Conservation agriculture in Southern Africa: Advances in knowledge

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Abstract

The increasing demand for food from limited available land, in light of declining soil fertility and future threats of climate variability and change have increased the need for more sustainable crop management systems. Conservation agriculture (CA) is based on the three principles of minimum soil disturbance, surface crop residue retention and crop rotations, and is one of the available options. In Southern Africa, CA has been intensively promoted for more than a decade to combat declining soil fertility and to stabilize crop yields. The objective of this review is to summarize recent advances in knowledge about the benefits of CA and highlight constraints to its widespread adoption within Southern Africa. Research results from Southern Africa showed that CA generally increased water infiltration, reduced soil erosion and run-off, thereby increasing available soil moisture and deeper drainage. Physical, chemical and biological soil parameters were also improved under CA in the medium to long term. CA increased crop productivity and also reduced on-farm labor, especially when direct seeding techniques and herbicides were used. As with other cropping systems, CA has constraints at both the field and farm level. Challenges to adoption in Southern Africa include the retention of sufficient crop residues, crop rotations, weed control, pest and diseases, farmer perception and economic limitations, including poorly developed markets. It was concluded that CA is not a ‘one-size-fits-all’ solution and often needs significant adaptation and flexibility when implementing it across farming systems. However, CA may potentially reduce future soil fertility decline, the effects of seasonal dry-spells and may have a large impact on food security and farmers’ livelihoods if the challenges can be overcome.

Key words: conservation agriculture, mulching, no-tillage, rotation, sustainable intensification, Southern Africa

Introduction

The increasing demand for food from limited land resources requires new sustainable ways of food production. Short-term needs of farmers must be balanced with long-term environmental sustainability. The solutions must be viable at the field, farm and community levels, and beyond. They need to take into account the complexity of the systems in which farmers operate1,2 and the environmental implications their actions might have3.

Farming systems in Southern Africa are constrained by numerous factors, including inherently infertile sandy soils in some areas4,5, drought6 and limited access to, and use of, mineral and organic fertilizers7–9. Average annual fertilizer use in sub-Saharan Africa is below 10kg ha−1 of NPK fertilizer,7,10, significantly smaller than in Asia and Latin America11. Farmers own relatively small land holdings; e.g., in Malawi the average household land size is <1.2 ha12, and maize is often grown in monoculture with few legumes or other crops in rotation13,14. Markets for both agricultural inputs and outputs are not well developed, leading to high input and low output prices15.

Since the 1920s, the moldboard plow has been used as a land preparation tool in Southern Africa in an attempt to reduce labor requirements, bury weeds, mobilize nutrients and prepare a fine soil tilth16,17. Intensive use of the plow is reported to have increased chemical, physical and biological soil degradation18,19, and increased soil erosion.
and run-off, soil crusting and sealing, reduced aggregate stability, limited water infiltration and less available soil moisture have been documented. In manual systems since the 1930s in Malawi, smallholder farmers have been encouraged to plant crops on ridges, rather than on the flat or in mounds. Crop ridges are constructed using a broad-bladed hoe and, in the next season, the ridge is split and reformed in the previous furrow. There is a growing body of evidence that the continued use of a hoe to the same depth results in the formation of a compacted horizon immediately below the ridge. The intensive cultivation of soils has led to losses in soil carbon and reductions in biological activity. However, there are also conflicting results from the region and elsewhere that show no causal relationship between intensive tillage and carbon loss. Limited retention of surface crop residues adds to the decline in soil carbon in conventional systems. Furthermore, accelerated soil erosion in tilled systems decreases the amount of important plant nutrients (e.g. N, P and K) through the loss of arable top-soil.

Recently there has been increased demand for ‘greener’ solutions to tackle the soil fertility decline in Southern Africa. The way to achieve this is uncertain and often contested. Different approaches have been proposed to increase the productivity of land, ranging from simple technology interventions, such as increased fertilizer use and/or improved seed varieties, to more systems-oriented solutions, such as agroforestry, permaculture, integrated crop-livestock systems or conservation agriculture (CA). Breeding improved varieties is often proposed as a direct route to increasing crop productivity and closing the yield gaps in the environments of smallholder farmers in Southern Africa. However, it is rather unlikely that one single intervention such as seed or fertilizer will solve all of the smallholder farmers’ challenges and thus combinations of synergistic technologies are required.

CA, a crop management system of three basic principles applied in a mutually reinforcing manner, has been proposed as one of the options to alleviate soil fertility decline. CA is based on a combination of: (1) minimum soil disturbance, i.e., no soil inversion with the plow or hoe; (2) surface crop residue retention as mulch with living or dead plants; and (3) crop rotations and associations of different crop species over time. Commonly used terms in CA and conventional tillage systems are described in Table 1. CA is widely adaptable and the application of its principles may vary among individual farmers depending on the site and the farmer’s circumstances.

Over the past 40 years, the application of CA within large-scale commercial farming systems has greatly expanded in Latin America, the United States and Australia. Based on these successes there was a major push by the international donor community in the late 1990s to also adapt this cropping system for smallholder farmers in Southern Africa. Nevertheless, concerns were raised about the widespread promotion of CA in Southern Africa without adequate (research) evidence that CA increases yields and livelihoods of farmers and improves soil quality indicators. Giller et al. argued that farmers can only apply CA in certain ‘niches’ under very specific circumstances, which was contested by many scholars, with opinions summarized on this website. Related studies questioned the suitability of CA for the majority of farming systems in Southern Africa and stated that an ‘across-the-board recommendation of conservation agriculture’ would be wholly misplaced, and this sparked further debate.

One of the main arguments against promoting CA in Southern Africa is that CA was successfully applied within large-scale, mechanized commercial farming systems in the Americas and Australia, and little was known about its potential to increase productivity and reduce soil degradation within the smallholder farming systems of Southern Africa, where small and fragmented landholdings are common and the farming systems are generally more complex.

Like all agricultural technologies, CA cannot be considered as a panacea to all farmers’ problems under all circumstances, and hence the ‘one-size-fits-all’ argument can hardly be defended. Nonetheless, there is increasing empirical research evidence on the merits and demerits of farm-level application of CA in Southern Africa. This review summarizes and synthesizes the immediate farm-level impact of CA in the region, focusing mainly on publications based on multi-year on-station and on-farm trials. The paper is structured as follows: the section ‘Effects of CA on Smallholder Cropping Systems’ synthesizes the effects of CA on smallholder cropping systems in Southern Africa and the section ‘Constraints to Adoption of CA Systems in Southern Africa’ presents a detailed analysis of the biophysical and socio-economic challenges that hinder the adoption of CA in the region. Finally, the brief conclusion focuses on the key lessons learned from the empirical evidence synthesized.

**Effects of CA on Smallholder Cropping Systems**

Initial research from 1988 to 2002 largely focused on the effects of CA on soil quality, such as the effects of selected CA and non-CA systems on soil erosion, carbon, weeds and water dynamics. These studies from Zimbabwe highlighted that reduced tillage and mulch cover reduced erosion and increased soil moisture, which led to overall greater yields, especially in dry years. The results also showed that timing of planting and other operations was more important than the type of tillage system employed, particularly in the sub-humid parts of the country.
Table 1. Commonly used terms in conservation agriculture and conventional crop management systems of Southern Africa.

<table>
<thead>
<tr>
<th>Agricultural practice</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conservation agriculture practices</strong></td>
<td></td>
</tr>
<tr>
<td>Basin planting (also called pot-holing and conservation farming)</td>
<td>A technology, developed by the Zimbabwean commercial farmer Brian Oldrieve, based on manually dug planting basins of different sizes (15 cm × 15 cm × 15 cm in Zimbabwe and 15 cm × 30 cm × 25 cm in Zambia). Basins are constructed during the winter season thereby spreading labor requirements during the off-season.</td>
</tr>
<tr>
<td>Ripping (also called rip-line seeding, MR and tine ripping)</td>
<td>Ripping and rip-line seeding practice developed in Southern Africa based on seeding with an animal traction chisel-tine opener (the Magoye ripper) that is mounted on a plow beam. Rip-lines are created in April (Zambia) or at the onset of the cropping season in November (Zimbabwe). Sometimes opening wings are used on the ripper attachment (mainly for sandy soils). The implement creates a furrow of approximately 10–15 cm width and 10 cm depth.</td>
</tr>
<tr>
<td>Direct seeding (also called seeding with a dibble stick, pointed stick, jab-planter and animal traction direct seeding)</td>
<td>There are currently three direct seeding systems used in Southern Africa. Seeding with a dibble stick (a pointed stick) where farmers make two holes and place seed and fertilizer. A more mechanized version is the jab-planter (matracas) that supplies seed and fertilizer in planting holes created by the implement. Finally there are animal traction direct seeding systems using Brazilian and locally produced direct planters, where the implement creates a rip-line, supplies seed and fertilizer and covers the line in one operation.</td>
</tr>
<tr>
<td>No-till tied ridging</td>
<td>This is generally not considered a CA seeding system due to considerable soil movement during land preparation. In this system, farmers create ridges and furrows using hand-held hoes. Ridges are closed every 80–100 cm across the ridge direction to conserve rainfall water. The systems has proved to be an efficient water conserving technology but cannot be classified as CA in the strict sense.</td>
</tr>
<tr>
<td>Residue retention (also called mulching)</td>
<td>Describes the retention of crop residues [living or dead plant material such as maize stalks, leaves or mowed green manure cover crops (GMCCs)] in the form of surface mulch. Different to some conventional systems, it is not incorporated with the plow and should lead to good groundcover (30% or more) for erosion control and reduced evaporation.</td>
</tr>
<tr>
<td>Intercropping</td>
<td>A crop-association practice where the main crop (commonly maize in Southern Africa) is interplanted with other crops. Grain legumes (e.g. cowpea, pigeonpea, common beans, groundnuts), are the most prevalent intercropping species in Southern Africa but GMCCs (such as velvet beans, lablab and fish bean) are also used.</td>
</tr>
<tr>
<td>Rotation</td>
<td>Rotation is the repetitive sequence of crops in the same place in a defined order. Farmers in Southern Africa generally practice rotations between maize and leguminous crops (cowpeas, soybeans, groundnuts, common beans), green manure crops and non-leguminous cash crops (cotton, sunflower and cassava).</td>
</tr>
<tr>
<td>GMCC</td>
<td>Green manure cover crops are crop species planted under CA for the purpose of groundcover and fertility improvement. Common species used for GMCC include velvet beans, lablab and sunnhemp.</td>
</tr>
<tr>
<td><strong>Conventional agriculture practices</strong></td>
<td></td>
</tr>
<tr>
<td>CMP</td>
<td>Conventional moldboard ploughing (CMP) is normally performed using a single-row moldboard plow to a shallow depth (10–15 cm). Plowing completely inverts the soil and prepares a clean seedbed with fine tilth, depending on the soil type. Farmers plow their land either during the off-season (July–August) or at the onset of the cropping season in November, once the soil is soft after the first rains.</td>
</tr>
<tr>
<td>Tillage</td>
<td>Often synonymously used with moldboard plowing but can also be done with implements like disk harrows or hand hoes.</td>
</tr>
<tr>
<td>Monocropping</td>
<td>In contrast to rotation and intercropping systems, monocropping is the repeated planting of the same crop or crops in the same place year after year. This system is often practiced in rural areas of Southern Africa with cereals (maize and sorghum) or cassava. In some areas maize is continuously grown for 3–4 seasons and then rotated for one season with either groundnuts or cowpeas.</td>
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Note: seeding systems are described in Johansen et al. and Sims et al.

**Effects of CA on infiltration and soil water**

Rainfall distribution patterns during the growing season in Southern Africa are characterized by mid-season dry spells. Thus, higher infiltration rates under CA and surface crop residue retention have the potential to buffer growing crops against intermittent periods of drought stress. The effect of CA on water infiltration and soil moisture in Southern Africa has already been reported in detail by Thierfelder and Wall. No-tillage and residue retention increase infiltration rates, an effect which appears almost immediately when the soil is covered with mulch. Infiltration measurements at Henderson Research Station, Zimbabwe and Monze Farmer Training Centre, Zambia with a mini-rainfall simulator showed clearly that CA treatments were able to maintain higher infiltration rates compared with conventionally plowed treatments without residue retention across sites.
This increase in infiltration rate was mainly due to an increase in biological activity, reduction in soil surface disturbance and the continuity of macropores. Similarly, studies conducted under the semi-arid conditions of Zimbabwe showed that over time CA practices improved hydraulic properties (unsaturated hydraulic conductivity and capillary sorptivity) of a clay loam soil. However, studies also showed that the effect of CA on water infiltration was dependent on soil type, with the potential negative effect of waterlogging on granitic sandy soils, which have a tendency to accumulate too much water.

Water balance studies over a 5-year period (1994/5–1998/9) on clay soils at Hatcliffe, Zimbabwe by Nyagumbo, allowed water losses through runoff and evapotranspiration to be compared between a CA system in the form of mulch ripping (MR) and conventional moldboard plowing (CMP). Using an improved simple water balance technique derived in situ over five seasons (1994/5–1998/9), only 26% of the total rainfall under CMP was contributed to groundwater recharge compared with 50% under MR. Average runoff of seasonal rainfall was also reduced under MR, with only 1% of rainfall lost due to run off compared with 20% under CMP. Although the difference between seasonal evapotranspiration under CMP and MR was small (51% compared to 46%) soil moisture storage within the top 45 cm of soil was significantly greater under MR compared with CMP (Fig. 2). Field water balance modeling studies in South Africa showed that no-till systems (rip-line seeding systems without mulch retention) reduced surface runoff by 28% and increased deep drainage by 19% on a sandy clay loam soil compared to CMP.

Studies on soil moisture by Thierfelder and Wall confirmed that CA treatments on an Arenosol at Henderson, Zimbabwe and a Lixisol at Monze, Zambia, had more available soil moisture than conventionally plowed treatments. The results of these studies showed
that CA techniques increase soil water balance attributes when compared with conventional plowing. Furthermore CA systems often resulted in higher water productivity compared to conventional plow-based tillage systems, by up to $\pm 10 \, \text{kg ha}^{-1} \, \text{mm}^{-1}$, depending on seasonal rainfall patterns\textsuperscript{59}. Only one study has been conducted on deep drainage and leaching on a granitic sandy soil, using lysimeters, at Domboshawa Training Centre, Zimbabwe. The results suggest no-till tied ridging system resulted in 21% more deep drainage and consequent nitrate leaching than CMP\textsuperscript{60}, which could potentially have negative effects on plant growth.

In summary, CA generally increases water infiltration and improves available soil moisture. This can potentially reduce the negative effects of in-season dry spells, reduce run-off and provide more available water for plant growth. Nevertheless, there are also findings that water infiltration in CA systems is dependent on soil type, with the potential negative effect of waterlogging on granitic sandy soils\textsuperscript{23,30}.

**Effects of CA on physical and biological soil quality attributes**

Studies on physical and biological properties in Zambia showed more stable soil aggregates (41–45%) in directly seeded CA systems compared with the conventional system (24%)\textsuperscript{13} (Fig. 3). This stability promoted better water infiltration and soil water storage in the directly seeded CA systems compared with the conventional practice. Stable soil aggregates protect soil organic carbon (SOC) and improve soil structure under CA or no-till systems on soils with 22% clay and 7% silt\textsuperscript{67}. In Zimbabwe, the positive impact of CA on soil aggregate stability was observed on both light and heavy textured soils under semi-arid and sub-humid conditions\textsuperscript{30}.

In the semi-arid southern regions of Zimbabwe, bulk density of a clay loam soil decreased over time in CA systems (rip-line seeding systems and planting basins) compared with the conventional practice\textsuperscript{68}. Soil bulk density is a function of soil texture, SOC content and aggregate stability\textsuperscript{69}. In a long-term tillage experiment on both red clay and sandy soils under sub-humid climate conditions, Nyagumbo\textsuperscript{59} observed significantly lower top soil bulk densities under MR compared with CMP on both sandy soils and clay soils. In sandy soils, significant differences were apparent only in the top 0–10 cm and greater bulk densities were recorded under conventionally plowed plots. On clay soils, significantly lower bulk densities in MR compared to conventionally plowed plots were observed at depths of 10–40 cm. The higher bulk density of the top soil under plowed uncovered fields was attributed to faster disintegration of soil aggregates by the impact of raindrops, which resulted in surface compaction, particularly in sandy soils with poor soil structure\textsuperscript{70}. These results suggested that physical benefits are associated with reduced tillage management, although soil type plays a critical role. Tillage is often promoted as a way of loosening up the soil before planting. The results do, however, suggest that this is only a temporary measure as most soils quickly lose their stability after tillage, slump and lead to even greater compaction\textsuperscript{43,71}.

There is general agreement that no-tillage and residue retention increases infiltration and reduces surface run-off leading to lower erosion rates\textsuperscript{23}. A 4-year study under rainfed conditions in Ethiopia\textsuperscript{72}, comparing CA and a conventionally plowed control (CP) showed that CA reduced soil erosion and run-off. In Zimbabwe, an 8-year
study showed increased average annual soil losses of 5.1 $\text{tha}^{-1}$ under conventional plowing compared with 1.0 $\text{tha}^{-1}$ under MR without soil inversion but residue retention. Recently, Thierfelder et al. showed that larger increases of cumulative soil erosion occurred on conventionally plowed fields compared to rip-line seeded CA treatments with sole maize or maize–legume intercropping (Fig. 4).

CA has also been associated with increased soil biological activity. Nhamo showed that there was more abundance and activity of soil biota under maize-based CA cropping systems than with conventional practice, both on an experimental research station and on-farm in Zimbabwe. Under residue-covered fields, termites were more abundant, particularly in the sandy soils. Tillage and removal of residue disturb their habitats and also limit energy sources for termites, while different mulches (maize or grass residues) that contain cellulose and crude protein attract termites. Increases in termite numbers show a clear effect on increased biological activity. This does not necessarily translate into entirely positive effects (i.e., increased nutrient mobilization through residue decomposition) as crops (especially cereals) might be attacked by specialized termite species, especially toward harvest when residue cover would have diminished. Furthermore, studies on two contrasting agro-ecologies in Zimbabwe showed that reduced tillage with residue cover yielded significantly greater species richness and macrofauna abundance than conventional systems, with a significant and positive correlation between residue application rates and species richness.

Although there are conflicting results on the effects of CA on termites, beetles and centipedes, increased earthworm activity has been observed in residue-covered fields compared to conventionally plowed fields in Zambia (Fig. 5). Soil texture, moisture and organic matter have a significant effect on earthworm densities, with decreased density in soils with high clay content and organic matter in Zimbabwe. Declining earthworm densities have been previously attributed to the effect of soil inversion by the plow, the effects of temporary reduction in soil pores, especially macro pores, and lower soil moisture on conventional fields without mulch protection.

In summary, CA leads to greater aggregate stability and, in the long-term, also reduces bulk density. Studies on biological soil fertility are rare and show that CA increases biological activity which can be positive (more earthworms) or can be potentially negative if termites are a problem at the site.

Effects of CA on soil carbon

In-situ retention of crop residues coupled with no-tillage has the potential to increase SOC. The conversion of fields from conventional tillage to no-tillage has been shown to increase SOC in a sandy loam soil in farmers’ fields in Malawi and on sandy soils in both Zimbabwe and Zambia. However, consistent and sufficient carbon inputs are a major determinant of changes in SOC rather than tillage, and lack of sufficient carbon inputs can lead to no, or very slow, increase.

Intercropping legumes and maize increased SOC under no-till, largely due to increased biomass production compared to no-till continuous maize cropping. On a sandy soil in Zimbabwe, SOC in the first 30 cm increased when maize was intercropped with pigeonpea compared to continuous maize under no-till (+12%) and
conventional tillage (+34%)\textsuperscript{73}. Furthermore in central Mozambique on similar soil types, Rusinamhodzi et al.\textsuperscript{81} reported a significant increase in SOC after 5 years of intercropping (Table 2). Farmers can use a pigeonpea–ratoon crop, reducing the need for tillage while increasing biomass accumulation, which together have the potential to significantly increase SOC. These results suggest that in the long-term CA may be important for maintaining SOC relative to conventional agriculture. However, the greatest increase might only be achieved when crops are adequately fertilized, sufficient biomass is produced and adequate residue amounts are retained\textsuperscript{30,80}. Without sufficient fertilization (e.g., through mineral fertilizer, manure and/or compost) farmers cannot raise their productivity to a level that enables them to retain at least 2.5–3 t ha$^{-1}$ of biomass, which is needed to cover at least 30% of the soil surface. Rotations and intercropping systems might also add to the carbon pool, but their potential to increase SOC largely depends on the agro-ecological environment and their overall biomass production\textsuperscript{73,81}.

It is worth noting, that while reduced tillage helps to reduce decomposition rates, it may also play a negative role in SOC stratification within the soil\textsuperscript{30}. SOC increases are expected over time if the amount of crop residues retained is more than the loss through the oxidation process\textsuperscript{30}. However, the importance of CA in the short term might be more in the maintenance of SOC rather than in its absolute increase. Nyamangara et al.\textsuperscript{80} generally found no significant increase in soil carbon and phosphorus in their study from Zimbabwe, although there was some accumulation in organic carbon in one agro-ecological region in CA fields relative to conventionally plowed fields when CA was practiced for a longer period.

**Pest and disease dynamics**

CA has been associated with increased insect pests and diseases. However, one of the main principles, crop rotation, is the most important strategy available for the smallholder farmer to break pest and disease life cycles\textsuperscript{13,82}. The parasitic weed striga (\textit{Striga asiatica} (L) Kuntze) is associated with large losses in maize production throughout Southern Africa\textsuperscript{83}. Estimates for grain yield loss due to striga in farmers’ fields range between 15 and 95\%\textsuperscript{84}. The effects of striga have also been associated with declining soil fertility\textsuperscript{85}. A study comparing CA with herbicides and conventional treatments with manual weeding only on 54 paired demonstration plots in Malawi\textsuperscript{86} showed a drastic reduction in striga emergence under CA fields (Fig. 6). Rusinamhodzi et al.\textsuperscript{81} also observed a significant decrease in striga when intercropping was used in a no-till system compared to continuous cropping of maize.

No-till, residue retention and increased soil moisture at the surface can promote the survival of pathogens until the next crop is planted\textsuperscript{87}. Predominant insect pests and diseases of maize in Southern Africa include grey leaf spot (GLS), maize streak virus (MSV), rust, ear rots and striga\textsuperscript{88}. GLS is caused by the fungal pathogen \textit{Cercospora zeae-maydis} and is a serious foliar disease associated with yield loss in Southern Africa\textsuperscript{89}. The increase of GLS in temperate maize has been linked to reduced tillage practices\textsuperscript{90}. With crop residue retention, the fungal pathogen responsible for GLS remains in the debris of
diseased plants, providing an earlier and more extensive source of inoculum for the next maize crop. This facilitates earlier infection of the next maize crop and allows more secondary cycles of the fungus. Work is currently underway in Southern Africa to determine if there is increased prevalence of GLS in CA-based systems and what can be done with conventional and molecular breeding to overcome this challenge.

MSV is transmitted through leafhoppers (Cicadulina spp.). Little is known about the effects of CA on leafhopper populations and MSV infection and further research is required. Ear rots are caused by a range of fungi including Fusarium graminearum, F. verticillioides, Aspergillus flavus and A. parasiticus. Lipps and Deep showed that reduced tillage decreased the prevalence of F. graminearum.

The incidence of white grubs (larvae of Phyllophaga ssp. and Heteronychus ssp.) has been highlighted as a potential pest under CA based on one observation in farmers’ fields in Barue, Mozambique. This was also observed on an on-station, long-term trial at Chitedze, Malawi. However, when maize–legume rotations (i.e., maize–cowpea rotations) were introduced on these sites, white grub damage was not observed. Together these results suggest that while pests and diseases carried over through residues can be a threat to successful implementation of CA systems, appropriate rotations and chemical control measures can be used to overcome most of these challenges for the smallholder farmer.

**Effects of CA on productivity**

Significant yield benefits under CA in Southern Africa are possible, although they may be site-specific and in response to different agro-ecological environments. Studies have shown that rotation as well as appropriate fertilization are critical for CA results to become significant. This was successfully shown in component omission trials in Malawi, Mozambique and Zimbabwe.

In some environments the benefits of CA started after 1–2 seasons, whereas in other environments the benefits required more seasons for effects to build up, which is in agreement with a recent meta-analysis. For example, in the high-rainfall environment of Zidyana EPA, Malawi, characterized by sandy loam soils, substantial maize yield benefits were obtained after five seasons.

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Table 2. Selected top-soil (0–20 cm) properties of fields under different durations of maize–pigeonpea intercropping in Ruaca, central Mozambique (source: [81]).

<table>
<thead>
<tr>
<th>Duration of intercropping</th>
<th>Bulk density (mg m$^{-3}$)</th>
<th>pH</th>
<th>Organic C (%)</th>
<th>Total N (%)</th>
<th>Available P (mg kg$^{-1}$)</th>
<th>Exch. K (cmol, kg$^{-1}$)</th>
<th>Exch. Ca (cmol, kg$^{-1}$)</th>
</tr>
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<tbody>
<tr>
<td>0*</td>
<td>1.5</td>
<td>5.9</td>
<td>0.2</td>
<td>0.02</td>
<td>0.7</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
<td>1.4</td>
<td>6.0</td>
<td>0.6</td>
<td>0.04</td>
<td>2.8</td>
<td>0.2</td>
<td>2.2</td>
</tr>
<tr>
<td>3</td>
<td>1.4</td>
<td>5.9</td>
<td>1.2</td>
<td>0.08</td>
<td>6.9</td>
<td>0.3</td>
<td>3.6</td>
</tr>
<tr>
<td>5</td>
<td>1.3</td>
<td>6.0</td>
<td>1.4</td>
<td>0.09</td>
<td>8.4</td>
<td>0.3</td>
<td>3.8</td>
</tr>
</tbody>
</table>

* Corresponds to continuous sole maize production.

Figure 6. Incidence of striga (S. asiatica L.) on CA plots (with and without legume intercropping) and conventionally plowed field after 5–8 years of treatment, central and southern Malawi (Thierfelder, 2012, unpublished data).
This lag period between implementation and effects of CA is mainly related to the need to produce sufficient crop residues and improve degraded soil fertility, applying the right fertilizer and seed, equipment, planting at the right time and inclusion of a systematic rotation scheme. In on-farm trials in Monze, Zambia, incremental benefits of CA systems compared to CP treatments were significant following the third cropping season⁹⁷ (Figs. 7 and 8), contrary to the suggestion that CA needs a very long time until yield benefits materialize⁵¹.

Although maize yield benefits in CA systems take 3–5 seasons to occur, with some exceptions in unfavorable environments, the trend is not as clear when maize is intercropped or rotated with legumes, which tend to respond less to fertility increases and water conservation. Increased water accumulation in the soil can cause root rot, thereby reducing the yield of legumes⁹⁸. Legume yield data from Malende, Monze (Zambia) from 2007 to 2012 showed very variable results between two CA treatments and the conventional control⁹⁷, with significant yield differences only after the sixth cropping season (Fig. 9).

In low-yielding environments CA has potential to double the maize yields obtained under conventional tillage, which was previously shown by Thierfelder and Wall⁵⁰ in a study carried out at Zimuto Communal Area, Zimbabwe. Under semi-arid conditions of southern Zimbabwe, CA (planting basin and rip-line seeding systems) produced 102–142% more cowpea grain compared to conventional practice in a drought year⁶⁸.

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**Figure 7.** Effects of rip-line and direct seeding CA treatments as compared to conventionally plowed control treatments at Malende Agriculture Camp, Monze, Zambia, 2006–2012 (adapted from⁹⁷).

**Figure 8.** Effect of two CA treatments and a conventional plowed control treatment on maize grain yield at Malende Agriculture Camp, Monze, Zambia, 2006–2012 (adapted from⁹⁷).

However, in a season with above average rainfall, CA and conventional systems produced similar cowpea yields.
Maize yields under no-till with mulch retention were marginally better than under conventional tillage in a regional study on long-term trials in Southern Africa94, i.e., closer to the 1:1 line (Fig. 10) but the inclusion of rotation or intercropping systems led to yields that were closer to the 1:2 line, implying that in some instances yield under CA was almost double that in conventional tillage. The results also highlighted the importance of legumes within a rotation and crop diversity. Substantial yield increases were observed, and in some cases maize yields following legumes were almost double that of continuous maize under no-till. At Henderson Research Station in Zimbabwe, there was a significant increase in maize yields planted after sunnhemp after several years73.

CA has generally been reported to increase labor use efficiency and returns per unit labor compared to conventional agriculture99. For instance, significantly higher labor productivity (in kg person-day−1) and returns to labor (USD person-day−1) for CA were observed compared to conventional farming across low, average and high seasonal rainfall levels in Zimbabwe99–101. Mazvimavi et al.79 also showed that farmers practicing CA increased yields by 10–100% compared with conventional, depending on fertilizer rates and management, experience of the farm household and seasonal rainfall patterns.

Similar results were reported by Ngwira et al.28 in Malawi, where the cost of producing a kilogram of maize was shown to be less under CA systems compared to conventional practices. Although labor input in this study was small compared with previous studies, they showed that CA reduced farm labor requirements (Table 3). Related studies in Malawi showed that returns to labor were more than twice as high under CA using monocropping and intercropping with legumes, both on and off farm, as under conventional tillage practice using the conventional ridge and furrow system28,102.

The use of planting basins, a technology promoted by most development organizations in Zambia and Zimbabwe, based on manually dug planting holes103, spreads out the labor requirement for land preparation and encourages timely planting, thereby reducing the peak labor load at planting104. Although using basins required more labor for smallholder farmers in Zambia as compared to the hand hoe and animal traction system105, Haggblade and Tembo106 highlighted that the major advantage of using basins was the disaggregation of peak labor times. However, Umar et al.105 stressed that farmers perceived labor requirements very differently and, whereas basin planting was perceived to be more labor intensive, significant labor reductions were recorded on animal traction ripping. Results for manual CA systems in Malawi28,102 showed labor savings of about 9 and 19 person days ha−1 in land preparation and weeding under CA. Manual CA systems practiced in Malawi involve direct seeding using a dibble stick, which requires significantly less labor than preparing the traditional ridges and furrows manually.

Figure 9. Effect of two CA treatments and a conventional plowed control treatment on cowpea grain yield at Malende Agriculture Camp, Monze, Zambia, 2006–2012 (adapted from97).
Other results do, however, highlight that reduced labor requirements around planting in CA systems can be offset by increased labor for weeding, particularly in the early stages of adoption\textsuperscript{104,107}. Nevertheless herbicides can be used to reduce labor requirements under CA if they are available and affordable to smallholder farmers\textsuperscript{108,109}.

Although it is true that CA often conforms to what Pampel and van Es\textsuperscript{110} termed as an ‘environmentally profitable practice’ (i.e., good for the environment and profitable), this is not always the case. Particular location-specific constraints might result in reduced yields, or institutional factors may favor alternative practices\textsuperscript{51,111}. Thus, it is necessary to consider site-specific conditions in determining the financial attractiveness of CA. Even where the financial incentives may appear attractive, a consideration of non-financial factors (e.g., risk of crop failure) is required to understand the actual and potential adoption of CA\textsuperscript{112}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Effects of conservation agriculture on maize grain yield: (a) yield advantage of no-till plus mulch over conventional tillage, (b) yield advantage of no-till and residue retention with non-legume rotation over no-till and residue retention without rotation, (c) yield advantage of no-till and residue retention with legume rotation over no-till and residue retention without rotation and (d) yield advantage of no-till and residue retention with 3-year rotation over no-till and residue retention without rotation (source:\textsuperscript{94}).}
\end{figure}
Constraints to Adoption of CA Systems in Southern Africa

Although the practice of CA can provide many benefits for smallholder farmers in Southern Africa, large-scale spontaneous adoption has been hampered by a number of constraints. These constraints include trade-offs between residue retention and livestock feed in mixed crop–livestock systems, the need for crop rotations and intercropping, weeding intensity and control, labor constraints and lack of access to complementary inputs. Often, significant knowledge gaps and the perception of farmers that tillage is necessary to produce crops are major impediments to widespread adoption of CA.

The majority of studies on CA in Southern Africa highlighted the beneficial effects of CA on selected parameters. However, these past researches were largely conducted within experimental stations and did not take into account socio-economic constraints in real farm situations that could hinder the widespread adoption of CA. Recently, more studies reporting results from on-farm and on-station trials have been published concentrating on some of the above-mentioned challenges and constraints. Innovative ways of enhancing already developed legume, grass and agroforestry species as fodder are therefore required and need to be integrated into CA systems. This will allow part of the crop residues to be used in CA systems and to feed livestock as fodder during the dry season. New ways of additional residue production through intercropping and relay cropping are other alternatives that should be explored.

Trade-offs in mixed crop–livestock systems

Crop and livestock production are closely integrated in mixed smallholder farming systems of Southern Africa. Crop residues are used for bedding in kraals (animal paddocks) during the rainy season, construction (fencing and thatching) and as a source of fuel. With the advent of CA systems, Southern Africa smallholder farmers face the challenge of trade-offs between keeping crop residues for application on the field as mulch and feeding them to livestock. Crop residues are also used for bedding in kraals (animal paddocks) during the rainy season, construction (fencing and thatching) and as a source of fuel. Comprehensive information on the use of crop residues in these systems is often lacking. Innovative ways of enhancing already developed legume, grass and agroforestry species as fodder are therefore required and need to be integrated into CA systems. This will allow part of the crop residues to be used in CA systems and to feed livestock as fodder during the dry season. New ways of additional residue production through intercropping and relay cropping are other alternatives that should be explored.

Intensification

Rotations in land-constrained farming systems. Although farmers are aware of the benefits of crop rotations, socio-economic factors often hinder integrating rotations within their farms. In Malawi, for example, the government subsidized maize seed and inputs (inorganic fertilizer, agrochemicals) to achieve maize self-sufficiency at the national level, which encouraged monocropping. In areas where farm sizes are


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<tr>
<td>Gross receipts</td>
<td>528.6</td>
<td>881.5</td>
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<tr>
<td>Variable costs</td>
<td></td>
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<tr>
<td>Inputs</td>
<td>238.5</td>
<td>341.0</td>
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<td>Labor days</td>
<td>61.7</td>
<td>39.9</td>
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<tr>
<td>Labor costs</td>
<td>159.5</td>
<td>103.2</td>
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<td>Sprayer costs</td>
<td>1.7</td>
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<tr>
<td>Total variable costs</td>
<td>398.1</td>
<td>445.9</td>
</tr>
<tr>
<td>Net returns (US$/ha)</td>
<td>130.5</td>
<td>435.5</td>
</tr>
<tr>
<td>Returns to labor (US$/day)</td>
<td>1.8</td>
<td>5.2</td>
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Note: CP, conventional practice; CA, conservation agriculture sole maize; CAL, conservation agriculture maize–legume intercrop. Labor data (in person hours and minutes) was obtained from one on-farm trial per site for each operation (laying crop residues, tillage, herbicide application, planting, fertilizer application, weeding, harvesting, etc.). Price data were based on all applied inputs (seed, herbicides, fertilizers, etc.) from each of the plots during the entire period of the study.
small, farmers often dedicate most of their land area to the staple food crops (maize, sorghum) rather than rotational crops such as legumes\textsuperscript{13}, which has serious implications for the nutrition of smallholder farmers. Where the size of the land holdings are greater, such as in Zambia, there is greater potential for crop rotations, although markets may limit successful implementation\textsuperscript{94}. The income generated through a range of different crops (including legumes) can be less than the production costs. Furthermore, seed companies are often not interested in seed production of most legume crops. These crops are self-pollinating, so farmers can easily recycle rather than buy new seed.

**Intercropping systems—the struggle to produce more from given land.** Intercropping maize and legumes is another way to achieve food security and cash income for smallholder farmers, and abundant literature from Southern Africa supports this observation\textsuperscript{81,102,130–133}. Although intercropping with legumes is associated with many benefits, including improving soil structure and fertility and the potential to increase farm income through selling legume grain, the potential of legumes within farming systems of Southern Africa is currently limited by a plethora of constraints. These include poorly developed markets for seed and produce, lack of appropriate germplasm and phosphorus-deficient soils\textsuperscript{134,135}. Intercropping maize and pigeonpea has been shown to be highly profitable in Southern Africa, with a tripled rate of return compared to maize cropping alone, although the new spatial arrangement increased labor requirements for weeding by 36\%\textsuperscript{81}. In a maize–pigeonpea intercropping system, Ngwira et al.\textsuperscript{102} also reported higher rates of return compared to maize cropping alone, although maize yields were lower in this study due to drought stress competition between main- and intercrop. The authors concluded that intercropping maize and pigeonpea under no-till was an attractive option due to associated maize yield improvement and economic returns when the prices of maize and pigeonpea grains are favorable. However, the late maturity of pigeonpea can be a problem in mixed crop–livestock systems as free-grazing of cattle and goats can destroy the entire crop before harvest.

In contrast, Waddington et al.\textsuperscript{132} showed intercropping was an unattractive option compared to growing maize in monoculture, based on the results of a 12-year study on conventional agriculture in Zimbabwe. This was attributed to the small yield benefits compared to the relatively high investment costs for legume intercropping. In central Mozambique (Fig. 11) the emergence of a market for pigeonpea was a major driver for intercropping, despite destruction by livestock of the late maturity pigeonpea crop\textsuperscript{81}. It is important to note that the crop used for intercropping is crucial, and poorly chosen intercrops and the timing between both crops may have a negative effect on productivity, particularly when the farmer has limited access to already scarce resources. Intercropping maize and cowpea can potentially reduce maize yields by up to 86\% as compared with a sole maize stand\textsuperscript{131} if the timing between both crops is poor (e.g., when cowpea is seeded too early, competition is too high), or can reduce the cowpea yield when cowpea is seeded too late and maize is shading too much. These results suggest that the benefits of intercropping are not universal but vary across locations, seasons, timing between the main crop and the intercrop, and the crops used for intercropping. Socio-economic constraints can also have an overriding effect on

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\textbf{Figure 11.} The proportion of farmers practicing maize–legume intercropping between 2007 and 2011 in Ruaca and Vunduzi communities in central Mozambique. Proportions are based on a total of 52 households in Ruaca and 43 households in Vunduzi (adapted from\textsuperscript{81}).
the widespread uptake of intercropping. Thierfelder et al.\textsuperscript{73} observed that despite the plot-level benefits of intercropping as reported in literature, the benefits were only measured at the field scale and lacked proper integration at the farm and community level\textsuperscript{128,129}.

Weed incidence when converting to CA

A major challenge to the adoption of CA in smallholder farming in Southern Africa is related to weeds and their management\textsuperscript{51,105,113}. The dynamics of weed populations under CA are different from conventional tillage practices, including more complex interactions between weeds and crops under CA\textsuperscript{136,137}. In the semi-arid south of Zimbabwe annual and perennial monocotyledonous and dicotyledonous weed species (e.g. *Cynodon dactylon* L., *Richardia scabra* L. and *Commelina benghalensis* L.) were found to thrive differently under conventional and no-tillage practices\textsuperscript{113} and have been reported to be major problems when tillage is minimized and residues are retained\textsuperscript{138}. Weed density varied across crops, with the density of annual and perennial weed species higher under sorghum compared to cowpea\textsuperscript{113}. However, during periods of low rainfall, crop residue retention was found to be associated with increased mid-to-late season weed growth, in part due to improved soil moisture conservation in a clay-loam soil (Cambisol) in Zimbabwe\textsuperscript{113}. Mulch initially suppressed annual weeds but perennial rhizomes and their extensive root structure persisted under no-tillage and led to increased late-season weed growths. Weed species found in Southern Africa are affected differently by mulching, and mulch levels of >4tha\textsuperscript{-1} suppress a wider spectrum of weeds\textsuperscript{113}.

The application of pre-emergence herbicides can limit weed development under CA, although there are potential problems of evolved weed resistance to herbicides\textsuperscript{139}. Mwale\textsuperscript{140} reported a greater reduction in weed populations and weed seed banks under CA with herbicide application compared with conventional tillage systems, particularly during the first 55 days after planting maize. Herbicide use in CA can therefore potentially relieve farmers from weeding operations during the critical times that coincide with periods of food insecurity in most households. In a study carried out in Zimbabwe, the use of herbicides in combination with manual weed control was found to be beneficial both in time spent on weeding, reduction in weed densities and overall gross margins\textsuperscript{109}. However, labor reductions as such have little benefit to farmers if the saved labor is not used for additional income generation. Discussions with farmers revealed that the saved labor is used for additional cultivation, dedication of land area to higher-value crops, production and value addition to farm products (e.g., making doughnuts, jam or marmalade and drying cowpea leaves to sell as relish on the market), and off-farm labor, which in turn has a direct impact on farmers’ livelihoods. Although chemical weed control can be (but does not need to be) a component in CA systems, the suitability of promoting such a system among resource-poor farmers has been questioned due to accessibility and affordability\textsuperscript{141}, as well as the dangers of handling herbicides\textsuperscript{102}.

The use of green manure cover crops such as oats (*Avena sativa* L.), grass pasture\textsuperscript{142} and velvet beans (*Mucuna pruriens* L.) has been shown to be effective in managing weeds in maize/cover crop rotations\textsuperscript{143}. However, legumes that do not contribute to the household food basket have often been rejected by farmers in the past, which indicates a constraint to integrate green manure cover crops (GMCCs) into the smallholder farming systems\textsuperscript{134}. There is therefore a need to evaluate the profitability and sustainability of these cropping systems over a longer period under different farmers’ circumstances.

Labor constraints

The availability and costs of labor play a pivotal role in the likelihood of farmers to adopt a new technology. Certain forms of CA practices (e.g., the basin systems, based on manually dug planting basin) can be more labor intensive than conventional agriculture if compared to animal traction moldboard plowing, particularly during the initial stages of adoption\textsuperscript{115}, which can be a huge constraint to the widespread adoption on large farm areas. When CA includes planting basins and manual weeding, high labor demand is largely associated with the digging of planting basins and weeding practices\textsuperscript{99,107}.

The labor intensity of manual CA systems is, however, expected to decline, especially on loam and clay soils as farmers gain experience in using the technology. Once the initial digging in undisturbed soil is done the soil becomes softer in the basins in the following seasons\textsuperscript{101,106}. This does not, however, apply to the sandy soils, as basins cannot be maintained throughout the winter period. In summary, labor constraints are one of the major impediments to widespread adoption of CA, which has been shown in recent studies by both ICRISAT and Foundations of Farming, which reported that farmers in Zimbabwe tended to have only 0.5 ha or less of their farms under CA from land sizes of 4–6 ha\textsuperscript{116}.

Lack of access to complementary farm inputs and an enabling environment

The effect of the intertwined challenges discussed above is compounded by lack of access to complementary farm inputs, such as fertilizer, herbicides and pesticides, that could offset some of the adversities. Lack of access to inputs in Southern Africa are due to low purchasing power, distorted or missing markets and lack of social infrastructure\textsuperscript{8,144}.

Perceived economic constraints to the adoption of CA are likely to vary between countries as well as market environments as they are determined by the distance to markets, infrastructure and an overall enabling
environment. To discover these relationships a Qualitative Assessment Tool for Conservation Agriculture (QAtoCA) was tested in Malawi and Zimbabwe to identify the major constraints to adoption of CA and to dissect complex interactions within the community, markets and political environment. Focus group discussions in a guided process revealed that the overall likelihood of adoption for CA in Malawi was 86% compared to only 64% in Zimbabwe. These results showed that the environment for adoption of CA at both the village and regional scale is much more positive in Malawi than Zimbabwe, where constraints such as competition for residues between livestock and CA tended to reduce adoption. Malawian farmers use manual seeding technologies and herbicides for weed control and found CA to be an attractive option because of the reduced labor requirements during land preparation. Zimbabwean farmers, on the other hand, use more animal traction for land preparation and found that, with no access to herbicides, manual requirements for basin preparation and weed control were more labor demanding under CA. Other economic factors in Zimbabwe were also a major deterrent to the CA adoption compared to Malawi, where the markets were perceived to be more favorable. At the time of the study, Zimbabwean farmers faced serious problems accessing attractive markets for maize, the most common crop, that were not governmentally controlled. In summary, access to complementary farm inputs and an enabling economic and political environment are crucial for farmers in the decision process to adopt CA. If the adversities are too challenging, the likelihood of farmers adopting the technologies will be slim.

**Conclusion**

This review highlights recent advances in understanding the practice of CA in Southern Africa. Results show that CA has many environmental sustainability benefits, which can be summarized as: increases in infiltration, resulting in greater available soil moisture and a higher potential for groundwater recharge; reduced soil erosion and run-off; improved soil structure, more biological activity, e.g., through greater macrofauna abundance and diversity for system resilience; better soil quality. CA was also shown to offer direct benefits to farmers, including increased crop productivity, which could lead to better yields and hence increased food security, although there is often a time delay until yield increases in maize and other crops become significant. Regional labor productivity studies show benefits of CA systems over conventional practices, although little work has been done so far to clearly understand the risk implications of CA at the farms and on a larger scale. In cropping systems traditionally based on manual land preparation, CA offered an opportunity for labor savings to other economic activities through reduced labor on land preparation, particularly when applied in combination with herbicides. However, where animal traction is common (e.g., in large parts of Zimbabwe and Zambia), hoe-based CA systems suffered setbacks of increased labor compared to moldboard plowing. In similar circumstances, where farmers used only the hoe for land preparation, CA still offered huge advantages in terms of enabling farmers to plant timely, as basin preparation was carried out in winter and reduced labor at peak labor times.

Nevertheless, the review also shows that CA promotion and adoption is constrained by a number of biophysical, socio-economic and socio-cultural factors, which are varied and depend on the site and the farmer’s circumstances. These constraints include challenges of retaining residues in areas where mixed crop–livestock systems are common; application of rotations and sustainable intensification strategies due to dysfunctional input and output markets; the control of weeds in CA systems; pests and diseases; institutional, labor and market constraints. Often the mind-set and knowledge of smallholder farmers about no-tillage and residue retention plays a critical role in the adoption process of this relatively new way of farming.

If sustainable intensification through CA should be one of the pathways to agricultural development in...
Southern Africa, there is a need to better understand farmer decision processes, and more research is essential to overcome, or at least find solutions for, these critical biophysical and socio-economic challenges.

Generalizing the economic performance of CA under different circumstances is not appropriate. Site-specific factors determine technologies that offer the best results for individual farmers. Given the glaring paucity of empirical evidence about the farm-level impact of CA on labor productivity and the financial viability of CA in Sub-Saharan Africa, it is imperative to suggest a case-by-case analysis of CA impacts on labor productivity over time and from a society-wide perspective.

This review of CA as a crop management system for smallholder farmers in Southern Africa revealed that it is not a ‘one-size-fits-all’ solution to all of the farmers’ problems, and often there is a need for significant adaptation and flexibility in its application. CA is therefore not a fixed recipe but a set of principles that have to be adapted and fine-tuned to the needs of the farmers. However, the benefits of practicing CA can potentially reduce future soil fertility decline, the effects of seasonal dry-spells and socio-economic constraints, and may have a large impact on food security and farmers’ livelihood if the challenges can be overcome.

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