6 Conservation agriculture as a determinant of sustainable intensification

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Key points

- Retention of crop residues improved water infiltration and reduced water run-off and water erosion soil losses.
- Maize yields improved under conservation agriculture-based sustainable intensification (CASI) across eastern and southern Africa, averaging 11%, while yield variability was reduced by about 4%.
- Maize–legume rotations accounted for 20–50% of yield increases under CASI (depending on the legume under rotation), increased macrofauna diversity, increased nitrogen fixation and lowered the incidence of crop diseases.
- Intercropping reduced maize yields but resulted in higher net benefits to farmers by providing two crops from the same piece of land. Intercrops were a preferred option for land-constrained farmers.
- Yield benefits from CASI, particularly CASI basins, were lower for poorly drained or waterlogged sites. CASI basins should be restricted to well-drained sites with a high probability of erratic rainfall seasons, such as the semi-arid regions.
- Herbicide use was common and preferred because it reduced labour requirements.
- In Malawi and Mozambique, improving agronomic practices like planting density, planting configurations, inorganic fertiliser, improved seeds and timely weed management increased yields by more than 60%.
- Challenges in implementing CASI included the need to adapt and apply the three principles effectively across diverse settings. Initial weed management and a scarcity of crop residues for soil cover also limit adoption.
- Further research is needed to address the competition for crop residue use, between feeding livestock and soil cover, in mixed crop–livestock systems.

Introduction

Challenges around the intensification of maize–legume cropping systems in eastern and southern Africa (ESA) have been explained by high levels of soil degradation and poor soil fertility and nutrient mining (Dixo, Gulliver & Gibbon 2001; Wagstaff & Harty 2010; Vanlauwe & Zingore 2011; Jama et al. 2017; Kihara et al. 2016). Soil health has been widely recognised as an important contributor to the sustainability of agroecosystems. Persistent promotion of conservation agriculture-based sustainable intensification (CASI) has occurred in Sub-Saharan Africa (SSA), although the life in the soil has not been fully understood. CASI, by definition, refers to practices that reduce soil disturbance, provide permanent soil cover and use crop rotations or associations (Kassam et al. 2009). CASI has demonstrated the potential to curb further erosion from degraded soil resources (Enfors et al. 2011; Huang et al. 2012; Kassam et al. 2009). CASI has increased soil moisture conservation and mitigates yield losses from in-season dry spells (Nyagumbo & Rurinda 2012). The crop rotation component of CASI consistently reduced pests and diseases (Govaerts et al. 2006) and improved soil fertility (Maltas et al. 2009). Rotations and intercropping have also diversified farmers' incomes and spread the risk of complete crop failure (Wang et al. 2003), and increased N soil fertility for resource-constrained farmers (Peoples et al. 2009). While the yield, soil health and water conservation benefits of CASI are well established, other effects of CASI (e.g. soil faunal biodiversity) remain poorly understood. SIMLESA tested CASI technologies using improved maize and legume varieties in on-farm and on-station experiments over three to eight seasons. This chapter highlights the agronomic findings from these studies, with particular attention to yield and environmental outcomes.

Assessment of CASI systems

CASI systems that were best suited to two contrasting agroecologies for each country were selected based on local farm power sources, farmer preferences for legume crops and technical feasibility in that environment (Table 6.1; Figure 6.1). Where mechanisation was scarce, planting basins allowed for land preparation to commence during the dry season and alleviated labour bottlenecks at the onset of the cropping season (Nyagumbo et al. 2017). Direct seeding using dibble sticks or jab planters were used as the crop establishment techniques in Malawi, Mozambique, Kenya and Ethiopia. These are common techniques in the region (Thierfelder et al. 2014) but had not been compared with CASI basins. Ox-drawn rippers and direct seeding with the Fitarelli seeder were also used in animal traction–based systems of Manica district in Mozambique.

Table 6.1 Major agroecologies and a summary of conservation agriculture-based sustainable intensification (CASI) systems tested in each of the five SIMLESA countries

Country	Agroecology	CASI systems tested
Ethiopia	mid-altitude, subhumid, high-potential	maize–bean intercrops and rotations animal traction ripper (minimum tillage), crop residue retention improved drought-tolerant maize and legume varieties
	mid-altitude, dryland	maize–haricot beans maize–bean intercrops and rotations crop residue retention
Kenya	humid to semi-arid	zero tillage control of weeds with appropriate herbicides crop residues retained on the soil surface after every harvest maize–bean intercrops vs sole maize and beans
	high-altitude, humid	zero tillage + *Desmodium*: no-till maize intercropped with *Desmodium* herbicides weed control and crop residue retention crops are maize–bean intercrops
Tanzania	high-potential zone	maize–pigeonpea intercrops agronomic efficiency
	low-potential zone	maize–pigeonpea intercrops agronomic efficiency
Malawi	mid-altitude	maize–soya rotations with or without herbicides maize variety compatibility with conservation agriculture
	lowlands	maize–peanut rotations maize–pigeonpea intercrops vs sole maize crop establishment using conservation agriculture dibble stick vs basins
Mozambique	subhumid	maize–common beans rotations and intercrops maize–soybean rotations and intercrops animal traction ripping vs direct seeding basins vs direct seeding animal traction ripping vs direct seeding
	semi-arid	maize–cowpea intercrops vs rotations

Note: CASI = conservation agriculture-based sustainable intensification

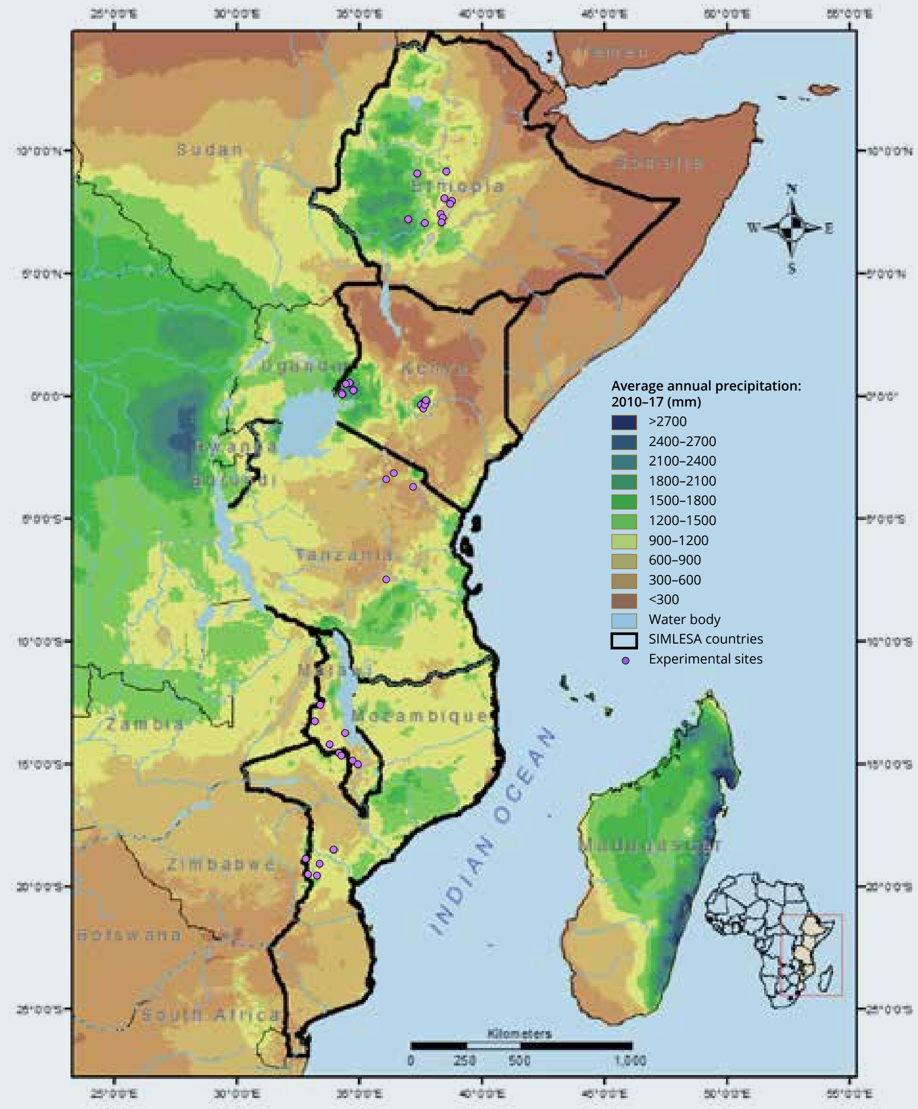

Figure 6.1 Five SIMLESA countries, location of experimental sites and average annual precipitation (2010–17)

Regional comparisons across countries

Soil carbon content

Given the short duration of the long-term trials (three years), significant changes in soil carbon were not expected. Compared to the initial assessments of soil carbon in Malawi in 2013, after three years of CASI, no differences between cropping systems were observed. In Kenya, soil carbon within the top 20 cm of the soil did not indicate differences between cropping systems (Micheni et al. 2015). In Melkassa, Ethiopia, soil carbon under CASI increased slightly (Figure 6.4).

CASI practices had significant effects on soil properties after five or more years. Differences between cropping systems were apparent in Malawi in 2016, after six seasons of CASI implementation (Figures 6.2 and 6.3). These results align well with findings obtained elsewhere (Steward et al. 2018).

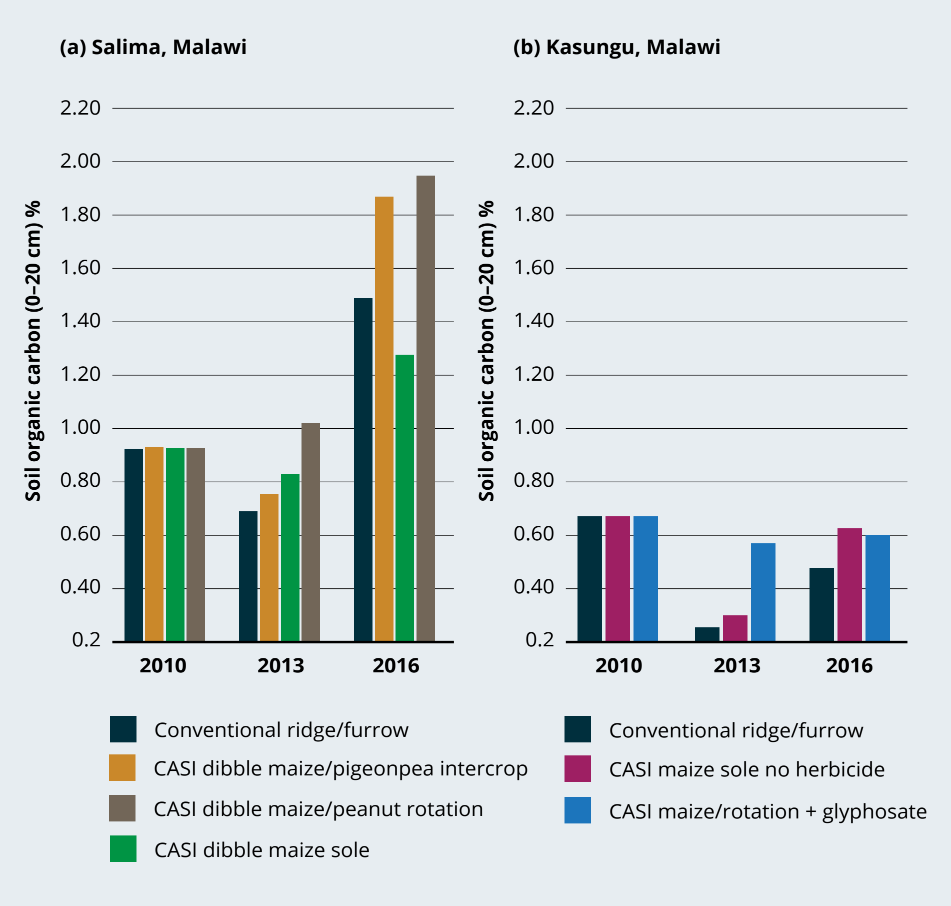

Figure 6.2 Soil organic carbon under CASI across cropping systems over time in (a) the lowland district of Salima, Malawi and (b) the mid-altitude district of Kasungu, Malawi

CASI = conservation agriculture-based sustainable intensification

Water

Unlike maize yield benefits, soil moisture content improved across districts, increasing rainfall use efficiency (e.g. Teklewold, Hassie & Shiferaw 2013 in Ethiopia). This is in contrast to conventional ridge/furrow systems that had poor water infiltration and surface ponding resulting in high run-off, soil loss and degradation in Malawi. These results were also confirmed by higher time to pond in CASI systems compared with conventional ridge and furrow systems in 2013 (Figure 6.3).

Soil moisture increases from CASI systems were also observed in Mozambique's Angonia district, where CASI systems had a significant effect on soil moisture in the top 20 cm of the soil. However, in Angonia, the use of CASI basins contributed to excessive waterlogging and led to yield decreases of at least 2.5% over the first four years of SIMLESA (Nyagumbo et al. 2016). CASI practices resulted in less run-off and soil loss from erosion than conventional ploughing practices at Bako Agricultural Research Center, Ethiopia (Table 6.2). These results agree with experiments in Zimbabwe (Nyagumbo 2008; Vogel, Nyagumbo & Olsen 1994).

CASI practices in Ethiopia also improved rainwater infiltration and conserved more soil moisture than conventional practices (Figure 6.4). Rainwater productivity in a maize–bean intercrop under CASI was 10 kg/mm/ha compared to 7.4 kg/mm under conventional practice (Merga & Kim 2014). Overall, CASI systems had higher soil water content than conventional practices. This has been attributed to improved soil properties such as bulk density and organic carbon (Liben et al. 2018). CASI systems, especially residue retention, reduced run-off and soil loss from erosion. Improved soil cover helped control rainfall erosivity, while reduced soil disturbance improved soil aggregate stability and reduced the erodibility of the soil.

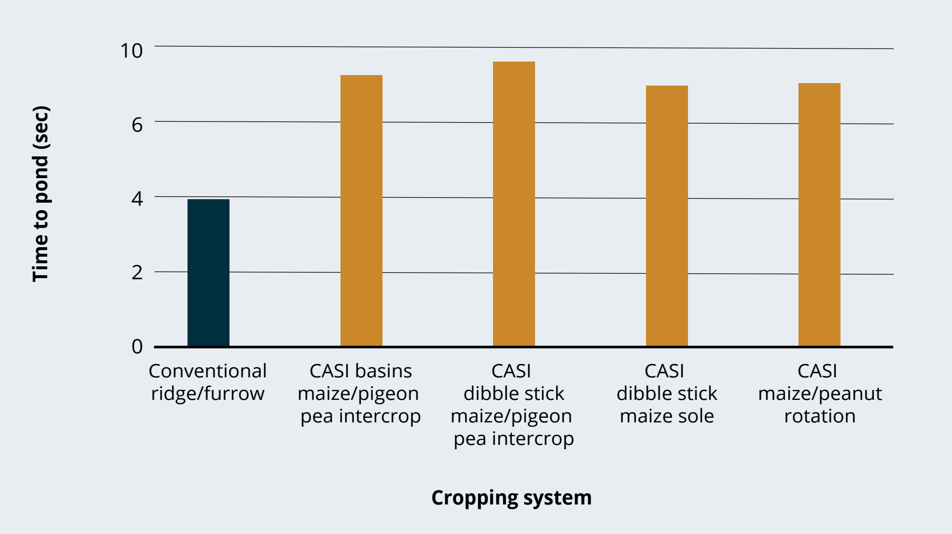

Figure 6.3 **Mean time to pond water infiltration assessments in the lowland communities of Balaka, Ntcheu and Salima (Malawi) in 2013, for conventional agriculture and CASI basins, dibble stick, dibble stick intercropping with cowpea and peanuts**

CASI = conservation agriculture-based sustainable intensification

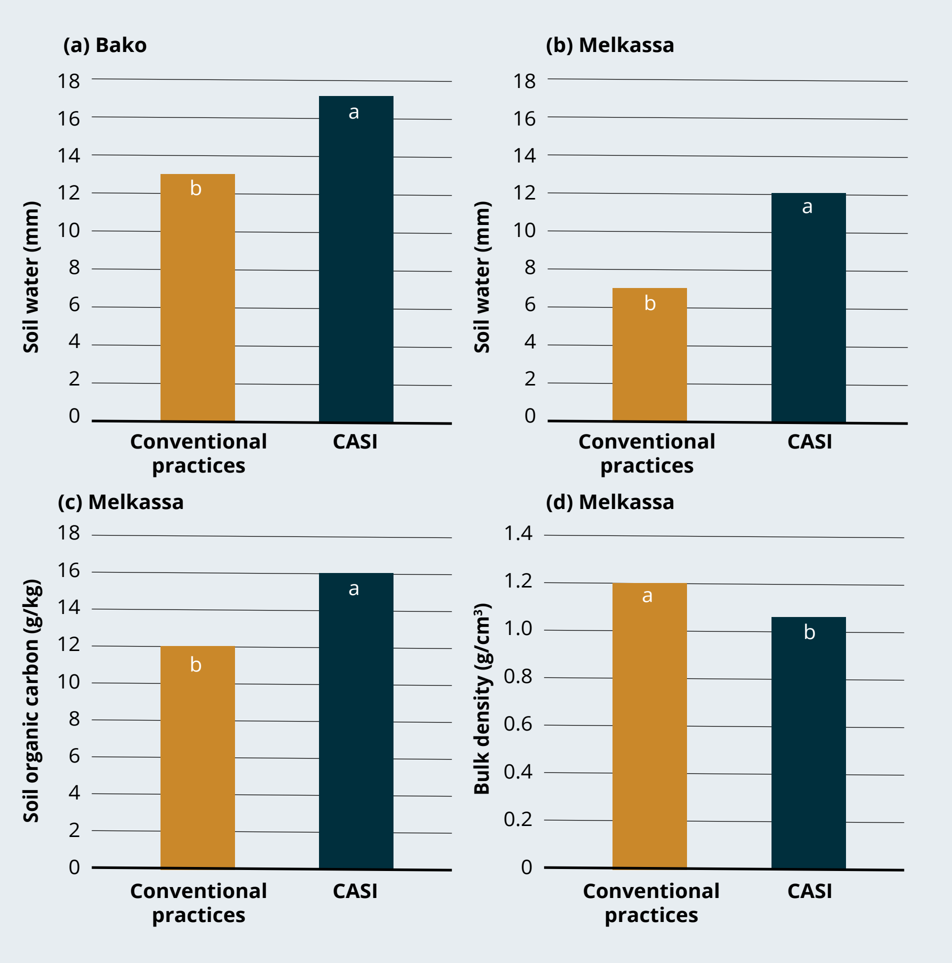

Figure 6.4 Soil water content, soil organic carbon and soil bulk density with conventional practices and CASI practices at Bako (humid) and Melkassa (semi-arid) in Ethiopia

Notes: CASI = conservation agriculture-based sustainable intensification. In this graph, a and b indicate that the two bars reflect values that are significantly different; a is significantly larger than b.

Table 6.2 Effects of CASI systems on soil erosion at Bako Agricultural Research Center

Practice	Soil loss (t/ha/yr)	Per cent
Sole maize using conventional tillage	5.21	100
Maize–common bean intercropping and farmer practice	3.44	66
Maize–common bean intercropping and conventional tillage	2.71	52
Sole maize, mulch and minimum tillage	1.95	37
Maize–common bean intercropping under CASI	1.8	35

Note: CASI = conservation agriculture-based sustainable intensification
Source: Degefa 2014; MSc thesis

Soil biology (fauna and bacteria)

In Kenya, macrofauna and mesofauna richness was not affected by management practices, except for macrofauna in Nyabeda (Table 6.3). Topsoil macrofauna richness was significantly lower for the farmer practice than the other treatments, while residue incorporation in conventional tillage increased macrofauna in the subsoil. On the other hand, the abundance of macrofauna and mesofauna were not affected by treatments at both 0–15 cm and 15–30 cm soil depths, except for mesofauna in Kakamega (Table 6.4). Here, the topsoil mesofauna abundance was higher ($p < 0.05$) in zero tillage compared with conventional and farmer practice treatments. Across management practices, soil fauna richness declined with depth, reaching nearly ≤50% of top soil levels at 15–30 cm. The decrease in faunal richness with depth could be associated with the reductions in organic matter levels (Ayuke et al. 2003; Ayuke, Brussaard et al. 2011; Ayuke, Pulleman et al. 2011; Fonte et al. 2009).

Microbial richness was lowest across almost all microbial species under zero tillage without residue application. Residue removal significantly reduced the diversity of several soil microbial phyla (Table 6.5) involved in atmospheric nitrogen fixation, phosphorus solubilisation and carbon and nitrogen turnover. Richness for most species was highest with residue application under a 13-year trial, zero tillage system. Glomeromycota, the phylum for arbuscular mycorrhizae, was significantly higher under zero tillage than in conventional tillage. Increased microbial diversity under zero tillage with surface residues was previously observed at the same site (Kihara et al. 2012).

Table 6.3 Macrofauna and mesofauna diversity (richness) across long-term and short-term trials in Nyabeda and Kakamega, Kenya

	Macrofauna		Mesofauna	
Treatment	**0–15 cm**	**15–30 cm**	**0–15 cm**	**15–30 cm**
Nyabeda				
farmer practice	2^{b}	3.7^{ab}	4.3	3.0
CTMSr + CR	8^{a}	5.3^{a}	5.3	5.7
ZTMSr + CR	7^{a}	2.7^{b}	4.3	2.3
ZTMSi + CR	5^{ab}	2.7^{b}	4.7	3.3
p-value	0.038*	0.050*	0.429	0.125
Kakamega				
farmer practice	5.7	5.0	2.0	2.0
CTMBi + CR	6.7	5.3	3.7	3.7
ZTMBi + CR	11.3	7.0	5.7	2.3
p-value	0.384	0.417	0.058	0.502

Notes: CT = conventional tillage, ZT = zero tillage, MSr = maize–soybean rotation, MSi = maize–soybean intercropping, MBi = maize–bean intercropping, CR = crop residue. The a and b suffixes indicate differences across countries within a treatment where yield values with a b suffix are significantly lower than yield values with an a suffix. Asterisks indicates a significant difference between conservation agriculture-based sustainable intensification practices and conventional yields while n.s. indicates 'no significance'. *** = $p < 0.01$, ** = $p < 0.05$, * = $p < 0.1$.

Table 6.4 Macrofauna and mesofauna abundance across long-term and short-term trials in Nyabeda and Kakamega, Kenya

Treatment	Macrofauna 0–15 cm	Macrofauna 15–30 cm	Mesofauna 0–15 cm	Mesofauna 15–30 cm
Nyabeda				
farmer practice	107	203	1,814	970
CTMSr + CR	672	133	4,219	3,080
ZTMSi + CR	395	107	4,684	1,224
ZTMSr + CR	496	149	2,954	759
p-value	0.203	0.927	0.321	0.318
Kakamega				
farmer practice	219	171	633^{b}	338
CTMBi + CR	336	192	844^{b}	1,224
ZTMBi + CR	1,163	272	4,937^{a}	1,097
p-value	0.089	0.546	0.030*	0.372

Notes: CT = conventional tillage, ZT = zero tillage, MSr = maize–soybean rotation, MSi = maize–soybean intercropping, MBi = maize–bean intercropping, CR = crop residue. The a and b suffixes indicate differences across countries within a treatment where yield values with a b suffix are significantly lower than yield values with an a suffix. Asterisks indicates a significant difference between conservation agriculture-based sustainable intensification practices and conventional yields while n.s. indicates 'no significance'. *** = $p < 0.01$, ** = $p < 0.05$, * = $p < 0.1$.

Studies on macrofauna abundance in Zimbabwe in both arid and semi-arid conditions also confirmed the findings in Kenya that the application of residues increased macrofauna activity and improved soil health (Mutema et al. 2013; Mutsamba, Mafongoya & Nyagumbo 2016). Under crop residue-covered fields, termites were more abundant, particularly in the sandy soils. Tillage and removal of residues disturbed their habitats and limited their energy sources, while different mulches (maize or grass residues), which contain cellulose and crude protein, attracted them. Increases in termite numbers have a clear effect on increased biological activity. This did not necessarily translate into entirely positive effects (i.e. increased nutrient mobilisation through residue decomposition) as crops (especially cereals) could be attacked by termites, especially towards harvest when residue cover has diminished (Giller et al. 2009). The SIMLESA studies in Mozambique also showed increased termite activity with crop residue retention (Nyagumbo et al. 2015).

Table 6.5 Effects of treatments on different phyla at the SIMLESA trials (CT1 and KALRO Kakamega) in western Kenya

Treatments	Microbial richness (Chao 1)	Microbial diversity (Shannon-Wiener)	Cyanobacteria	Actinobacteria
CT + CR (CT1)	1,249	4.4	18.4^{a}	228^{ab}
RT + CR (CT1)	1,280	4.4	18.6^{a}	270^{a}
RT – CR (CT1)	877	4.2	3.9^{b}	115^{b}
CT + CR (KALRO)	1,271	4.6	14.6^{ab}	173^{ab}
RT + CR (KALRO)	1,222	4.5	14.9^{ab}	169^{ab}

Notes: CT + CR = Conventional tillage + crop residues; RT + CR = Reduced tillage + crop residues; RT – CR = Reduced tillage without crop residues; CT1 = SIMLESA trials; KALRO = Kenya Agricultural and Livestock Research Organization. The a and b suffixes indicate differences across countries within a treatment where yield values with a b suffix are significantly lower than yield values with an a suffix.

CASI practices had higher potential of promoting ecosystem health and productivity through increasing soil faunal biodiversity than conventional tillage, and should be promoted. The enhancement of faunal abundance under reduced tillage systems can be attributed to the presence of organic residues, reduced soil disturbance and enabling conditions that favour faunal colonisation and establishment (Aislabie, Deslippe & Dymond 2013). Crop residues provided sources of food substrates for microbial species and their removal can deprive microbes of inputs necessary for their growth, development and survival (Aislabie, Deslippe & Dymond 2013). Zero tillage without residue application was less desirable because it tended to reduce soil faunal abundance, and thus undermined the benefits (e.g. soil aggregation, organic matter decomposition, nutrient transformations and cycling) of other conservation agriculture practices.

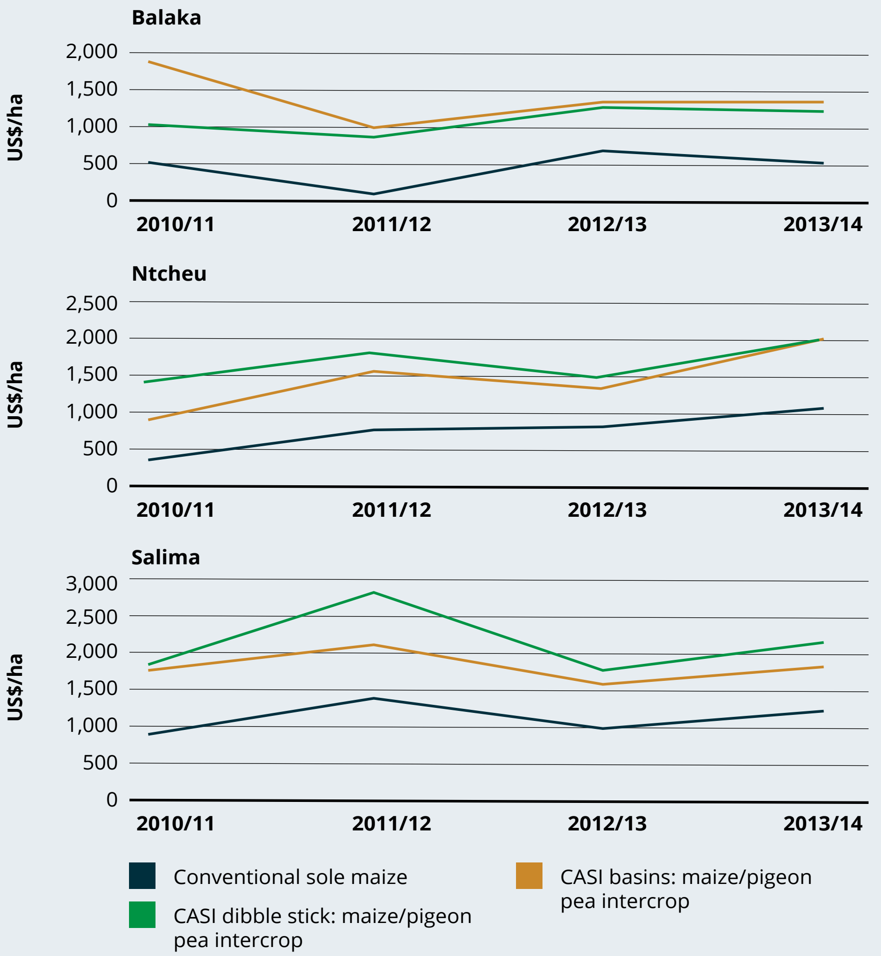

Figure 6.5 Gross margin analysis of CASI practices in Malawi for conventional sole maize cropping, conservation agriculture in basins and with dibble stick

CASI = conservation agriculture-based sustainable intensification

Gross margins

Maize–pigeonpea intercropping under CASI and basins under CASI maize sole systems, on average, produced higher gross profit margins over a period of four seasons in Malawi than the conventional sole systems (Figure 6.5). Similar findings emerged from Tanzania and Ethiopia, where higher net benefits were realised from CASI systems than from improved conventional practice. Results from Kenya also suggest that labour savings from the use of herbicides increased profits. There are therefore clear benefits of CASI practices in terms of labour savings, increased maize yield and better economic returns on investment. However, these benefits are generally context-specific as they varied across experimental sites and associated market conditions.

Over the entire period of SIMLESA experimentation, CASI yields were 11% higher than those of conventional cropping systems (Nyagumbo et al. 2018). The highest increase in yield was observed under rotation under CASI, while intercropping under CASI showed a slight decrease in maize grain yield. Yields remained stagnant in the first three years for most countries. At that stage, yields began to progressively increase at rates that depended on the agroecology of the site. Yield depressions from CASI mostly occurred in Ethiopia and Mozambique in agroecologies experiencing excessive waterlogging. Results also suggest that CASI tended to depress yields when rainfall was above normal. Increased yields in seasons with low rainfall have been reported in Zimbabwe (Michler 2015). Yield variability from CASI was reduced by a modest 4% across ESA (Table 6.6).

Table 6.6 Comparison of CASI and conventional maize grain yields across ESA

Countries	CASI		Conventional practices		*t*-probability	Relative difference (%)	Coefficients of variation	
	Maize yield (kg/ha)	Nitrogen (kg/ha)	Maize yield (kg/ha)	Nitrogen (kg/ha)			Conservation agriculture	Conventional practices
Ethiopia	3,568^{a}	466	3,590^{a}	156	0.903$^{n.s}$	−1	53	57
Kenya	2,762^{a}	499	2,397^{b}	528	0.004**	15	77	78
Malawi	3,678^{a}	678	3,433^{a}	227	0.109$^{n.s}$	7	55	55
Mozambique	2,766^{a}	1,225	2,494^{b}	314	0.007**	11	58	63
Tanzania	1,533^{a}	151	1,258^{b}	294	0.006**	22	71	76
Overall	**3,032**^{a}	**3,019**	**2,474**^{b}	**1,519**	**<0.001**	**11**	**63**	**66**

Notes: CASI = conservation agriculture-based sustainable intensification. The a and b suffixes indicate differences across countries within a treatment where yield values with a b suffix are significantly lower than yield values with an a suffix. Asterisks indicates a significant difference between conservation and conventional yields while n.s. indicates 'not significant'.
** = $p < 0.05$.

Beyond CASI: improved agronomy

While the results presented so far indicate benefits from using CASI practices, in this section we use results from Kasungu district, Malawi, to illustrate the contribution of improved agronomy. Improved agronomy in this case comprised improved maize variety, use of recommended fertiliser and better planting configurations. In Figure 6.6, the yield under a range of CASI treatments is compared with the farmer practice treatment (farmers check) in the experiment, and yield measured in the surrounding field (true farm practice). Maize yields from farmer practices were often much lower than those from improved management regimes and improved agronomy. For Kasungu, mean yields computed over six years show that the relative yield increases of CASI practices compared with the farmers' own true farm practice was 71%. Of this increase, 73% was due to improved agronomy and 27% was due to conservation agriculture practices.

Similarly, for Mozambique, more than half the yield gains could be attributed to better agronomy (Nyagumbo et al. 2018), while in Tanzania, CASI (Rusinamhodzi et al. 2017; Sariah et al. 2018) did not do better than conventional tillage with the same level of inputs. This implies that investments in good agronomic practices potentially offer farmers the largest return to investments in the short term, although adoption of CASI practices can give them an extra increase and sustainability in the long run. The use of good agronomic practices by farmers therefore could be the 'lowest hanging fruit' that policymakers can promote to close the maize yield gap in SSA (Van Ittersum et al. 2013).

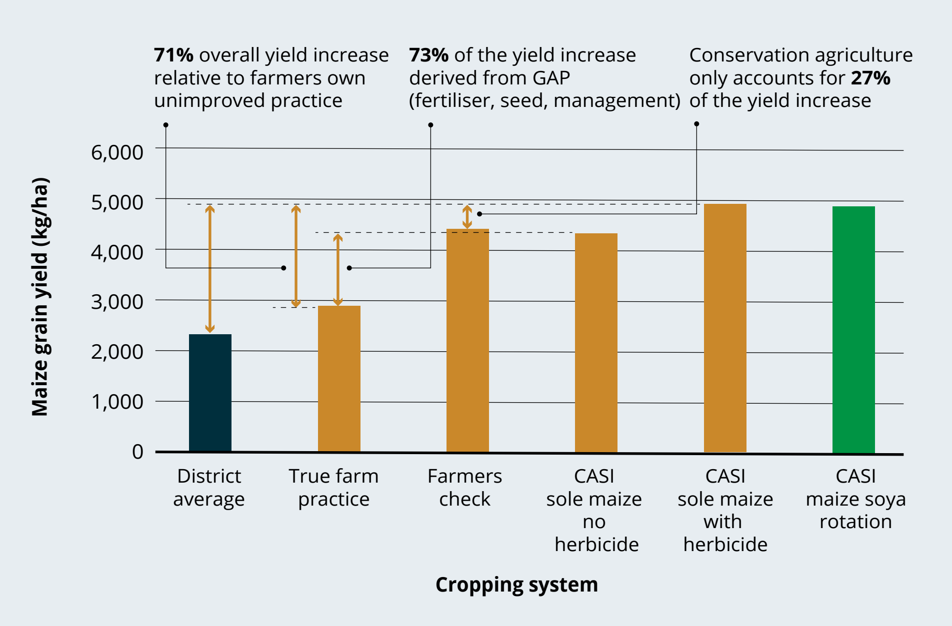

Figure 6.6 **Mean maize yields from Kasungu district, Malawi, over six seasons (2010–11 to 2015–16) relative to local averages and true farmer practices and CASI**

CASI = conservation agriculture-based sustainable intensification

Conclusions

Across the five countries, CASI increased yields by 11% above the conventional practice. Yield responses were influenced by amount of seasonal rainfall and soil-related factors such as drainage and fertility status. High rainfall or high-potential agroecologies benefited less from CASI than low-potential or drier agroecologies, as found in Ethiopia, Mozambique and Malawi (Nyagumbo et al. 2016). CASI systems generally had a modestly lower yield variability (63% compared to 67% with conventional practices), suggesting CASI could contribute marginally to more stable yields and be a climate-smart technology. Results clearly showed that the application of crop residues immediately improved hydraulic properties of the soil with increased water infiltration and rainwater use efficiency and reduced run-off and soil loss (Degefa, Quraishi & Abegaz 2016). CASI technologies could therefore contribute to improved resilience and climate change adaptation when water is limiting for crop production.

Many field trials were established for more than five years, providing an opportunity to assess changes in soil properties over time. Soil organic carbon (0–20 cm) did not change much in the first three years. However, after five years, soil carbon had increased at some sites in Malawi and Ethiopia, but not in Kenya or Tanzania. There were also changes in soil pH and bulk density at some sites. In terms of soil health, the studies clearly show that macrofauna abundance and diversity increased when CASI systems with residue cover applications were employed. This was found in Kenya and Mozambique (Nyagumbo et al. 2015) and previous studies prior to SIMLESA in Zimbabwe. Many factors that affect soil properties can explain variability across sites, such as agroecology, soil type, biomass production or mulching rates and crop management.

Improved agronomic practices, including planting density, planting configurations, inorganic fertiliser, improved varieties and timely weed management, offered farmers the opportunity for the largest yield gain. In Malawi and Mozambique, good agronomic practices accounted for more than 60% of the yield increases over conventional farmer practices. Low plant population densities were a particular challenge in Mozambique. Investments in spreading knowledge of good practice could provide the fastest pay-off in terms of productivity increases on farmers' fields.

Herbicides were a popular technology investment towards weed control under CASI systems due to labour reductions, especially for youth and women (Micheni et al. 2015). Yield was not affected by weeding methods (manual, mechanical-controlled and herbicide-assisted systems) as long as weed control was carried out well and was timely (Nyagumbo et al. 2016). This shows both the value of good agronomy as well as the fact that herbicides are not a prerequisite for successfully implementing CASI.

Many farmers across the SIMLESA countries have embraced crop rotation and intercropping. Crop rotations and intercrops improved soil cover and can restore soil fertility through nitrogen fixation from the legumes. Across ESA, results clearly demonstrate maize yield benefits from rotations under CASI systems, with maize yield increases of up to 50%. In most cases these yield advantages of CASI increased progressively over time and were more apparent after the third cropping season. Rotation benefits, however, tended to depend on the legume crop employed and its capacity to fix nitrogen that would benefit the subsequent maize crop. Peanuts and soybeans were the most effective at increasing subsequent maize yields. Although intercrops reduced maize yields compared with rotations, most land-constrained farmers preferred intercrops due to the dual benefits—food security and profitability—of two crops from the same piece of land (e.g. maize–pigeonpea intercrops in Tanzania and maize–cowpea intercrops in Mozambique).

In some cases, yields were reduced on poorly drained or waterlogged sites due to excessive moisture under CASI, particularly with the CASI basins, for example in Mozambique, and the lowlands of Malawi in the Ntcheu and Salima districts (Nyagumbo et al. 2016). Yet the same CASI basins had beneficial water conservation effects that translated to higher yields in Balaka (Malawi) and the Chimoio and Gorongosa districts of Mozambique, where rainfall was more erratic and soils were well drained (Nyagumbo et al. 2016). This suggests the use of CASI basins should be restricted to well-drained sites with a high probability of erratic rainfall seasons, which is characteristic of semi-arid regions.

Despite some successes, key challenges to the adoption of CASI technologies remain. Aside from the knowledge-intensive nature of CASI, early stage weed control required more labour than farmers had available, and shortages of crop residues for soil cover limited the uptake of CASI technologies (Valbuena et al. 2012). An improved understanding of the interactions between residue application rates, nitrogen, rainfall and soil type is necessary to address the trade-offs that occur when crop residue retention limits availability of livestock feed. The competition for crop residues for soil cover and livestock feed requires new system-level innovations. Identifying alternative sources of soil cover and livestock feed in crop–livestock environments can be a first step.

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