Food Sec. (2017) 9:537–560
DOI 10.1007/s12571-017-0665-3

REVIEW

How climate-smart is conservation agriculture (CA)? – its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa

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Received: 22 December 2015 / Accepted: 23 February 2017 / Published online: 7 April 2017

Abstract Climate resilient cropping systems are required to adapt to the increasing threats of climate change projected for Southern Africa and to better manage current climate variability. Conservation agriculture (CA) has been proposed among technologies that are climate-smart. For a cropping system to be labelled "climate-smart" it has to deliver three benefits: a) adapt to the effects of climate and be of increased resilience; b) mitigate climate effects by sequestering carbon (C) and reducing greenhouse gas emissions (GHG); and c) sustainably increase productivity and income. Research on smallholder farms from Southern Africa was analysed to assess if CA can deliver on the three principles of climate-smart agriculture. Results from Southern Africa showed that CA systems have a positive effect on adaptation and productivity, but its mitigation potential lags far behind expectations. CA systems maintain higher infiltration rates and conserve soil moisture, which helps to overcome seasonal dry-spells. Increased productivity and profitability were recorded although a lag period of 2–5 cropping seasons is common until yield benefits become significant. Immediate economic benefits such as reduced labour requirements in some systems will make CA more attractive in the short term to farmers who cannot afford to wait for several seasons until yield benefits accrue. The available data summarizing the effects of CA on soil organic C (SOC) and reductions in greenhouse gases, are often contradictory and depend a great deal on the agro-ecological environment and the available biomass for surface residue retention. There is an urgent need for more research to better quantify the mitigation effects, as the current data are scanty. Possible co-interventions such as improved intercropping/relay cropping systems, agroforestry and other tree-based systems may improve delivery of mitigation benefits and need further exploration.

Keywords No-tillage · Sustainable intensification · Resilience · Climate-smart agriculture · Climate variability

Introduction

Agricultural production and food and nutrition security in sub-Saharan Africa is threatened by the projected increase in cli-

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mate variability and change (Wheeler and von Braun 2013; Lobell et al. 2008). In a world that has to feed 9 billion people by 2050, climate change is one of the biggest hazards to the survival of mankind (Godfray et al. 2010; IPCC5 2014a). Studies from FAO suggest that agricultural production will need to increase by about 70%–100% by 2050 to keep pace with the increasing population (Godfray et al. 2010). The effects of climate change could potentially interrupt the progress of the last three decades towards a world without hunger (Wheeler and von Braun 2013) and could significantly affect all aspects of food security (i.e. food availability, access to food, stability of food supplies, and food utilization) (Schmidhuber and Tubiello 2007).

Smallholder farmers in the tropics and sub-tropics will be less able to cope with changes in climate because they have far fewer adaptation options than farmers in temperate zones (Brown and Funk 2008). Furthermore, the outlook is bleak for farmers in sub-Saharan Africa due to declining soil fertility (Sanchez 2002; Kumwenda et al. 1998), increased and severe soil degradation (Oldeman et al. 1990; Nkonya et al. 2015) and a rapidly increasing population (Godfray et al. 2010). The large economic dependence on agriculture in sub-Saharan Africa further increases vulnerability to climate change (IPCC5 2014b).

With climate change, Southern Africa is likely to experience more frequent dry spells and increased heat stress. Maximum temperatures are predicted to increase by an average of 2.6 °C across Central to Southern Africa (Cairns et al. 2012). The region is also projected to experience increased rainfall variability and increased frequencies of extreme weather events such as floods and droughts (IPCC5 2014b). Recurrent droughts already cause frequent failure of rain-fed maize (>40%) in areas of Southern Africa, north east South Africa and northern Botswana (Cairns et al. 2013; La Rovere et al. 2010). In general, the frequency of dry periods is expected to increase, but there is greater uncertainty around precipitation projections (Thornton et al. 2011). Higher average temperatures will exacerbate drought stress during dry periods due to increased crop transpiration and further depletion of plant available soil moisture (Cairns et al. 2013; Lobell et al. 2013).

Using results of 20 general crop simulation models, Lobell et al. (2008) showed that maize production in Southern Africa could decrease to 70% of current production levels by 2030, which calls for concerted efforts for breeding and cropping systems research (Cairns et al. 2013). Maize, the principal food security crop across much of Africa (Dowswell et al. 1996), will be most affected in the region as compared to other crops (Lobell et al. 2008). Ramirez-Villegas and Thornton (2015) projected that the area suitable for maize production is likely to decrease by 30–50% in sub-Saharan Africa, given current climate change forecasts. A recent study in Tanzania projected that a 2 °C increase in temperature will reduce maize yields by 13%, while a 20% increase in intra-seasonal precipitation variability will reduce maize yields by 4.2% (Rowhani et al. 2011). Smallholder farmers confronted with these challenges need to adapt to the changing climate to avoid increased food insecurity and hunger in the years to come. However, the short term needs of farmers must be met in combination with long term sustainability of agriculture (Gilbert 2012) and solutions must be viable at the field, farm, community levels and beyond, as well as taking into account the complexity of the environment in which farmers operate (Rufino et al. 2007; Rufino et al. 2011; Ncube et al. 2009; Tittonell et al. 2012).

A series of interventions has been summarized under the umbrella of “climate-smart agriculture” (CSA); defined by their ability to deliver on three fundamental aspects: a) adaptation to the effects of climate change, thus building resilience into the system; b) provision of mitigation benefits in terms of reduced greenhouse gas emissions and building carbon (C) stocks (both above and below ground) and c) improved reliability, sustainability, productivity and profitability of agricultural production systems (FAO 2013; Lipper et al. 2014; Scherr et al. 2012; Neufeldt et al. 2013). CSA is not one particular plot-based practice or technology but a suite of practices that are integrated in an agricultural system, often across different scales. Scherr et al. (2012) suggest that climate-smart agricultural systems should have: a) climate-smart practices as pre-requisites at the field and farm scale; b) biodiversity across the landscape; and c) management of land use interactions at the landscape scale. However, some of the interventions may require significant investment costs in the short term, which may be a deterrent to adoption of CSA by smallholder farmers (McCarthy et al. 2011).

One of the promising CSA technologies for Southern Africa is conservation agriculture (CA) (FAO 2013; Thierfelder and Wall 2010a; IPCC5 2014a). CA is based on the intertwined principles of minimum soil disturbance, crop residue retention and crop diversification through crop rotations or intercropping (FAO 2015; Hobbs 2007; Kassam et al. 2009) and requires local adaptation and good agriculture practices to deliver its benefits. CA systems have been tested on commercial farms globally and are currently practiced on more than 157 million ha (Kassam et al. 2015). However, the extension and adoption on smallholder farms was slower than in the commercial farming sector (Wall et al. 2013; Derpsch et al. 2016) and, in the early 2000s, was less than 1% of the area under CA (Derpsch et al. 2010) but with an increasing trend (Kassam et al. 2015). Smallholder farmers preferentially adopted the no-tillage or minimum soil disturbance component while residue retention and crop diversification lagged behind (Thierfelder et al. 2012).

CA systems and its planting methods have been increasingly studied in Southern Africa since 2004 in many different forms and ways (Thierfelder et al. 2015b). Its suitability for smallholders in sub-Saharan Africa has been the subject of much debate in recent years (Giller et al. 2015; Giller et al. 2011; Giller et al. 2009; Andersson and D'Souza 2014) leading eventually to a consensus that CA, like every agriculture system, is best suited to particular contexts (Wall 2007), although the niche might be larger than expected (Baudron et al. 2015b) making it an option for large farming areas. Despite numerous benefits, many adoption challenges have been summarized in recent reviews (Thierfelder et al. 2015b; Baudron et al. 2015b; Andersson and D'Souza 2014) and amongst them are: a) lack of knowledge and capacity of farmers to implement CA; b) lack of sufficient biomass retention on the soil surface in intensive crop/livestock systems (Valbuena et al. 2012); c) lack of access to critical CA inputs (e.g. specialized machinery, fertilizer and herbicides); d) high costs of inputs (e.g. for specific seed, fertilizer and herbicides); e) lack of access to credit for initial investments; f) lack of functional output markets for rotational crops; and g) tradition and resistance to change. Additionally, weed pressure under CA, especially if no herbicides are used, has been identified as one of the main disincentives for smallholder farmers to adopt the technology (Farooq et al. 2011; Andersson and D'Souza, 2014; Giller et al. 2015), and this happens mostly in the first two to three seasons of conversion to CA (Rusinamhodzi 2015; Mazvimavi and Twomlow 2009). Increased weed pressure under CA, if no herbicides are used, may even increase labour requirements for smallholders (Mashingaidze et al. 2012), often affecting women farmers. While herbicides have been proposed to reduce weed pressure under CA (Muoni et al. 2014), their use in smallholder farming systems may be limited in some areas because farmers cannot access and afford them (Andersson and D'Souza 2014). In other areas they have been used more regularly due to input support programs (Ngwira et al. 2014).

Maize stover is the most common surface crop residue retained, but grass, leaf litter or other available biomass are also used as surface mulch. Farmers in Southern Africa occasionally use relay crops or green manures to increase the surface crop cover. The optimum quantity and quality of residues retained is dependent on biophysical factors, the levels of intensification and competing demands for biomass (Jaleta et al. 2013; Baudron et al. 2015a; Valbuena et al. 2012).

Another diversification and climate-risk reduction strategy are rotations of cereals with legumes such as cowpeas (*Vigna unguiculata* (L.) Walp.), soybeans (*Glycine max* (L.) Merril), groundnuts (*Arachis hypogaea* L.) and beans (*Phaseolus vulgaris* L.) or cash crops such as sunflower (*Helianthus annuus* L.) and cotton (*Gossypium hirsutum* L.). It is an age-old practice and an essential part of CA systems and other agriculture systems of Southern Africa (Kamanga et al. 2010; Waddington 2003). However, these rotations are often unsystematic (one year of legume following several years of cereals) and more "value" is put by farmers on maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* (L.) Moench) as primary food security crops (Thierfelder and Wall 2010b; Giller 2001; Rusinamhodzi et al. 2012; Thierfelder et al. 2013a). In land-constrained circumstances, as are common in Malawi, maize-legume rotations may become increasingly unfeasible for smallholder farmers (Snapp et al. 2010).

CA may deliver on all pillars of climate-smart agriculture to varying degrees. However, the extent to which CA contributes to the aspects of CSA in Southern Africa has not been fully analysed and understood. To be able to determine if a cropping system is climate-smart, there is need to assess its biophysical and socio-economic benefits and challenges and its response to a changing climate to better understand what makes it climate-smart or the opposite. Cropping systems in Southern Africa first and foremost need to be more resilient to increased frequencies of erratic rainfalls, dry-spells, late onset of rains, increasing temperatures, terminal heat stress, and heavy rainfall, amongst others. Greater climate resilience could be achieved by changing from the predominant maize to more drought-tolerant sorghum or millet. However, to date, farmers have resisted this change and prefer growing maize although the risk of crop failure is high. Climate change may also affect crops through the increase of specific pest and diseases, which may change the resilience of systems. However, little is known yet about this relationship. Agriculture systems also need to increase, or at least maintain productivity and profitability for farmers to survive under variable climatic conditions. In the long-term, cropping systems need to maintain soil fertility and sequester greenhouse gases in order to mitigate the negative effects of climate change. As such, a cropping system needs to have the following properties: a) greater water infiltration and soil moisture conservation; b) reduced soil erosion and run-off; c) reduced evaporation; d) moderated high daily temperature amplitudes; e) improved soil fertility and thus enhanced fertilizer response rates; f) increased carbon sequestration or at least maintenance of carbon levels, g) reductions in greenhouse gas emissions; h) increased yields and net benefits amongst others.

Here we offer an overview of the ability of CA systems to respond to the projected effects of climate variability and change with particular emphasis on Southern Africa. The aim of this paper is to outline pertinent research gaps and to shape the future CA research agenda in Southern Africa (Table 1). The paper will deliberately highlight what we know and can confirm with great confidence based on field evidence. Thus, the paper focuses on the three pillars of CSA

Table 1 Available evidence of climate-smart-agriculture potential of CA and pertinent knowledge gaps

Climate smart agriculture pillar	Observable	Evidence	Effect	Confidence	Knowledge/research gaps
Adaptation (resilience)	Infiltration	+	+	+	Does higher infiltration lead to greater resilience at critical growth and plant development stages?
	Soil moisture	+	+	+	Water dynamics and water-use-efficiency in different soil types under different CA systems
	Temperature amplitude	+	+	−/+	Effects of no-tillage and residue retention on daily temperature amplitude and its effect on heat stress
	Heat stress	−	+	−	Does CA moderate heat stress and how does it affect productivity?
	Pest and diseases	−	−	−	Pest and disease dynamics under a changing climate
	Early planting	+	−	+	Quantification of yield benefits in response to early planting
Mitigation	Carbon sequestration	+	−/+	−	Soil organic carbon sequestration under CA and diversified cropping systems. CA with trees and its effects on carbon sequestration.
	Greenhouse gas emissions	−/+	−/+	−	Which GHGs will be reduced and which will increase?
	Erosion	+	+	+	How does reduced erosion translate to greater mitigation?
Productivity/ Profitability	Yield	+	+	+	How long does it take until yield benefits become evident in contrasting environments? How is yield affected and to what extent by drought, heat and waterlogging?
	Profitability	+	−/+	−/+	What CA systems increase profitability and how long does it take? What benefits can be expected for different groups of the society (e.g. gender and youth)?

These factors and knowledge gaps are not necessarily relevant for CA systems only but for many agriculture systems in Southern Africa. It presents the link between future projected conditions and the need to mitigate

Evidence: - not existing; −/+ somehow existing; + existing;

Effect: - negative; −/+ indifferent; +positive;

Confidence –low; +/− medium; + high

namely adaptation to climate change, mitigation potential of CA and its effects on productivity and income, concentrating on smallholder farmers of Southern Africa. The paper concludes by answering the question, how climate-smart is conservation agriculture for Southern Africa?

CA and its adaptation to climate-related stress

Worldwide, CA has been promoted as a strategy to conserve soil moisture, reduce erosion, enhance soil fertility, increase soil organic C (SOC), and reduce greenhouse gas emissions (Six et al. 2002; Kassam et al. 2009; Derpsch et al. 2010; Johnson et al. 2005; Reicosky 2000), besides reducing production costs (Mueller et al. 1985; Johansen et al. 2012; Sorrenson et al. 1998).

The most important climate-related stress for crop growth in Southern Africa is limited available soil moisture that may hamper germination, plant development and yield. This stress occurs due to late on-set of rains, erratic rainfall, in-seasonal dry-spells, heat stress and early cessation of rains. It is important for a cropping system to be labelled climate-smart if some of these abiotic stresses can be overcome due to greater resilience of the system. We evaluated how CA affects water infiltration, available soil moisture and factors that may lead to early planting.

Effects of CA on water infiltration

One of the most immediate benefits of the combined practice of no-tillage, residue retention and crop rotations is the ability to maintain high rates of water infiltration (Thierfelder and Wall 2009). Greater water infiltration increases available soil moisture, which buffers CA systems against in-seasonal dry-spells and heat stress. Increased rates of water infiltration occur in CA systems because lack of tillage and surface residues create a favourable environment for soil macrofauna to move to the soil surface and back into deeper layers, thus creating a soil pore system that facilitates air flux and water infiltration (Kladviko et al. 1986). Surface residue retention provides feed and conserves moisture for enhanced soil organism proliferation. CA in Zimbabwe improved pore volume in contrasting soils by at least 70%, five years after conversion to CA, which likely increased water infiltration in soils (Nyamangara et al.

2014a). Deep rooting legumes that are rotated with maize also improve the soil structure and the pore systems which increase the soil moisture and groundwater recharge (Thierfelder and Wall 2010b; Rusinamhodzi et al. 2012; Nyamadzawo et al. 2003, 2007). Root exudates serve as binding agents for different particles to form and stabilize aggregates. Additionally, roots enmesh soil and organic matter to form aggregates that influence pore structure and water infiltration and storage (Bronick and Lal 2005).

Increased infiltration reduces surface run-off and soil erosion thus providing additional environmental services downstream. If less fertile topsoil is being eroded, there is reduced silting of dams and eutrophication of lakes (Brown and Wolf 1984). Often these environmental costs and side effects of CA are not taken into account (Ward 2015), which leads to the underestimation of the social benefits of more sustainable practices (Pimentel et al. 1995; Reeves et al. 2005).

Infiltration has been recorded for a number of years in regional CA long-term trials in Zimbabwe, Zambia, Malawi and Mozambique (Fig. 1a–d). It was measured with a mini-rainfall simulator on a range of CA treatments with residue retention and a conventional control treatment with residue removal. The methodology has been previously described by Thierfelder and Wall (2009). The magnitude of differences in final infiltration rate between a ploughed control treatment and associated CA treatments varied according to the treatment comparison and the underlying soil type of the trial. Infiltration rates on CA treatments at Henderson, Zimbabwe were 55–65% greater than the conventionally ploughed control (Fig. 1a). At Monze, Zambia final infiltration rate on CA systems was 201–222% higher than the conventional control (Fig. 1b). At Sussundenga, Mozambique and Chitedze, Malawi the infiltration rates on CA systems were 84–139% and 94–136% greater, respectively (Fig. 1c, d).

However, it has to be stated that increased infiltration does not necessarily lead to improved maize productivity as excessive rains might also have negative effect on soil moisture, leading to waterlogging in excessive and unevenly distributed rainfalls (Thierfelder and Wall 2012). In years of excessive rainfall, a water-saving cropping systems such as CA turns

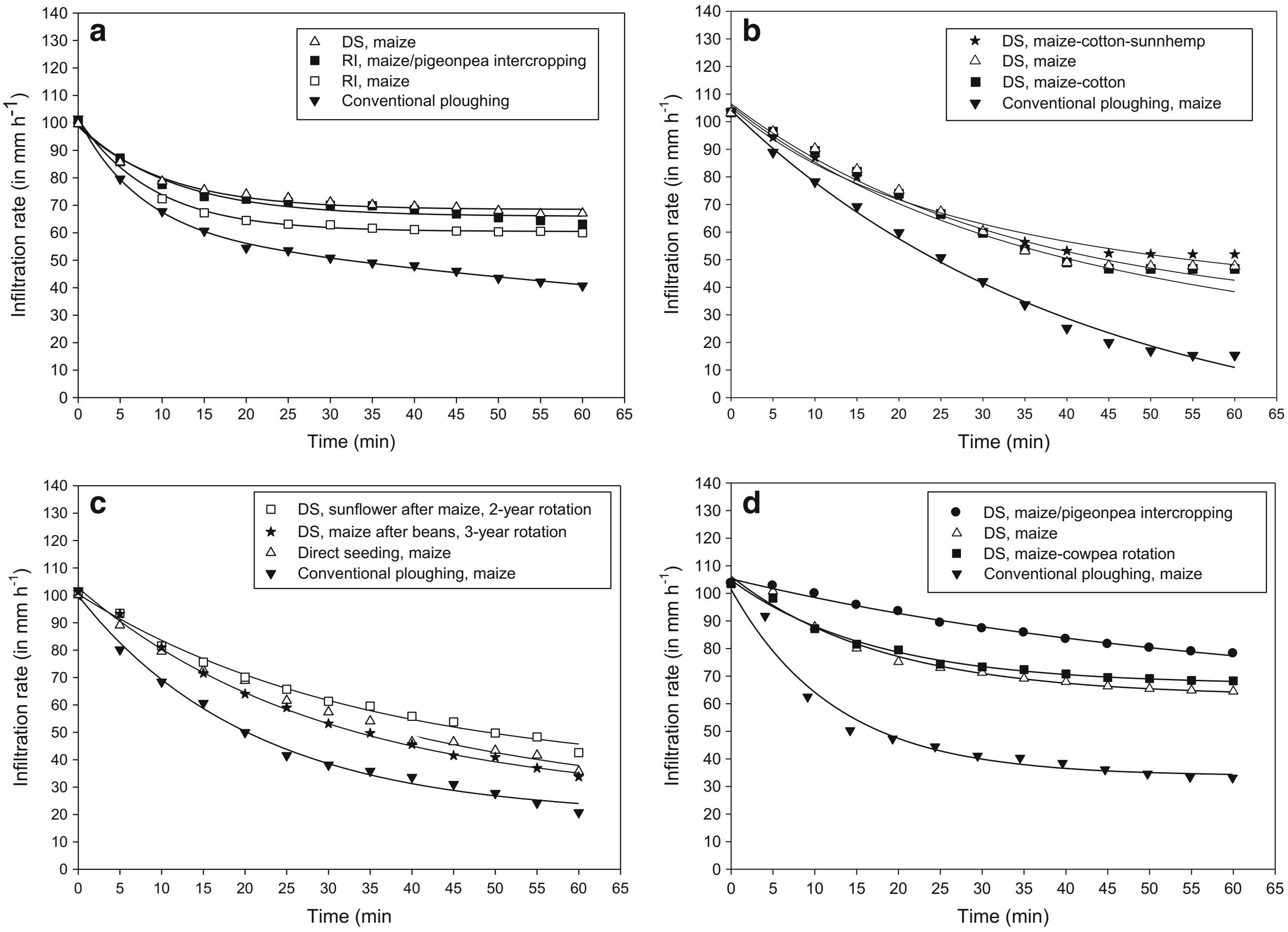

Fig. 1 **a**–**d** Infiltration rate in conservation agriculture and conventional treatment as measured with a mini-rainfall simulator in four regional long-term trials, Henderson Research Station, Zimbabwe **a**, Monze Farmer Training Centre **b**; Sussundenga Research Station, Mozambique **c**; Chitedze Research Station **d**, January 2010. Note: DS- direct seeding into no-tilled soil with residue retention; RI- ripline seeding into no-tilled soil with residue retention

its benefits into a threat (Thierfelder and Wall 2012). Nevertheless, the projected increase in frequencies of dry spells for Southern Africa (Lobell et al. 2008; Cairns et al. 2012) will likely see greater benefits from enhanced water infiltration than negative effects from waterlogging.

Soil moisture conservation

Conservation agriculture systems with residue retention increase water infiltration and maintain higher soil moisture due to reduced evaporation (Roth et al. 1988) and moderation of heat stress (Cairns et al. 2013; Lal 1974). However, substantial soil evaporation reductions only occur when soil cover approached 100% (Bussière and Cellier 1994; Klocke et al. 2009), which is rarely achieved in smallholder systems (Mupangwa et al. 2012). Nonetheless, benefits can be expected from CA systems in their potential to adapt to increased severity and frequency of seasonal dry-spells (Thierfelder and Wall 2010a) if they can be buffered by greater available soil moisture in the system. In a study from southern Zambia, Thierfelder and Wall (2010a) found that greater soil moisture was maintained at 0-60 cm depth in dry-spells of 3–4 weeks duration. Shortages in available soil moisture are particularly relevant if they occur at critical periods of crop production (e.g. germination and/or anthesis).

In another experiment under semi-arid conditions of south-western Zimbabwe, volumetric soil water content was measured using a capacitance probe in conventional, ripper and basin systems at Matopos Research Station and Gwanda trial sites (Mupangwa 2009). Soil water was measured at 0.10 m depth increments up to 0.60 m during 2006/07 and 2007/08 cropping seasons. Soil water content in millimetres was determined by multiplying volumetric water content by thickness of each layer from which soil water was measured. Soil water measurement procedures at the Gwanda on-farm sites are also described in Mupangwa et al. (2016). All data were analysed using analysis of variance (ANOVA). Results from clay soil at Matopos Research Station, in Southern Zimbabwe led by ICRISAT (Mupangwa, unpublished) showed that conventionally ploughed sorghum fields maintained lower ($P < 0.001$) levels of soil moisture down to 0.60 m soil depth as compared with basin planted and ripline seeded fields on each occasion moisture measurements were taken (Fig. 2). The same applied for available soil moisture measurements from on-farm trials seeded with maize in Gwanda (Fig. 3). In some instances the ripper and basin systems had higher ($P = 0.013$) soil water content than the conventional treatment at the Gwanda sites. The gap between conventionally ploughed and CA treatments generally widened in periods of seasonal dry-spells while it narrowed during wet periods (Mupangwa, unpublished data). Available soil moisture was much lower in the maize fields in Gwanda (Fig. 3), due to an average rainfall of only 265 mm in cropping season 2007/2008 as compared with 416 mm in 2006/2007 at Matopos Research Station (Fig. 2). The average soil moisture in Matopos was 119 mm on both CA treatments whereas it was only 104 mm on the conventionally ploughed control plot in that particular year. This is a 14% moisture benefit, which can significantly affect plant production (Thierfelder and Wall 2010b; Thierfelder and Wall 2009; Rockström et al. 2009) in this drought-prone area. In Gwanda, the moisture benefit was 18–24% on the two CA treatments (average soil moisture 83–87 mm) as compared with the ploughed control treatment (70 mm) (Fig. 3).

Results from two regional long-term trials at the Monze Farmer Training Centre, Zambia (Monze) and Henderson Research Station, Zimbabwe (Henderson) previously

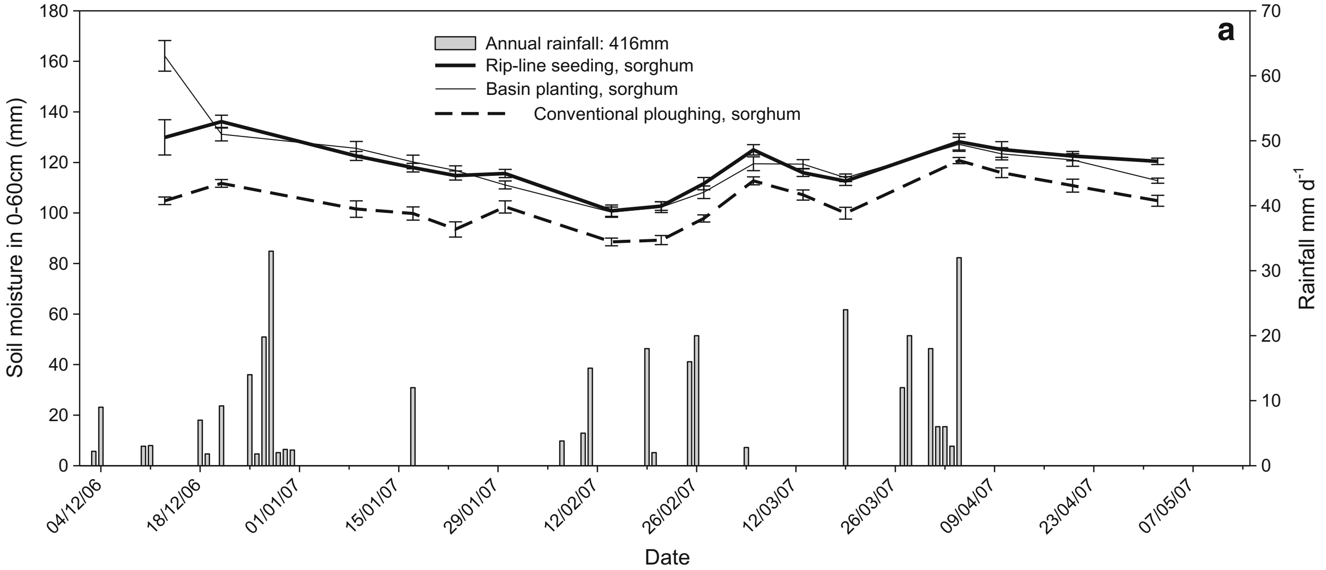

Fig. 2 Soil water content in the 0–60 cm profile at Matopos Research Station, Zimbabwe during the 2006/07 growing season. *Vertical bars* show the standard error of the difference (SED) ($n = 6$)

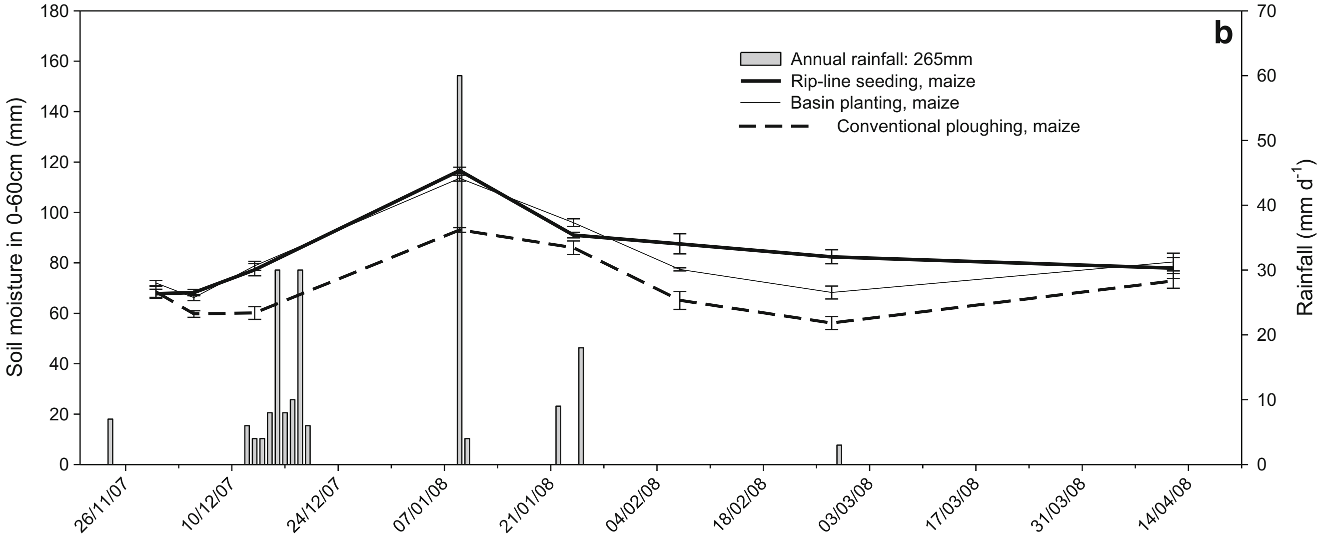

Fig. 3 Soil water content in the 0–60 cm profile across 4 on-farm sites in Gwanda district, Zimbabwe during the 2007/08 growing season. *Vertical bars* show the standard error of the difference (SED). (NB: Soil texture across the farms was loamy sand. Moisture was taken from fields with maize (Variety SC403) at all sites)

described by Thierfelder and Wall (2009), showed that there were differences between conventionally ploughed control treatments compared with different CA treatments on-site (Fig. 4). At Monze the available soil moisture at 0–60 cm

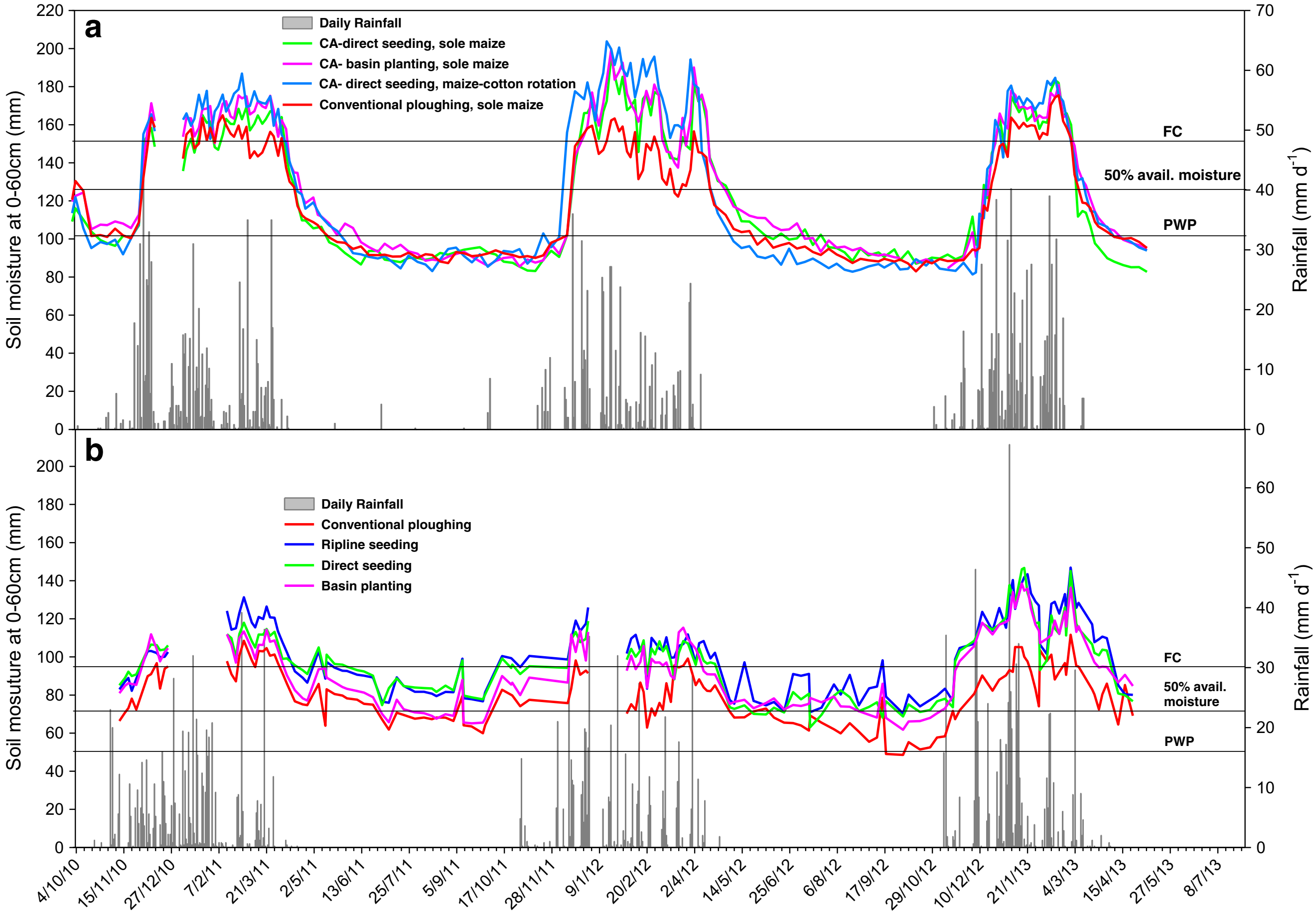

Fig. 4 Available soil moisture (in mm) in 0–60 cm soil depth in three CA systems and a conventionally ploughed control, Monze Farmer Training Centre, Zambia **a** and Henderson Research Station, Zimbabwe **b**, October 2010 – June 2013

depth closely followed the rainy season dynamics and CA systems consistently maintained a higher water content during the rainy season (Fig. 4). Similarly, the residual soil moisture at the beginning of the rainy season was consistently higher for CA treatments at Henderson (Fig. 4). The mean integrated soil moisture content showed an increase in soil moisture during the cropping season at both sites (Table 2), which ranged from 2%–19% in the different years in Monze and 10%–35% at Henderson (Table 2). The magnitude of soil moisture conservation was dependent on the soil texture: sandy loam at Monze and loamy sand and sand at Henderson (Thierfelder and Wall 2009). Increased available soil moisture at sowing provides a buffer against early season dry spells and is a major contributor to yield potential for low rainfall environments (Chenu et al. 2011). This translated into yield benefits at both sites (Table 2) and its magnitude depended on the rainfall distribution throughout the year.

Labour savings and early planting

A key aspect of adaptation is the flexibility to respond to new situations. Under a changing climate, it is essential that farmers make use of the first effective rains as this usually prolongs the growing season and results in greater yields. Labour bottlenecks at the onset of rain leading to delays in planting have strong effects on the performance of maize (Mazvimavi and Twomlow 2009). No-tillage seeding practices especially the ones that enable faster seeding (i.e. direct or ripline seeding systems) and/or spreading of labour for planting such as in the basin planting systems (Sims et al. 2012), give farmers a distinct advantage at the onset of rains. For example, basins are traditionally dug during the dry winter season (Mazvimavi and Twomlow 2009) and ripline or direct seeding can be done at seeding without having to wait for a field to be ploughed (Thierfelder et al. 2016b; Nyamangara et al. 2014b) reducing the labour demand. Part of the yield advantages resulting from CA systems occur due to timely planting which shows great adaptation potential of the system (Oldrieve 1993).

Early planting also allows farmers to prepare a larger area or plant additional crops during the year (e.g. planting an early maturing maize followed by cowpeas or beans). This flexibility can cushion farmers in marginal environments where crop production is dependent on optimal use of limited soil moisture (Thierfelder et al. 2014; Nyamangara et al. 2014b; Rusinamhodzi et al. 2012).

In summary, adaptation of CA systems to the negative effects of climate variability and change through greater infiltration and increased soil moisture retention is well documented and widely accepted (IPCC5 2014a; Ngwira et al. 2013; Thierfelder and Wall 2009). Besides potential labour savings during planting and weeding (especially if herbicides are

Table 2 Mean integrated soil moisture in 0-60 cm soil depths and maize grain yield in three conservation agriculture treatments and one conventionally ploughed control at the Monze Farmer Training Centre, Zambia and Henderson Research Station in four cropping seasons 2009–2013

	2009/2010			2010/2011			2011/2012			2012/2013		
	Soil moisture mm	Change %	Yield kg ha^{-1}	Soil moisture mm	Change %	Yield kg ha^{-1}	Soil moisture mm	Change %	Yield kg ha^{-1}	Soil moisture mm	Change %	Yield kg ha^{-1}
Monze farmer training centre												
Conventional ploughing, maize	141.8 c		3011 b	143.2 c		3067 b	136.0 c		3378 c	130.8 b		2477 b
CA-Direct seeding, maize	148.3 b	5	3874 ab	146.9 b	3	4473 a	151.9 b	12	4283 b	132.8 b	2	3489 a
CA-Basin planting, maize	156.2 a	10	3968 ab	154.7 a	8	4523 a	154.4 b	14	4167 bc	137.3 a	5	2943 ab
CA-Direct seeding, maize-cotton	156.5 a	10	4690 a	156.6 a	9	4197 a	162.0 a	19	5174 a	137.4 a	5	3797 a
LSD ($P < 0.05$)	5.1		991	3.6		741	5.6		887	3.9		1003
Henderson research station												
Conventional ploughing, maize	89.9 d		1373 c	90.1 c		4402 b	82.7 d		2464 b	88.1 c		2104 b
CA-Ripline seeding, maize	121.1 a	35	2288 ab	106.6 a	18	5871 ab	105.4 a	27	3888 a	117.8 a	34	2739 ab
CA-Direct seeding, maize	109.0 b	21	1818 bc	103.4 a	15	5365 ab	101.7 b	23	3864 a	112.8 b	28	3257 a
CA-Basin planting, maize	99.1 c	10	2398 a	98.9 b	10	6125 a	97.9 c	18	3423 ab	111.1 b	26	3096 ab
LSD ($P < 0.05$)	4.5		562	4.2		1625	3.5		999	3.2		1068

Adapted from: Thierfelder and Wall (2009, 2010a, b) means followed by different letters in column are significantly different at $P<0.05$ propability level used), it is the moisture conservation aspect that makes it most attractive to farmers in moisture limiting situations which are common in Southern Africa and are predicted to increase in years to come with increased climate variability and change (Lobell et al. 2008).

Furthermore, reduced labour requirements for seeding allow for timely seeding with the first effective rains, which often leads to greater yields, making use of the full cropping season. This can lead to the use of longer season maize varieties, greater hectarages under maize, double cropping where possible, and cropping in marginal environments, which may all benefit farmers under climate uncertainty.

Mitigation

Besides adaptation, mitigation is critical in making a cropping system climate-smart. There are basically two mitigation elements that can be associated with CA systems: a) sequestration of SOC; and b) reduction of greenhouse gas (GHG) emissions. While results on SOC have largely been variable (Govaerts et al. 2009; Cheesman et al. 2016; Luo et al. 2010) solid information on GHG emissions under CA is slim (Kimaro et al. 2015; Smith et al. 2008b), especially from studies in Africa.

Effects of CA on carbon sequestration

In general among terrestrial ecosystems, soils contain the largest pool of C, storing up to 1502 Pg C ($Pg = 10^{15}$ g) in the top one metre (Jobbágy and Jackson 2000) with about a tenth of that in arable land. Consequently, management of soils can significantly impact C stocks in the soil pool and in the atmosphere. CA has potential influence on soil organic matter decomposition and the loss of C from the soil. For example, Havlin et al. (1990) observed greater SOC under no-tillage particularly when maize was rotated with soybeans. This was greater than under conventional tillage even when the conventional systems were rotated. Using a global database, West and Post (2002) calculated that, on average, no-tillage sequestered 57 ± 14 $g\ C\ m^{-2}\ yr.^{-1}$ SOC following conversion from conventional tillage. In contrast, Powlson et al. (2014) argued that often no-tillage only alters the depth distribution of SOC with little potential to sequester C as a whole compared with conventional tillage systems. Similarly, Baker et al. (2007) concluded that SOC is sequestered only in the top-soil under no-tillage. Luo et al. (2010), analysing the results of 69 paired experiments, showed that C increased for no-tillage systems in the first 10 cm but declined at depths of 20–40 cm. However, there was an overall net increase in C under no-tillage.

In Southern Africa, the results from studies of the effects of CA on C sequestration have been variable, and a summary of the published literature is shown in Table 3. For example in Zimbabwe, Thierfelder and Wall (2012) observed positive changes in soil SOC with CA in the top 20 cm soil depths, although these changes were marginal on clay soils while greater on sandy soils. In a study in Zambia, Thierfelder et al. (2013c) recorded greater SOC under CA compared with conventional agriculture in the top 30 cm soil depths (Fig. 5). After five years' CA treatment, using direct seeding with a maize cotton rotation SOC was 46% (9.7 $Mg\ ha^{-1}$) greater compared with a conventional plough treatment with sole maize: here SOC continuously declined over the research period. In a study in Zimbabwe, Nyamadzawo et al. (2008) measured greater SOC under no-tillage than conventional tillage in a fallow system and the increased organic C was attributed to large biomass produced during the fallow period. In a study from central Mozambique, Rusinamhodzi et al. (2012) intercropped maize with pigeonpea (*Cajanus cajan* (L.) Millsp.) for up to five years and showed huge increases in SOC, which became larger the longer the intercropping lasted. Similar results were observed by Ngwira et al. (2012) from Malawi, where they observed a 76% increase in SOC when maize was intercropped with legumes. Carbon increases were also observed in trials in Zimbabwe in a wheat-cotton rotation (Gwenzi et al. 2009) and in a maize-soybean rotation (Mujuru et al. 2013) (Table 3).

In contrast to these afore mentioned results, a recent meta-analysis of field-based CA studies from Southern Africa carried out by Powlson et al. (2016) suggested that there was only a small increase in SOC under CA if only no-tillage and cereal residue retention were practised although the increase was more substantial once diversified crop rotations were introduced. Cheesman et al. (2016), who did a regional study in Malawi, Mozambique, Zambia and Zimbabwe in 23 target communities with replicated on-farm trials, found little increase in SOC stocks. They compared CA systems with up to six years of CA treatment with a conventional tilled control practice. The main reason for lack of increase was attributed to low primary biomass production, the limited amount of crop residues retained, bush fires or grazing cattle and the long dry season which increased decomposition and export of plant material by termites (Cheesman et al. 2016). In a study across 15 districts of Zimbabwe on 450 farms, Nyamangara et al. (2013) observed little change in SOC under CA, mainly due to most farmers not applying the three principles of CA. However, C sequestration was dependent on the agro-ecology and increased with duration of CA practice. In a separate study in Zimbabwe, Nyamangara et al. (2014a, b) observed that, after CA treatment for 5 years, there was about a 70% increase in SOC in sandy soils and a 40% increase in finer textured soils compared with conventional agriculture. (Nyamangara et al. 2014a). In Malawi, on different study sites, Ngwira et al. (2013) observed no differences between

Table 3 Conservation agriculture effects on soil organic carbon (SOC) in Southern Africa

Soil depth (cm)	SOC			Cropping system	Time under CA	CA principle			Soil texture	Country (MAP; mm)	Reference
	Conv	CA	Units			*Tillage	$^{\xi}$Mulch	§Rotation/ Intercrop			
0–30	25.7	28.9	Mg ha^{-1}	Maize legume	2–6	DS	+	IN	sandy loam; loamy sands; sandy clay loams	Malawi, Mozambique, Zambia, Zimbabwe −23 sites (400–1600)	Cheesman et al. 2016
0–30	14.9	16.8	Mg g^{-1}	Continuous maize	9	RP	–	–	Clay	Zimbabwe	Chivenge et al. 2007
		17.2				RP	+	–		(800–1000)	
		20.4				TR	–	–			
	4.2	4.6				RP	–	–	Sand		
		6.8				RP	+	–			
		4.8				TR	–	–			
0–15	2.9	5.6	g kg^{-1}	Wheat – cotton	6	RP	+	RT	Sandy loam	Zimbabwe (482)	Gwenzi et al. 2009
		5.8				NT	+	RT			
0–10	5.2	6.4	Mg ha^{-1}	Maize - legume	4	RP	+	RT	Sandy	Zimbabwe (800–1000)	Mujuru et al. 2013
		6.9				ATDS	+	RT			
	19.1	18.2				RP	+	RT	Clay		
		18.0				ATDS	+	RT			
0–10	14.3	15.4	g kg^{-1}	Maize – legume	6	DS	+	–	Sandy clay loam	Malawi	Ngwira et al. 2013
		13.3				DS	+	RT		(935)	
	9.1	8.6				DS	+	–	Loamy sand	(1375)	
		10.6				DS	+	RT			
0–20	5.9	10.4	g kg^{-1}	Maize	5	NT	+	IN	Loamy sand	Malawi – 4 sites (500–1500)	Ngwira et al. 2012
0–10	7.0	8.7	g kg^{-1}	Maize –agroforestry	10	NT	+	RT	Loamy sand	Zimbabwe	Nyamadzawo et al. 2008
	5.9	6.0				NT	+	–		(750)	
0–20	4.4	5.4	g kg^{-1}	Maize - legume	9	BS	+	RT/–	Various	Zimbabwe (750–1000)	Nyamangara et al. 2013
	9.4	9.0								(750–1000)	
	5.6	7.8								(500–750)	
	5.0	5.6								(450–650)	
0–15	9.4	15.9	Mg ha^{-1}	Maize – legume	5	BS	+	RT/–	Sandy	Zimbabwe	Nyamangara et al. 2014a
0–15	20.5	28.4	Mg ha^{-1}		5	BS	+	RT/–	Clay loam	(variable; 450 farms)	
0–20	0.2	1.4	%	Maize - legume	5	NT	+	IN	Sandy	Mozambique (900)	Rusinamhodzi et al. 2012
0–10	0.6	0.8	%	Maize – legume – cotton	4	ATDS	+	–	Loamy Sand	Zambia	

Table 3 (continued)

Soil depth (cm)	SOC Conv	CA	Units	Cropping system	Time under CA	CA principle *Tillage	ξMulch	§Rotation/ Intercrop	Soil texture	Country (MAP; mm)	Reference
											Thierfelder and Wall 2010b
		0.7				ATDS	+	RT		(748)	
		0.8				ATDS	+	RT			
0–10	3.2	4.5	Mg ha^{-1}	Maize	5	ATDS	+	–	Sandy	Zimbabwe	Thierfelder et al. 2012b
	7.1	9.0				ATDS	+	–		(650–800)	
0–10	8.1	10.6	Mg ha^{-1}	Maize – legume	4–6	NT	+	–	Sandy	Zambia	Thierfelder et al. 2013b
		11.4				NT	+	+		(700–1000)	

CA conservation agriculture

*Tillage: *DS* dibble stick, *NT* no till, *TR* tied ridging, *RP* ripper, *ATDS* direct seeder, *BS* planting basins

ξ Mulch: + with mulch; – no mulch

§ Crop diversification: RT – rotation; IN – intercrop; – no intercrop or rotation

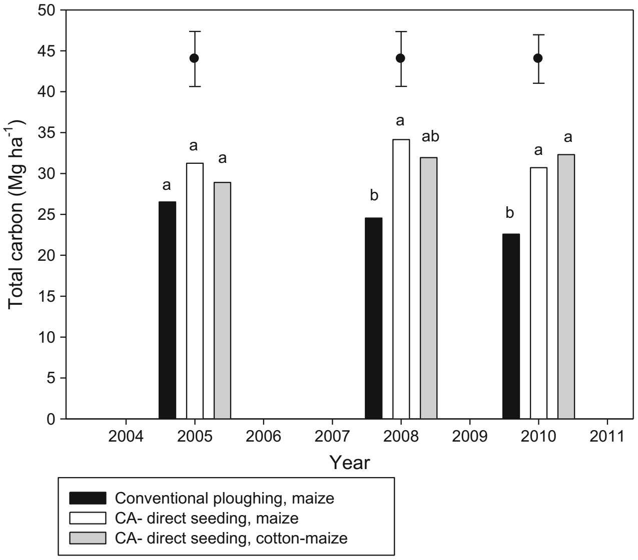

Fig. 5 Total carbon stocks at Monze Farmer Training Centre, Zambia, 2005–2010. Adapted from Thierfelder et al. (2013c). Note: *Error bars* show the standard error of the difference (SED); means followed by different *letters* in column are significantly different at $P<0.05$ probability level

CA and conventional agriculture after six years of experimentation. Similarly, Chivenge et al. (2007) observed no changes in SOC, nine years after conversion from conventional tillage to reduced tillage systems in a sandy soil, except when crop residues were returned to the soil as mulch. However, in the same study in a clayey soil, SOC was greater under reduced tillage and was associated with increased protection of organic C within aggregates compared with conventional tillage, suggesting that the potential for C sequestration also depends, to a large extend, on soil conditions.

One specific form of CA, commonly labelled as CAWT (CA with Trees), has recently gained more attention as their proponents see great potential and benefit of integrating tree-based elements into traditional maize-based systems with associated benefits in C sequestration (Garrity et al. 2010; Verchot et al. 2007; ICRAF 2009). There is general agreement that agroforestry system could enhance the sequestration of C (Nair et al. 2009; Tonucci et al. 2011). However, recent research suggests that there are poor data on this (Nair 2011). Little research has been done to date to quantify the effects of tree-based elements in a cereal-based CA system on SOC, which highlights an emerging research gap.

Greenhouse gas emissions

Globally, few studies have focussed on GHG emissions under CA, and they are even scarcer in Africa. Additionally, most of the studies have focussed more on the effects of different fertilization strategies on GHG emissions (Mapanda et al. 2011; Gentile et al. 2008; Millar et al. 2004) than on the contributions of different CA components and there are very few systems studies that have had a combined look at the effects of all CA principles on GHG emissions (Kimaro et al. 2015). Furthermore, many of the studies have focussed on the different GHG separately, yet there is a need to have a holistic evaluation of the emissions under CA, in order to fully evaluate the mitigation potential of this cropping system. Globally Six et al. (2004) observed that the potential for no-tillage to mitigate GHG emissions in the temperate climates can only be realized in the long term. There were no differences in N_2O emissions after three decades between no-tillage and conventional tillage although the emissions tended to be lower under no-tillage than conventional tillage, particularly when there were rotations (Six et al. 2004).

In contrast, Venterea and Stanenas (2008) observed greater N_2O emissions under no-tillage compared with conventional tillage and that emissions were greater when N fertilizer was placed on the surface. Similarly, Liu et al. (2006) observed greater N_2O emissions under no-tillage than conventional tillage but CH_4 emissions were greater under conventional tillage. Linn and Doran (1984) observed greater water filled pore space in the upper 7.5 cm soil depth under no tillage compared with conventionally tilled soils and this resulted in greater CO_2 and N_2O emissions under no tillage than conventional tillage. In a meta-analysis, van Kessel et al. (2013) observed that there were no differences between conventional tillage and reduced tillage systems on N_2O emissions. However, when disaggregated by climate, in experiments carried out over 10 years, N_2O emissions were 27% lower under reduced tillage than conventional tillage in drier climates. No tillage increases soil moisture conservation (Alvarez and Steinbach 2009; Thierfelder and Wall 2010b) and is thus expected to increase N_2O emissions (Grandy et al. 2006). The decrease in N_2O emissions in the long term under no tillage may be due to increased soil organic matter, which increases aggregate stability and thus decreases anaerobic microsites where denitrification could have occurred (Six et al. 2004). This suggests that in the long-term, CA may cause a decline in N_2O emissions and this is relevant for Southern Africa where rainfall is predicted to become more erratic due to changing climate (Lobell et al. 2008). In Kenya, Baggs et al. (2006) observed that no-tillage following the addition of *Tephrosia ssp.* branches and leaves (brown manuring) resulted in a decrease in N_2O emissions compared with conventional tillage with the addition of *Tephrosia ssp.,* but there were no differences in CO_2 and CH_4 emissions. In that study, they estimated the global warming potential to be reduced by 41 g CO_2 equivalents with the conversion of conventional tillage to no-tillage. In Zimbabwe, Chikowo et al. (2004) observed that no-tillage lowered N_2O emissions eight weeks after the addition of *Sesbania sesban* (L.) residues in an improved fallow system.

Results from various studies showed that no-tillage reduced CO_2 emissions compared with conventional tillage agriculture practices (e.g. Al-Kaisi and Yin 2005, Bauer et al. 2006 and Sainju et al. 2008). Conventional tillage breaks down aggregates and exposes organic matter to microbial decomposition with release of CO_2 (Six et al. 2002). In a study done on chromic *Lixisols* in Zimbabwe, O'Dell et al. (2015) found out that a winter wheat cover crop produced a net accumulation of 257 g CO_2-C m^{-2} under no-tillage, while tilled plot with no cover crop produced a net emission of 197 g CO_2-C m^{-2} and the untilled plot with no cover emitted even higher rates of 235 g CO_2-C m^{-2}. Additionally, growing a cover crop during winter or even weeds led to a positive sequestration balance.

Form and placement of N fertilizer (Mengel et al. 1982) as well as soil moisture content (Wulf et al. 1999) in no-tillage systems have an effect on N losses and consequently on GHG emissions through volatilization, which may be reduced when surface mulch is applied. Oorts et al. (2007) also observed 29% greater CO_2 emissions under no-tillage than conventional tillage, and they attributed this to greater moisture conservation and hence increased biological activity under no-tillage. In a global meta-analysis, Abdalla et al. (2015) observed that conventionally tilled soils emitted 21% more CO_2 than untilled soils, with greater emissions occurring in sandy soils and arid in arid climates. However, out of the 46 studies used in the meta-analysis, only one study was done in Africa, which evaluated short-term greenhouse gas emissions under contrasting tillage in agroforestry systems in Kenya (Baggs et al. 2006). Consequently, there is still a need for research to evaluate the effects of CA on GHG in Southern Africa, particularly in systems where all three components of CA are implemented.

Influence of erosion on soil carbon

Soil erosion has traditionally been overlooked as a driver of SOC dynamics. However, until recently this has not been acknowledged properly (Stallard 1998; Lal 2003). While soil erosion studies in the region date as far back as the 1950s e.g. Hudson (1957), the role of erosion in C dynamics has been largely ignored. Lateral movement of SOC through erosion may induce losses of C from the soil into the atmosphere. During detachment and transportation, soil C is exposed and decomposed with emissions of CO_2 to the atmosphere. Conventional tillage has been shown to induce lateral transport of particulate and dissolved organic C (Jacinthe et al. 2002; Mchunu et al. 2011). Mchunu et al. (2011) in South Africa observed that soil and SOC losses under no-tillage were 68% and 52% less than conventional tillage, respectively, with most of the C in the sediments being particulate organic C. Soil erosion has also been observed to be greater under conventional agriculture compared with CA in trials in Zimbabwe (e.g. Thierfelder and Wall 2009 and Munyati 1997). However, other studies have concluded that soil erosion is a sink rather than a source of CO_2 to the atmosphere because the eroded C is buried in deeper horizons where it is protected from decomposition (Van Oost et al. 2007; Berhe et al. 2007).

In summary, there are contradictory statements about the ability of CA and no-tillage farming systems to mitigate the negative effects of climate change (i.e. sequestering C, reducing GHG emissions etc.). If there are benefits in SOC sequestration and GHG, they will mostly occur in the medium to long term, and its positive impact, will largely depend on the agro-ecological environment, the length of practice, the biomass input and the cropping systems. We expect that due to the typically semi-arid conditions of Southern Africa, changes in GHG balances due to adoption of CA will be relatively small in either direction (unless massive input of C and N is included).

CA and productivity increase

For farmers to cope with the effects of climate change and maintain or increase food security and nutrition over time, there is need to provide reliable and diversified crop yields from both cereals and legumes even under a changing climate (Thierfelder and Wall 2010a). Stable yields are possible if the cropping systems are more resilient to climate variability, have adequate nutrient supply and break pest and diseases cycles.

Effects of CA on grain yield

Numerous studies on smallholder farms have focussed on studying the effects of CA on maize grain yield under the prevailing conditions of Southern Africa. (Thierfelder et al. 2014, 2015a, 2016a, 2013b; Ngwira et al. 2013;Nyamangara et al. 2013, 2014b, Mazvimavi et al. 2010; Mazvimavi and Twomlow 2009). From regional studies in Malawi, Mozambique, Zambia and Zimbabwe increases in maize productivity were reported in more than 80% of cases when CA systems with maize were compared side-by-side with conventional systems in target communities of Southern Africa (Fig. 6a) (Thierfelder et al. 2015a). These studies also highlighted that the yield benefit increases over time, favouring CA systems in the medium to long-term. Wall et al. (2013), reviewing 23 studies from Eastern and Southern Africa across diverse environments found only five studies where a yield decline on CA fields of >10% over conventional control practices have been reported.

However, most studies and scholars would agree that there is no immediate yield benefit when practising CA and there is a delay of between 2 and 5 years until yield benefits of maize materialize (Thierfelder et al. 2013b, 2015a). This delay has biophysical and social reasons (Wall 2007; Thierfelder et al. 2015b). Changing to no-tillage with residue retention will result in short term nitrogen immobilization, increases in bulk density, reduced mobilization of nutrients from C mineralization, increased temporary weed pressure and a potential increase in

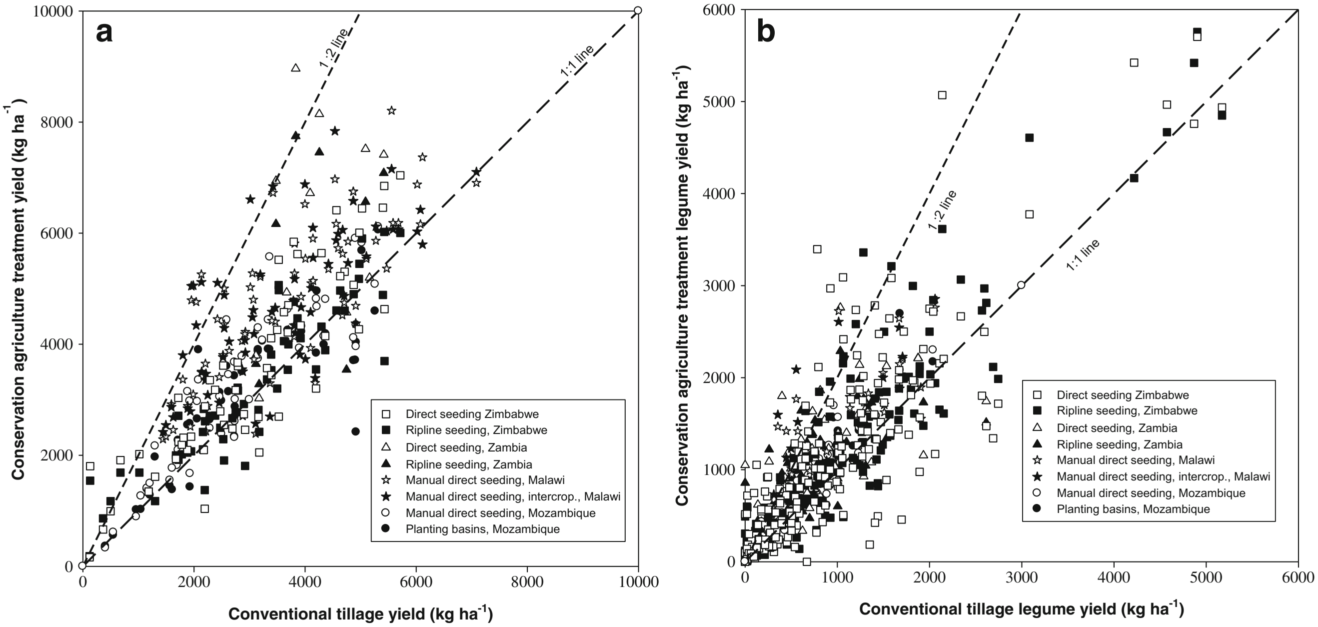

Fig. 6 **a** and **b** The overall relative advantage of conservation agriculture cropping systems over conventional tillage systems across sites and across seasons in southern Africa for maize **a** and legumes **b**. Data points on or below the 1:1 line do not show a relative advantage of conservation agriculture, and those on the 1:2 line show that CA yields were double those of conventional tillage. Adapted from Thierfelder et al. (2015a)

some pest and diseases (Giller et al. 2015; Gentile et al. 2011; Verhulst et al. 2010; Fernández-Ugalde et al. 2009). Farmers also have to learn new management steps when switching to CA such as a) new land preparation and planting techniques; b) new residue, weed and crop management strategies which all require c) knowledge and new skills thus potentially delaying the performance of CA systems. The slow yield response of CA systems has been highlighted as a major impediment to its immediate adoption (Giller et al. 2009). Cash-constrained and food insecure smallholder farmers in Southern Africa are believed to need immediate returns from a new technology in order to adopt it (Giller et al. 2009; Corbeels et al. 2014). However, Baudron et al. (2015b) have argued against this and said where farm labour and soil moisture are critical, the likelihood of adoption is high.

Yield benefits were closely related to the agro-ecological environment, in-seasonal rainfall distribution (Fig. 7a, b) and the CA systems used (Nyamangara et al. 2014b). While yield benefits in some drought-prone environments in Southern Zimbabwe occurred almost immediately, better results needed more time in more favourable environments on more fertile soil types (Thierfelder and Wall 2012). Moisture has been a major limitation when growing maize under CA below a threshold of 600 mm on granitic sandy soils (Nyamangara et al. 2014a; Nyamangara et al. 2013; Mupangwa et al. 2012; Mupangwa et al. 2007). Total maize crop failure has also been recorded in conventional, basin and ripper systems when 297–403 mm of poorly distributed seasonal rainfall was received in some parts of south-western Zimbabwe (Mupangwa 2009). It has been highlighted that CA system require sufficient crop residues to function. In areas of recurrent droughts and/or long dry-spells it will be extremely difficult to generate enough biomass for surface retention thus limiting the application of CA systems in such environments.

Crop diversification, through rotations or intercropping, an essential component of CA (FAO 2015), often includes legumes in Southern Africa, which are pivotal in improving yields in low input agriculture systems (Thierfelder et al. 2012; Thierfelder and Wall 2010b). Legumes fix nitrogen, improve soil fertility and nutrient cycling and thus improve crop productivity (Chikowo et al. 2006; Mafongoya et al. 2006; Rusinamhodzi et al. 2012). Legume based cropping systems have improved soil fertility, coupled with increased soil nitrogen and SOC (Drinkwater et al. 1998). Increasing biodiversity in agroecosystems is associated with greater nutrient cycling and crop productivity (Smith et al. 2008a). Additionally, greater biodiversity in ecosystems is associated with greater resilience because of the ability to break pest and disease cycles that often limit crop production in farming systems (Lin 2011; Krupinsky et al. 2002).

For legumes, significant yield benefits under CA often materializes slower as they do not immediately respond to soil quality improvements (Thierfelder et al. 2012, 2016a). However, in most cases and very similar to maize, and if there were no underlying soil fertility problems (i.e. low pH, P, Mg or Zn deficiencies), significant increases may be obtained after 5 years of CA practice (Fig. 6b).

These results are supported by a regional study (Thierfelder et al. 2015a) and are in contrast to results from a meta-analysis done by Pittelkow et al. (2015), which mostly evaluated sole no-tillage systems. They also did not take into account many of the moisture limiting situations in Southern Africa as they had incorporated very few studies from this area.

Productivity increase under drought stress

Under the conditions of Southern Africa, benefits in yield of maize grain in CA systems under drought or erratic rainfalls

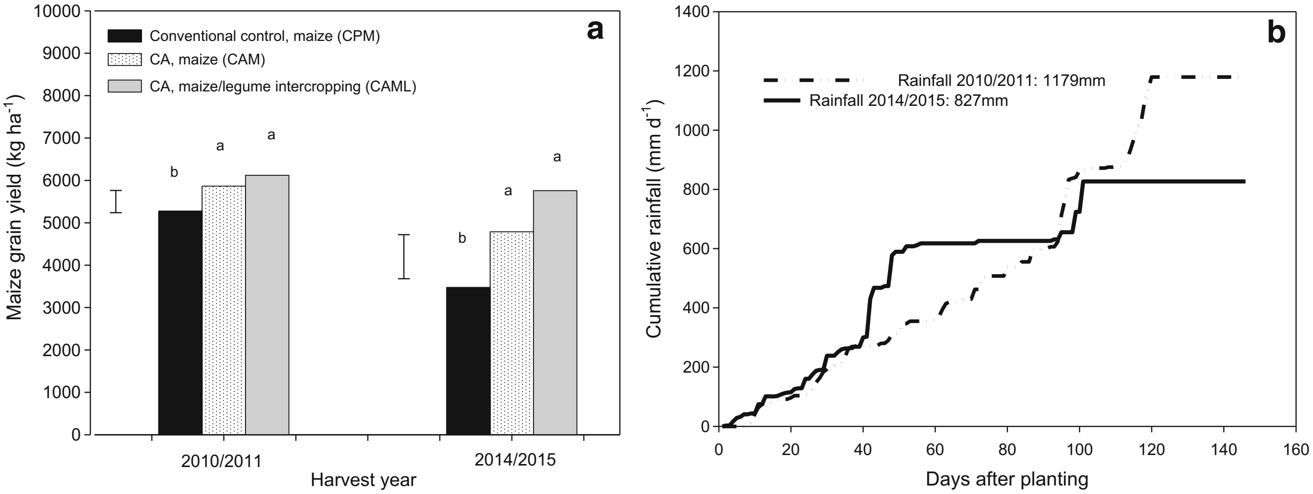

Fig. 7 **a** and **b** Maize grain yield in two CA and one conventionally tilled treatment **a** in a year (2010/2011) with well distributed rainfalls and a year (2014/2015) with moisture stress around anthesis **b**, Mwansambo, Central Malawi. *Error bars* show the standard error of the difference (SED). Adapted from Thierfelder et al. (2015b)

were recorded (Fig. 7a, b). When the rainfall was well distributed such as in year 2010/2011 (Fig. 7b), there was only a 12%–16% (or 592–847 kg ha^{-1}) maize yield benefit of practising different CA systems as compared to a conventional control (Fig. 7). In a year with a more than 40 day long dry spell (2014/2015) during the critical stages for kernel number development (e.g. anthesis), the benefit of CA was much greater and ranged between 38% and 66% (or 1314–2815 kg ha^{-1}). This leads to the conclusion that some CA systems can withstand seasonal dry-spells more effectively as has been previously documented by Thierfelder and Wall (2010a).

Profitability of CA systems

As mentioned above, an increasing number of studies have recently been published documenting the biophysical benefits (e.g. increased yield) of CA systems in Southern Africa. However, to date, the available data on economic benefits is still slim (Grabowski and Kerr 2014; Mazvimavi 2011; Mazvimavi and Twomlow 2009; Ngwira et al. 2013; Thierfelder et al. 2016c, 2016b). In general, the number of partial or whole-farm budgets is limited as capturing farm labour and gross benefits is very challenging. The reasons for low quality economic data are manifold: a) farmers often use family labour; b) there is no established market for residues; c) there are often no formal markets for legumes; d) if markets are available, the prices fluctuate considerably depending on the type of buyers, amongst other reasons. Partial budget procedures (CIMMYT 1988) have been used to calculate labour use and net benefits from three cropping systems in Mwansambo, Central Malawi (Fig. 8a, b) (Thierfelder et al. 2016c). The figures show a combined analysis over three cropping seasons. On average between 53% and 59% less labour was used to practise different types of CA which translates into a labour saving of between 33 and 37 labour days ha^{-1} (Fig. 8b). Relatively more labour was needed in Malawi on the conventional control treatment as the traditional land preparation of making ridges takes significantly more labour time, which often disadvantages women and children. Over the three years, net benefits were 855–1699 USD ha^{-1} greater on CA systems as compared with the conventional practice.

What is often overlooked in budget analyses is the potential increase in costs if farmers start using external inputs such as herbicides for weed control under CA. For cash constrained households this can be an impediment to successful implementation and uptake of CA amongst smallholder farmers, as pesticides are often not affordable or accessible. However, results from weed studies under CA also show a decline in weed pressure over time under CA no matter if they are controlled chemically or manually (Muoni et al. 2014), which could help farmers in the longer term.

In summary, CA systems have the potential to both increase maize and legume grain yield as well as economic returns and therefore fulfil the third requirement of being climate-smart. However, as stated in previous publications and by other authors, the yield benefit is not immediate and there is a time lag of 2–5 cropping seasons until significant yield benefits occur. A major driver of CA adoption around the world has been the increased profitability due to decreased labour and energy needs (Baudron et al. 2015b). The results from Malawi show that direct seeding systems of planting on the flat without land preparation (e.g. ridging) can have a positive influence on farm labour which increases the immediate acceptance by smallholder labour-constrained farmers, despite no immediate yield benefit in the CA system (Bunderson et al. 2015).

Overall assessment

CA is one of the most heavily researched agricultural systems in Africa; however, there are many facets of climate-smartness not covered in the literature. An overall assessment of CA,

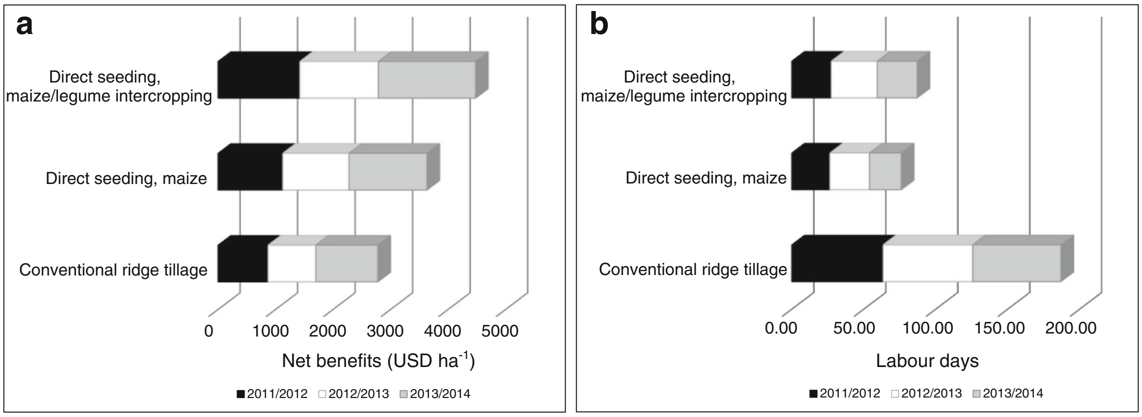

Fig. 8 **a** and **b** Net benefits and labour days of two CA cropping systems and a conventional control in Mwansambo, Central Malawi, 2011–2014. Adapted from Thierfelder et al. (2015b)

summarizing current knowledge based on literature gathered through a systematic review (Rosenstock et al. 2016) and evaluated through a small CSA expert interview ($N = 8$) provides a first appraisal on the many components of climate-smartness (Table 4).

CA and its principles are typically believed to positively affect factors related to productivity, physical resilience and climate change mitigation (Table 4). Notably, evidence and experts suggest that yields and yield stability will improve with CA component practices and systems, except when only using reduced or no tillage alone. However, some outcomes are either likely to be mixed, negative or undetermined. For example, as discussed above, CA may reduce or increase labour pressure by comparison to conventional practices depending on context and farming system. Similar effects may occur to farm-level income.

Perhaps the most widely suggested benefit of CA for CSA is to help adjust the physical resilience of production systems through adaptation; in particular, buffering production systems against changes in rainfall quantities, patterns and intensities. Full CA and CA with trees universally reduce the impact of these challenges. However, component CA practices have undetermined or even potentially deleterious effects. For example, reducing tillage can decrease resilience of soils when climate change increases the rainfall intensity due to soil crusting, sealing and decreased infiltration. In general, the impacts of individual component practices for resilience so far are not well worked out empirically.

Despite widespread promotion for climate change mitigation, CA is not likely to greatly contribute to climate change mitigation in southern Africa. CA is suggested to help principally with soil C sequestration. However, evidence shows that under certain circumstances SOC may increase with CA, while in other citations it decreases or stays the same, being controlled by local agro-ecological constraints and agronomic practices. Less is known about the impact of CA on soil fluxes, N_2O and CH_4 emissions due to the complex C and N dynamics set up by the decomposing nutrient rich materials and the change in hydrological conditions. At this time, the overall potential of CA for climate change mitigation, especially on balance of sequestration and emissions, is unknown and requires more research.

Our assessment depends on expert opinions and assumptions about the characteristics of soils, rainfall and agronomic practices. This assessment therefore represents a litmus test of likely impacts but is not definitive. Interpretation of this qualitative scoring should be done with caution as the cause-consequence relationship is variable due to edaphic factors at any given location and agro-ecology.

Conclusion

Conservation agriculture and its precursor, conservation tillage, in Southern Africa has been studied since the 1980s, with more detailed research starting in 2004 by various initiatives and research groups. Increasingly it has been promoted as a "climate-smart agriculture" cropping system, which should help farmers to adapt and mitigate the negative effects of climate variability and change as well as increasing the productivity and income of current farming systems. This paper summarizes what we know about the potential of CA to deliver on the three principles of climate-smart agriculture (i.e. adaptation, mitigation and productivity).

The results show that CA has potential to adapt to some negative effects of climate variability, which are commonly observed during in-season dry-spells. It is widely accepted that it increases infiltration and reduces evaporation due to increased biological activity, beneficial pore structure and surface protection through crop residues. In maize-based systems, the combined effect of increased infiltration and reduced evaporation often leads to greater soil moisture which helps to buffer in-season dry-spells and/or prolonged periods of low rainfall. However, too much rainfall may also lead to reductions in yield on CA fields, as they tend to accumulate too much water in periods of heavy rainfall. CA systems help farmers in Southern Africa to plant early, which has great impacts on final grain yields.

There is little knowledge to date about the potential of CA to mitigate negative effects of climate change e.g. to increase C sequestration or reduce GHG emissions. The main reason for the lack of knowledge is that very few studies have focussed on this in the past and present research and the available data are often insufficient, contradictory and sometimes misleading. However, increased mitigation (both C sequestration and reduced GHG emissions) is likely to be achieved if more diversified crop rotations are practised and/or tree-based components added to monocropped maize-based farming systems of Southern Africa. However, little work has been published so far on CA with trees to clearly quantify this effect. What we know to date is that little C is sequestered on cereal-based CA fields under the conditions of Southern Africa due to a range of reasons (e.g. insufficient biomass production and retention, long dry winter season, extensive grazing and bush fires amongst others). Incorporation of trees and shrubs as well as green manure cover crops may therefore increase the C input thus leading to a gradual increase in SOC over time. CA systems may decrease CO_2 but may also lead to greater N_2O emission thus making its mitigation potential climate neutral. Nevertheless, a decrease in soil erosion which is likely to happen with CA will also decrease the loss of precious organic matter in rich top-soils which will have an influence on the overall mitigation potential of CA.

Finally, CA has proved to increase productivity and profitability in numerous trials in Southern Africa. However, the yield benefit does not occur immediately and there is a lag period of 2–5 years until the yield benefit becomes apparent.

Table 4 Assessment of conservation agriculture (CA) systems and their components to key characteristics of climate smart agriculture in developing countries

	Indicators of climate-smart agriculture																
	Productivity						Adaptation [physical resilience (Field Scale)]							Mitigation			
Practices and systems	Grain yield	Yield stability	Labor	Income	Women's		Incr. temp.	Intra-seasonal droughts	Short-ening seasons	Unpredictable seasons	Rainfall intensity	Soil aggregation	WHC	Soil C	Biomass C	N_2O	CH_4
					Labor	Income											
Land preparation																	
Reduced tillage	+/−	+	−	+/−	++	+/−	+	+	+	+/−	−	+	+/−	+/−	+/−	+	+/−
No till	+/−	+	−	+/−	++	+/−	++	+	++	+/−	−	+	+/−	+/−	+/−	+	+/−
Residue management																	
Mulch	+	+	−	−	+	+/−	+	++	++	+	++	+	+	+	+/−	+	−
Diversification																	
Green manure	+	+	−	+/−	+	+/−	+	+/−	+/−	+/−	+	+	+/−	+	+/−	+	+/−
Crop rotation	+	+	+/−	+/−	+/−	+/−	+/−	+/−	+/−	+/−	+/−	+	+/−	+/−	+/−	+/−	+/−
Legume intercrop	+	+	+/−	+	+/−	+/−	+/−	+/−	+/−	+/−	+/−	+	+/−	+	+/−	+/−	+/−
Cropping systems																	
CA	+	+	+/−	+/−	++	+/−	+	+	+	+	+	+	+	+/−	+/−	+	+/−
CA w/ trees	++	++	+/−	++	+/−	+	++	+	+	+	++	++	++	++	++	+	+/−

Scoring based on authors' assessment of available literature review (Rosenstock et al. 2016) and an informal survey of CGIAR experts ($N = 8$). Agronomists were asked to identify the effects of each intervention on indicators of CSA systems (as described in Rosenstock et al. 2016). The results from this survey were averaged to determine whether the practice had a positive (+), negative (−), or undetermined (+/−) impact on the key CSA indicators

WHC water holding capacity, *C* carbon, N_2O nitrous oxide, CH_4 methane

The length of time until these benefits accrue depends on many factors such as the skills of the farmer, the level of precision in the operations, the soil type, fertility and climate stress at a particular site, and last but not least the level of inputs and other production factors that farmers are able to apply. Economic benefits will help farmers overcome and shorten this lag period. The examples of economic benefits gained from studies in Malawi are very positive and other systems studied in the region may not always be as promising as they depend to a large extent on the type of CA system applied and farmer context.

It is therefore evident from the paper that there is need to adopt the right mix of CA practices suitable to their specific agro-ecological and socio-economic contexts in order to reap the benefits of the system. This requires on-farm adaptation and participatory research.

The research question of this paper was “how climate-smart is conservation agriculture?”. Based on our assessment we can emphasize its adaptation potential (due to greater infiltration, moisture retention, and early planting) and the potential to increase productivity and profitability over time, although in some instances, increases in costs for herbicides or labour due to increased weed pressure may reduce the net benefits in the short term. There is still considerable uncertainty on how much CA will contribute to the mitigation aspect of climate-smart agriculture and more research is needed to quantify these benefits if there are any. This research will be important to guide large donor investments such as the 4pour1000 initiative formulated at the COP21 (http://4p1000.org/) and for climate-smart agriculture programs implemented by the African Climate Smart Agriculture Alliance (ACSA) expected to materialized in the next decade.

Acknowledgements The authors acknowledge the logistical support of CIMMYT, ICRISAT, ICRAF and QUAAFI who have supported this study at various stages. Funding is gratefully acknowledged from the CGIAR Research Programs CCAFS and MAIZE. We thank the farmers, extension officers, field coordinators and researchers from the national programs of Malawi, Zambia, Mozambique and Zimbabwe. Special thanks go the Total LandCare for supporting CIMMYT’s research on CA systems in Malawi, Zambia and Mozambique for more than a decade.

Compliance with ethical standards

Conflicts of interest The authors declare no conflicts of interest whatsoever in publishing this research.

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