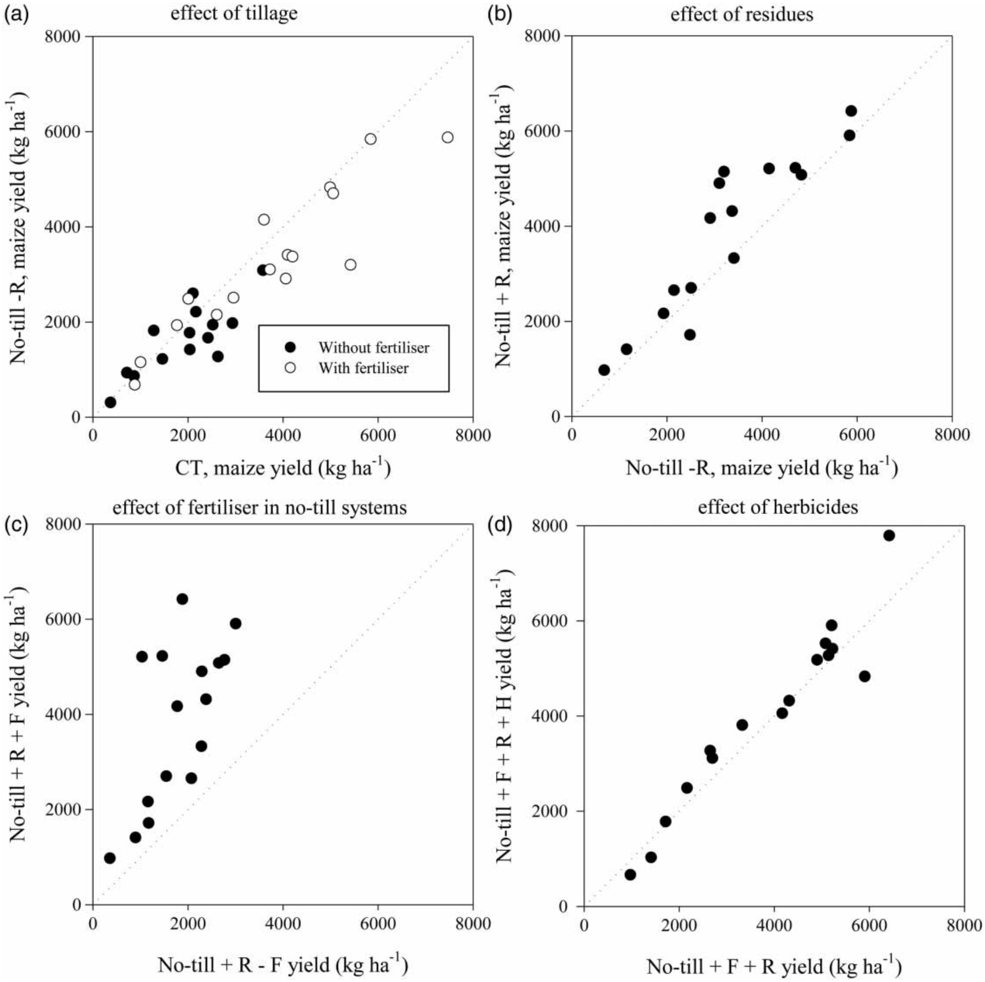

Figure 3. Effect of key components of conservation agriculture systems on crop yield. Yields of the specific component on the x-axis are put in context with yields of the other component on the y-axis. If both components are equal, they should be on the 1:1 line: (a) effect of tillage; (b) effect of residues; (c) effect of fertiliser in no-till systems; (d) effect of herbicides.

relatively more grain yield compared with no-tillage (Figure 3a). There was a positive yield response to no-tillage with residues instead of without (Figure 3b). Results showed that fertiliser application was important as its application more than doubled yield (Figure 3c). The use of herbicides was not beneficial over hand weeding on crop yield (Figure 3d).

Although the difference between NT with herbicides and NT with manual weeding was small, NT with herbicides was the best performing in four sites (site × season). The NT with residues and manual weeding was the best performing treatment in only one site, i.e. Monze.

3.2. *Effect of the components tested*

Treatment (tillage × fertiliser application), site and season had a significant effect on maize grain yield ($p < 0.001$). However, the interaction between these factors was weak. Decision trees

(Figure 4) constructed through the binary recursive procedure split the data at first based on tillage and fertiliser treatment suggesting that ‘treatment’ had an overruling effect on yield. The second most important factor was the site; sites were split into two, based on yield potential. Monze and Chitedze sites were considered as generally high-yielding sites; Balaka, Barue, Hwedza and Murehwa were grouped into the low-yielding category. Hwedza could be further isolated into its one group as the site with the least yield potential. The least important factor was the cropping season; the 2009 season was considered the lowest yielding compared with seasons after 2009. The effect of season on crop yield was apparent but the differences between treatments and control were maintained over the experimental period.

Overall, fertiliser application had a significant effect on crop yield regardless of tillage (Figures 3c and 4). Conventional tillage with sufficient fertiliser application yielded just as much as no-till with fertiliser application (Table 3). The omission of CA components had a significant effect on crop yield. Generally, there was more treatment effects in Malawi, Mozambique and Zambia compared with the Zimbabwean sites.

4. Discussion

The field results suggest that nutrient management and not the tillage has an overriding effect on crop yield despite the diversity in biophysical conditions. The retention of crop residues in adequate quantities to provide soil cover and fertiliser application under no-till practices provides the most yield benefits for farmers (Figure 3b). The sites studied often suffered mid-season dry spells; thus retention of mulch had an important role in moisture conservation and subsequent yield benefits compared with conventional tillage. However, this benefit only became apparent when residue application was combined with fertiliser. A number of authors have reported mulch retention as very important in semi-arid and sub-humid environments despite the challenge to find enough biomass for residue retention (Lal 1978, Roth *et al*. 1988, Mupangwa *et al*. 2007, Wall 2007, Thierfelder and Wall 2009). Besides increased crop yields, no-tillage with adequate crop residue retention has been found to maintain higher levels of soil organic matter, total N, and exchangeable bases than tilled plots (Lal 1976). These are likely to contribute to improvement in soil fertility and larger yields in the long term (Govaerts *et al*. 2005).

No-till practices without mulch depressed yields compared to conventional tillage. No-till without mulch cover often leads to soil crusting, reduce infiltration and moisture available to the crops (Thierfelder *et al*. 2005). When rainfall is sufficient and well distributed, the effect of tillage method on plant growth, root distribution, and crop yield is often minimized compared with drier years (Cassel *et al*. 1995). Intense rainfall on the unprotected soil surface will lead to surface sealing which may reduce yields (Freese *et al*. 1993). These findings suggest that if insufficient soil cover is available, routine and systematic disturbance of the soil surface with hand-hoes might be a useful strategy for breaking up soil surface crusts which could temporarily increase water infiltration (Belnap 1995). However, this is not a sustainable practice as this will further break down organic matter through increased aeration and higher decomposition (Thierfelder and Wall 2012).

Response to fertiliser, especially N, was very high; this confirms that N is the most limiting nutrient in the sites studied. Relatively more N input is required under NT than under CT although the yield differences between tillage methods are often small under semi-arid conditions (Liu and Wiatrak 2012). Smallholder farmers need to invest in fertilisers in order to realise the full benefits associated with CA. However, the results show that fertiliser is equally required for conventional agriculture to reap the benefits.

The lack of a clear response to herbicides application in comparison to hand-weeding suggests that hand-weeding is equally effective in controlling weeds or that herbicides application is as

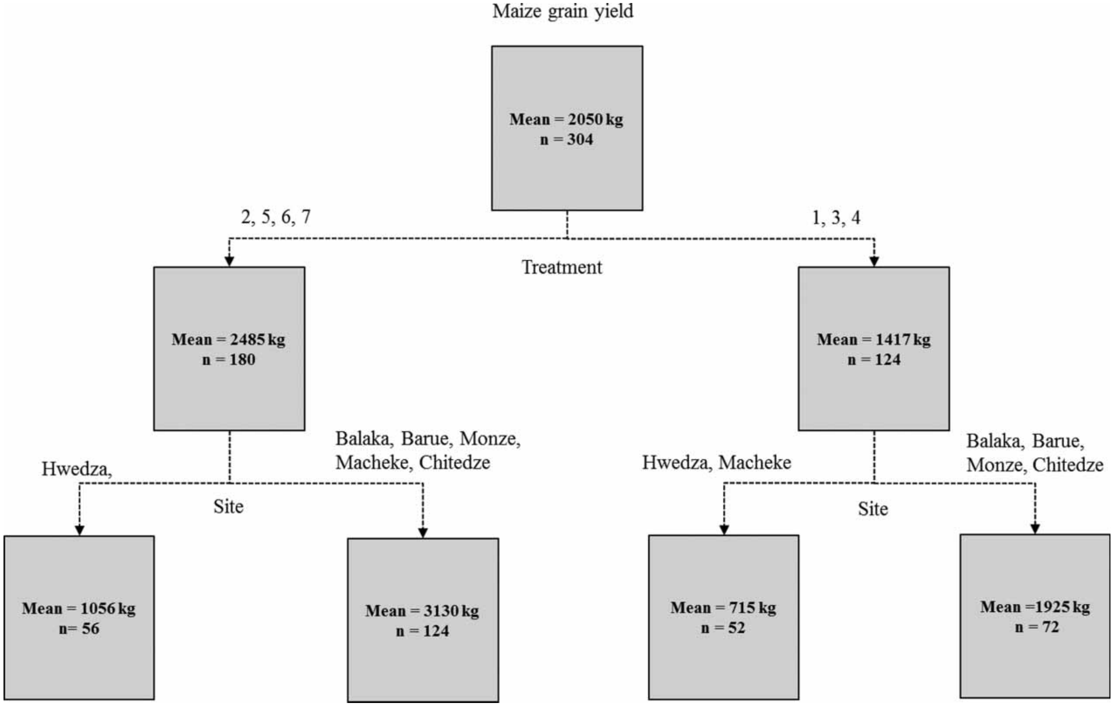

Figure 4. Decision trees constructed by the binary recursive partitioning procedure for maize grain yield (2008–2011) from ‘step trials’ in southern Africa. For each node, the average yield and the number of cases (*n*) are given. Treatments are described in Table 1.

Table 3. Crop yield as affected by tillage, mulch, fertiliser and weed control across the experimental sites.

Treatment	Malawi Balaka	Malawi Chitedze	Mozambique Barue	Zimbabwe Hwedza	Zimbabwe Murehwa	Zambia Monze
CT	1,593	2,471	2,425	618	1,463	3,577
CT + F	2,833	4,595	3,392	1,324	2,957	5,843
No-till	1,796	1,805	1,573	587	1,223	3,087
No-till + R	1,893	2,514	1,748	756	1,543	3,002
No-till + F	2,586	4,100	2,687	1,306	2,509	5,842
No-till + R + F	3,188	4,697	3,275	1,570	2,700	5,904
No-till + R + F + H	3,526	4,923	3,301	1,574	3,114	4,828
SED	254	494	263	150	375	715

R, residues; F, fertiliser; H, herbicides.

effective as hand-weeding. Herbicides in combination with minimal weeding have been found to be effective and economically beneficial to farmers in no-tillage systems (Mishra and Singh 2012, Ngwira *et al*. 2012, Rashid *et al*. 2012). However, in most smallholder farming systems, the absence of opportunity costs for labour could make herbicides more expensive in the perception of farmers. The weeding with hand-hoes results in increased soil movement, especially when complicated weed species such as couch grass (*Cynodon dactlon* L.) or wandering jew (*Commelina benghalensis* L.) are present and farmers heavily disturb the soil to eliminate the stolon roots of these weed species. Herbicides should therefore be used in such cases to ensure minimum soil movement.

Although it is very difficult to assign a specific effect to the individual components of the CA system due to its mutually reinforcing characteristics, fully factorial trials on CA that separate the effect of each component from others (Rusinamhodzi *et al*. 2011) may provide useful insights into the starting point to integrate CA into the smallholder farming systems. It will, however, be necessary to also incorporate the principle of rotation and/or association to get a clear answer to this research question.

A step-wise incorporation of CA principles into the farming system could be one strategy that may allow farmers to practice CA without making drastic changes to their present farming system (Figure 5). Farmers may start by not tilling the soil and gradually concentrate available resources on their fields, increase the productivity, and thereby increase the biomass production that may provide both livestock feed and soil cover. High biomass production has been found as one of the key requirements for the successful practice of CA in mixed crop–livestock systems (Valbuena *et al*. 2012). However, as our results show, no-tillage without residues and fertiliser application may lead to yield penalties in the beginning. Reduction in risk and the ability to meet food security as well as feed and mulch requirements will facilitate the widespread uptake of the technology over time.

The results show that the largest yield in CA systems can be expected if no-tillage, residue retention and fertilisation are implemented from the beginning. A slightly different approach could therefore be more beneficial for smallholder farmers when sufficient resources are available. Farmers could, instead of a step-wise implementation of one component after the other, simultaneously apply all principles on small areas of their farms. By concentrating their inputs (fertiliser and maybe herbicides) and resources (residues) on a small manageable area they can increase the productivity of this land much faster and benefit more in the short term. Once they have mastered the management and other resource demands on this small piece of land, they can expand to other areas depending on their landholding, and increase yield, income and food security over time.

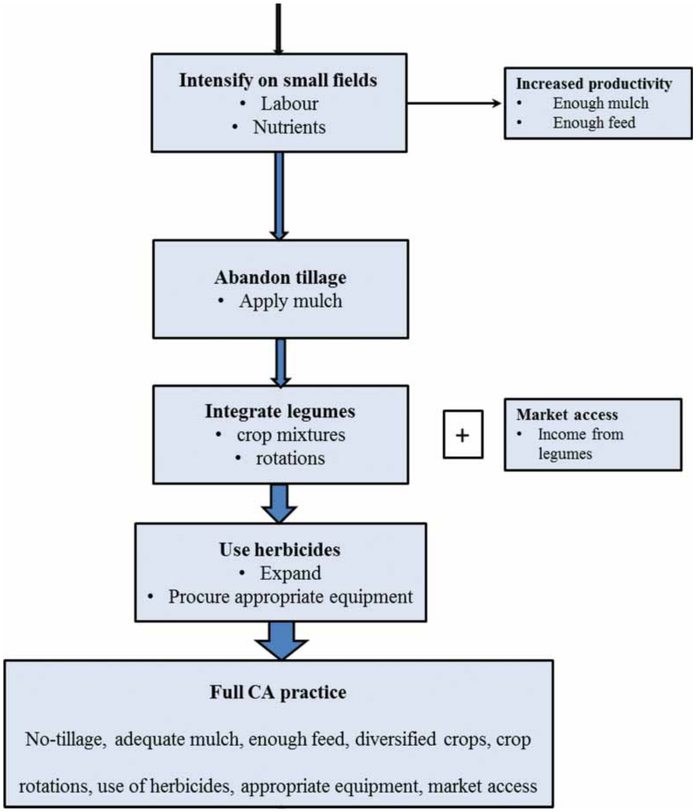

Figure 5. A sustainable pathway to the full integration of CA in the smallholder farming systems of southern Africa.

5. Conclusion

Retention of previous crop harvest residues and fertiliser application is critical for the success of CA systems. When insufficient crop residues are available for soil cover, soil crusting and sealing may occur, leading to reductions in rainfall infiltration and ultimately small crop yields. Results suggest that N deficiencies should be addressed in order to realise the full benefits of CA systems. Hand-weeding and herbicides application are both effective in weed control; herbicides use should, however, be promoted in order to reduce soil movement. A step-wise integration of CA in the smallholder farming systems is proposed as a possible strategy to avoid creating constraints. However, if sufficient resources including adequate amounts of crop residues are available, practising all principles of CA from the onset may provide the best yield in the cropping system.

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