Received: 2 September 2020 | Revised: 23 February 2021 | Accepted: 24 February 2021

DOI: 10.1111/sum.12715

RESEARCH PAPER

Soil Use and Management | BRITISH SOCIETY OF SOIL SCIENCE | WILEY

Evaluating the merits of climate smart technologies under smallholder agriculture in Malawi

Isaiah Nyagumbo[1] | **Munyaradzi Mutenje**[1] | **Peter Setimela**[1] | **Lovemore Chipindu**[1] | **Arisede Chisaka**[1] | **Pacsu Simwaka**[2] | **Blessings Mwale**[3] | **Amos Ngwira**[2] | **Walter Mupangwa**[1]

[1]International Maize and Wheat Improvement Center (CIMMYT), Harare, Zimbabwe

[2]Department of Agricultural Research Services (DARS), Chitedze Research Station, Lilongwe, Malawi

[3]Total Land Care, Lilongwe, Malawi

Correspondence
Isaiah Nyagumbo, International Maize and Wheat Improvement Center (CIMMYT) PO Box MP163, Harare, Zimbabwe.
Email: i.nyagumbo@cgiar.org

Funding information
U.S. Department of Agriculture, Grant/Award Number: FX18TA-10960C012

Abstract

The merits of three climate smart agriculture (CSA) technologies implemented by farmers were assessed in Machinga district of Malawi with respect to their soil quality and maize yield effects. Data were collected from farms implementing the three CSA technologies, namely conservation agriculture (CA), maize–pigeonpea (Maize-PP) intercrops and a local organic and inorganic soil amendment known as Mbeya fertilization (Mbeya-fert), from 2018 to 2019. With respect to resilience and adaptation, particulate organic matter, soil organic carbon (SOC), N, P, K, Ca and Mg all significantly improved while bulk densities were lowered under the three CSA systems. Higher annual biomass inputs and improved water infiltration from the Maize-PP intercrops were observed. With respect to productivity, CA and Mbeya-fert improved maize yields by 51 and 19%, respectively, compared to conventional farmer practices. With regard to climate change mitigation, increases in measured SOC in the top 20 cm depth compared to the conventional farmer practices amounted to 6.5, 12 and 10.5 t C ha^{-1} for CA, Mbeya-fert, and Maize-PP intercrops, respectively, over a period of 2–6 years. This suggests higher potential for carbon sequestration from CSA technologies. Furthermore, use of drought tolerant varieties, timely weeding and optimum plant populations, increased productivity. Improved gross margins from CSA practices were also apparent. Thus, employing these CSA technologies could enable farmers to be more resilient, productive and adapt better to climate change shocks leading to improved food security and livelihoods.

KEYWORDS

conservation agriculture, gross margin, intercrops, maize yield, soil organic matter

1 | INTRODUCTION

Climate smart agriculture (CSA) relates to agricultural practices and approaches which aim to sustainably increase agricultural productivity; adapt and build resilience of agricultural and food security systems to climate change at multiple levels; and reduce greenhouse gas emissions from agricultural systems (Faurès et al., 2017). CSA is an integrative approach which addresses the interlinked challenges of food security and climate change. The CSA approach aligns well to the United Nations Sustainable Development Goals (SDGs) (UN, 2015). CSA addresses or contributes to least five of these SDGs namely *Goal 1*. End poverty in all its forms everywhere; *Goal 2*. End hunger, achieve food security and improved nutrition and promote sustainable agriculture; *Goal 12*. Ensure sustainable consumption and production patterns; *Goal 13*. Take urgent action to combat climate change and its impacts; *Goal 15*. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss. Furthermore, the Paris Climate Agreement of the United Nations Framework Convention on Climate Change (COP21) in 2015 committed to retaining the increase in global average temperature to well below 2°C above pre-industrial levels, leading to current global efforts such as the 2 Degree Initiative.[1] This need for mitigating climate change and food security through Greenhouse Gases (GHG) reductions resulted in the '4 per 1,000' initiative launch at COP21 (http://4p1000.org) whose objective is to increase soil organic carbon (SOC) stocks globally by 0.4 per cent per year (Corbeels et al., 2019).

In Malawi, extreme climate events such as droughts, dry spells and floods are common, and they are likely to increase with climate change (Chinsinga et al., 2012; Pauw et al., 2010). These events significantly decrease rainfed crop yields, and the problem is also exacerbated by the inability of farmers to afford chemical fertilizers needed to address low soil fertility because of their high costs (Chianu et al., 2012). High input costs forced the Malawian government to implement a national input subsidy programme in 2006 (Denning et al., 2009), yet the prices of fertilizers remained largely unaffordable to many smallholder farmers (Chirwa et al., 2011).

Consequently, the high chemical fertilizer costs necessitated the widespread use of nitrogen fixing legumes and innovations involving combinations of organic and inorganic fertility amendments. Likewise, the use of pigeonpea as an intercrop in maize systems is also increasingly seen as an important climate smart and food security strategy (Rusinamhodzi et al., 2012). Pigeonpea also relays well with maize and fixes substantial amounts of nitrogen during periods (April–June) when the rainfall season is tailing off. Pigeonpea therefore makes a highly compatible intercrop in maize legume systems (Rusinamhodzi et al., 2017). Furthermore, in recent years, several CSA practices have been promoted in Malawi to alleviate nutrient deficits, improve crop yields and mitigate carbon emissions from agricultural systems (Kaczan et al., 2013; Ngwira et al., 2014). Some of the CSA practices or technologies include agroforestry, conservation agriculture (CA), drought tolerant germplasm, intercropping, tree fallows, water harvesting and irrigation technologies (Descheemaeker et al., 2016; Kassam et al., 2009; Steward et al., 2018).

To assess climate smartness, relevant key indicators are often used to evaluate the contribution of such technologies to sustainable productivity, resilience and mitigation to climate change. For example, yield, income and food security can be used as proxies for sustainable productivity while a range of soil quality indicators such as microbial activity, soil organic carbon (Six et al., 2000), water infiltration, soil loss, nitrogen content, pH and other soil chemical properties are used to assess resiliency attributes of the CSA practice (Agriculture Global Practice, 2016). For mitigation, measuring GHG emissions (CO_2, CH_4 fluxes), above ground biomass, total soil carbon and fuelwood consumption are often used as indicators (Hayati et al., 2010; Hobbs et al., 2008). Assessment of the above ground biomass could thus be used as a proxy to annual carbon injection in cropping practices as a means of understanding their mitigation merits (Musumba et al., ; Smith et al., 2017; Young et al., 2020). Residue cover, derived from above ground biomass in CA systems, also plays an important role in reducing rainfall erosivity as the energy of raindrops is attenuated by the presence of residues on the surface (Chowaniak et al., 2020).

The three most widely used CSA rainfed cropping technologies in communities around the Liwonde Forest Reserve, Machinga Agricultural Development Division, Malawi, are CA, maize–pigeonpea intercrops (Maize-PP) and a new innovation involving organic and inorganic fertilizer combinations locally known as MBEYA fertilizer (Mbeya-fert). However, the climate smartness, costs and benefits of these practices have not been evaluated.

Therefore, the objectives of this study were to evaluate the merits of these three CSA cropping practices in Machinga district of Malawi with respect to productivity; adaptation and mitigation indicators among farmers who voluntarily employed these technologies. Specifically, we sought to assess soil quality changes with respect to soil physical and chemical properties of fields under CSA practices, assess the yield merits of the implemented CSA practices relative to conventional farmer practices as proxies for productivity and establish if these measured soil quality and yield merits are influenced by household socio-economic characteristics of targeted households.

2 | MATERIALS AND METHODS

2.1 | Identification of CSA practices and sample households' selection

Three CSA practices namely CA, Maize-PP intercrops and the Mbeya-fert (Table 1) that had been extensively promoted in Machinga district were selected for this study.

[1]The 2 Degree Initiative for Food and Agriculture 's mission is that by 2030, 200 million small-scale agricultural producers across the globe have adapted their agro-ecological systems, livelihoods and landscapes to weather extremes and climate variability are more climate change resilient, and have put food systems on a low emissions development pathway. iiiii.

TABLE 1 Description of the conventional and CSA practices studied

Practice type	Practice	Description
Control-Conventional farmer practice	Ridge/furrow conventional tillage	Crop establishment using ridges (15−25 cm high) and furrows. Spacing 75−100 cm between rows. Ridge positions alternate annually. Maize planted on top of ridges at 25−50 cm in-row spacing. Fertilization based on inorganic basal NPK and urea top dressing applied depending on availability
CSA	Conservation agriculture systems (CA)	The use of improved drought and heat stress tolerant maize varieties, practising minimum tillage, rotations and retaining of crop residues for soil cover.
CSA	Maize–Pigeonpea intercrop systems (Maize-PP)	The use of Pigeonpea as an intercrop with maize grown on the flat or with the common ridge/furrow system.
CSA	Mbeya fertilization strategy (Mbeya-fert)	Mbeya manure constitutes a mixture of 10 kg of inorganic fertilizer (23% N: 21% P_2O_5: 0% K_2O: (+4%S)) and 20 kg of livestock manure (goat or chicken or cattle manure) + 5 kg of wood ash (well sieved) + 15 kg of maize bran locally known as madeya. After thoroughly mixing these constituents, approximately 20 l of water are sprayed to the mixture using a watering can. The wet mixture is then wrapped in plastic for decomposition and matures within 3 weeks.

The three technologies were identified from a broader range of CSA technologies scaled in the district by the project ‘Protecting Ecosystems and Restoring Forests in Malawi’ (PERFORM) which had been implemented between 2014 and 2018. The three selected CSA practices became the focus of this study after being identified by farmers as the most common CSA practices in use during initial participatory rural appraisal and focus group discussion meetings held in each of the five communities prior to this specific study.

The district, extension planning area (EPA) and villages were selected using purposive sampling as these were already specified in the project document. Five communities were selected for our study representing communities in which PERFORM project was implemented. The five communities in the district were Lower Ntubwi, Mbonechera, Upper Ntubwi, Domasi and Nsanama. Both biophysical and socio-economic assessments were carried out in four of the five communities Lower Ntubwi, Upper Ntubwi, Mbonechera and Domasi, while Nsamana only contributed to the socio-economic component of the study. Lower and Upper Ntubwi receives on average annual rainfall of 400–600 mm and 600–1200 mm, respectively. Mbonechera and Nsanama receive on average 600–800 mm and Domasi 600–1000 mm. Average annual temperatures range from 25 to 35°C and 20 to 30°C for Lower and Upper Ntubwi, respectively, whilst Mbonechera, Nsanama and Domasi have temperature range of 25–30°C. A baseline survey report of Machinga district in 2015 suggested that up to 60% of the farmers were always food insecure by March, while CA was practised by 20% of the households on an average of 0.41 acres (0.16 ha) out of the 1.6–1.8 acres (0.6–0.7 ha) cultivated per household (USAID, 2015).

Farmers participating from each target village in this study were randomly selected using stratified sampling. Stratification was based on the location, biophysical characteristics (mainly soil type), wealth status and number of years practising CSA technology (2–6 years.). For each village, a list of households was obtained from the village head with the assistance of the resident extension worker. Ten per cent of CSA practising households in each village were selected using stratified random sampling. On every farm, a field with the targeted technology was identified for sampling while another control field without the technology was also identified within the same farm (Table S1). Special considerations were taken to allow for equal sampling of fields in the high and low rainfall communities. To avoid confounding effects, fields on which more than one of the target CSA technologies were being implemented were deliberately avoided. Because of its widespread use, a relatively larger number of farmers practising CA were identified for sampling compared to those sampled for Maize-PP intercrops and Mbeya-Fert technologies. Using this method, a total of 112 households were sampled and used in the analysis. Household data from each farm including soil type and household size were collected for each of the three CSA technologies.

2.1.1 | Tested technologies

As stated above, during focus group discussions, farmers identified a wide range of agricultural and non-agricultural practices/technologies as contributing to resilience and climate smartness from which we identified CA, Mbeya-fert and Maize-PP intercrops, as the most prevalent cropping technologies warranting further studies.

Conventional ridge/furrow farmer practice: On each farm, control fields constituted the conventional farmer practice commonly used for growing maize in Malawi. This involves using the ridge/furrow land preparation system followed by planting of maize on the ridges at inter-row spacings ranging between 75 and 100 cm and in-row spacings of 25 and 40 cm after receiving sufficient rains. The ridges are broken down annually through splitting and scooping the soil into the previous year's furrow and covering any remaining residues. Fertilization is variable from farm to farm but may involve basal application at planting and top dressing with modest quantities of urea (46%N) 6–8 weeks after emergence and up to about 100 kg N ha^{-1} depending on availability. Weed control involves shallow hoe weeding at first followed by re-ridging or banking using hoes during the second weeding. Maize varieties used can be local or extension recommended improved varieties.

CSA Technologies had been implemented in the Machinga district from 2014 although duration of uptake by farmers mostly varied between 2 and 6 years.

CA involved reduced soil disturbance (hoe/dibble-stick prepared planting stations (Thierfelder et al., 2016), provision of permanent soil cover using maize residues or any other available biomass and annual rotations/intercrops of maize with a legume. As for the conventional practice, fertilization also depended on availability as the farmers implemented the technology with own resources.

Mbeya fertilization is a recently introduced innovation combining organic and inorganic fertility amendments popular with farmers in Machinga district. Preparation of Mbeya-fert involved mixing some 10 kg of inorganic fertilizer and 20 kg of livestock manure (goat or chicken or cattle manure) + 5 kg of wood ash (well sieved) + 15 kg of maize bran and then sprinkling 20 l of water before sealing the mixture in a plastic bag and decomposing it for 3 weeks after which the mixture is ready for use (Table 1). Farmers using this mixture claimed it enabled them to cover a larger area with the same quantity of basal NPK (One 50 kg NPK bag makes 250 kg Mbeya-fert) or urea fertilizer thereby improving fertilizer use efficiency per ha and saving on scarce financial resources. The Mbeya-fert is applied between the 25 cm maize planting stations applying 100–150 kg ha^{-1} as basal as well as for top dressing. Typical recommended application rates of well-prepared Mbeya-fert are between 50 and 100 kg ha^{-1}, but these were not measured in the study nor its nutrient composition. All other operations follow the conventional practice.

Maize–Pigeonpea (Maize-PP) intercrop. Pigeonpea is grown mainly as an intercrop with maize in Machinga district because of small land holding sizes. Maize is planted at the same density as in the conventional ridge/furrow system. Pigeonpea is then planted at the same time or up to two weeks after maize in between maize rows at approximately 1–2 m intervals between plants. All other practices such as weeding and banking follow the maize agronomic practices. Where applicable, farmers are also encouraged to use insecticide, especially for aphid control in the pigeonpea. Maize is harvested first, while the pigeonpea continues to grow on residual moisture and only harvested between July and August. This enables higher biomass production and ultimately improved nitrogen fixation that subsequently benefits the next crop and reduces erosion (Gonçalves et al., 2019; Maris et al., 2021; Muoni et al., 2019; Rusinamhodzi et al., 2017). This arises from the fact that pigeonpea, being a deep rooted and high biomass producing legume, can generate significant soil cover levels during the cropping season and after the maize has senesced. Pigeonpea is an important protein source contributing to food and nutrition security for the farmers and at the same time one of the few cash crops grown in the district. Pigeonpea is thus promoted as an important cash crop that potentially generates income for the smallholders and could improve their market participation.

2.2 | Annual biomass inputs residue cover and water infiltration assessments

2.2.1 | Biomass assessments

Annual biomass inputs from each cropping system were made after the dry long winter season and after some of it had been communally grazed by roaming livestock in October and November 2018 (Yang & Wander, 1999). This was done by randomly placing a 0.70 m*0.70 m quadrant on the ground and collecting all biomass at the surface into a khaki bag. The dry residues were weighed and recorded. In each plot, measurements were made three times to give a total of six observations on each farm (three in the CSA technology and three in the conventional non-CSA technology). Biomass measurements were done for the purpose of understanding annual carbon injection in cropping systems potentially contributing to carbon sequestration (Govaerts et al., 2009; Kell, 2011; Lal, 2015; Palm et al., 2014). Simplified annual C inputs were estimated by assuming that 40% of the dry annual biomass input is carbon (Yang & Wander, 1999). Percentage residue cover estimates in each quadrant were also assessed through visual observations in each plot and data recorded on a datasheet for each farm using the photo comparison method (Shelton & Jasa, 1995).

2.2.2 | Time to pond infiltration measurements

The *time to pond* technique was used to measure water infiltration characteristics (Verhulst et al., 2011). This is a quick and rapid technique in which differences in water infiltration patterns are evaluated by measuring the time taken for sprinkled water to flow out of a steel ring of about 50 cm diameter. The device has a provision for measuring volume of water infiltrated (ml) and the time it takes for the applied infiltrating water to start flowing laterally and hit the ring. The amount of time this takes depends on how well water infiltrates into the soil and so the longer this takes the more superior the technology. The original technique (Verhulst et al., 2011) was recently improved by agronomists at CIMMYT-Harare to reduce subjectivity of results caused by different water pouring intensities when different individuals use the technique. With the improved technique, water drops from a funnel which is a fixed distance from the ground across all measurements. In this study, all measurements were conducted with the water delivery funnel set at 45 cm above ground and 3 runs were conducted per plot.

2.3 | Soil quality assessments for CSA resilience

Soil samples were collected from the top 20 cm of each of the two fields on each farm before the start of the cropping season in October–November 2018. Samples were randomly collected with an auger on at least 10 random but evenly distributed positions on each field and then mixed to make one composite sample per cropping system on each farm. Collected samples were air dried and the soil analysed at Bvumbwe Agricultural Research Station laboratory. Soil bulk density (ρ_b) was determined from a core sample taken by driving a metal core of 4.5 cm diameter and 5 cm height into the side of a 50 cm dug pit to a depth of 20 cm. The soil was oven-dried at 105°C for 24 hr., and the ρ_b was calculated as dry mass of the soil divided by the core volume. Soil surface penetration resistance (kg cm^{-2}) was recorded on the soil surface of each plot during soil sampling time. A handheld pocket penetrometer (ELE-Unconfined Comp. Strength), measuring compaction in the top 5 cm soil depth, was used to collect penetration readings. Three readings per plot were recorded and averaged to find the average resistance value for each plot (treatment) per farmer.

Total soil organic carbon was determined using Walkley–Black method (Walkley & Black, 1934). Soil pH (in water) was determined using a digital pH meter (Fisher Scientific™ accumet™ AB15 + Basic and Bio Basic™ pH/mV/°C Meters) (H_2O) in 1:2.5 soil: water suspension (Jackson, 1973). The soil organic (SOC) stock was calculated on a per hectare basis using Eqn 1 (Gonçalves et al., 2019):

$$SOC_{stock} = TOC \times \rho_b \times d \times 10000. \quad (1)$$

Where SOC stock is the stock of organic carbon in Mg ha^{-1}, TOC is the total organic carbon in g kg^{-1}, ρ_b is the soil bulk density in Mg m^{-3}, and *d* is the thickness (depth) in cm. Analysis of SOC stock was done only for the top 20 cm soil layer because ρ_b was measured only for the top 20 cm because of limited number of core samplers.

Soil textural class analyses used the Bouyoucos hydrometer (manufactured by Gallenkamp) method (Bouyoucos, 1962) and classified using the textural triangle (Thien, 1979). Total nitrogen (%) was determined using Kjeldahl digestion method, and soil phosphorus was measured using Mehlich 3 (Chilimba et al., 1999). Exchangeable potassium was determined using a flame photometer, while calcium and magnesium were measured using the atomic absorption spectrophotometer (AAS).

Fractions for particulate organic carbon (POC) were determined by the wet sieving method (FAO, 2005). Soil subsamples of 50 g from the collected composite samples were dispersed with 10% sodium hexametaphosphate solution and wet sieved through 2 mm, 250 μm, 50 μm and <50 μm sieves. The same procedure was repeated with the dry 50 g (dry weight, DW) of fresh non-dispersed soil samples. The difference between dispersed and non-dispersed samples at second sieve (250 μm) gives the particulate organic carbon that is physically protected (POMP) by the soil aggregates and is stable. In both cases, the weight of sand was subtracted from the weight of the initial sieving of each fraction after dispersing the fractions (Wang et al., 2011).

The fractions that were determined are total particulate organic carbon of the dispersed soil (POMT), the unprotected particulate organic carbon of the non-dispersed soil (POMU), the particulate organic carbon that is physically protected (POMP) by the soil aggregates (Six et al., 2000) and the easily decomposable proportion of particulate organic carbon (POMR). In this study, we present only the results for POMR and POMP because the other two (POMT & POMU) are used to calculate the important former two.

2.4 | Assessing maize productivity of CSA practices

Yield assessments were carried out at the end of the 2018/19 cropping season including some from farms where previous data were collected on water infiltration and for which laboratory soil analysis had been carried out in October and November 2018. Maize yields were physically measured on farmers' fields where CA, Mbeya-fert and Maize-PP intercrop technologies had been employed and measurements were made on both the CSA and the control non-CSA technology fields within the same farm. A total of 64 farmers (Table S1) were sampled for the yield assessments thus falling short of the initial target of 80 as some of the farmers harvested their fields before arrival of the yield assessment team. For each of the two fields on each farm, 4 check plots (5m*4 rows) for crop cuts were randomly chosen in the CSA and non-CSA plots (Figure S1). These assessments also included agronomic practices carried out such as number of weeding runs carried out per cropping system, maize varieties grown, whether or not residues had been applied and plant densities at harvest.

2.5 | Statistical analysis

Annual biomass, residue cover and water infiltration data (time to pond and water intake) were assembled for each of the farmers and analysed using *t* tests for comparison of means, comparing CSA and the corresponding control non-CSA technology for the CA, Maize-PP intercrops and Mbeya-fert, respectively. To analyse the contribution of factors such as agro-ecology, soil texture and associated basic socio-economic attributes for each farm, a linear mixed model in R software version 3.5.3 (R Development Core Team, 2015) was applied since the distribution of these factors was unbalanced for each community. The linear mixed model was given by the formula.

$$Y = \beta_0 + \sum_{j=1}^{k-1} \beta_j \varnothing_{ij} + \varepsilon_{ij}$$

Where

- Y is the dependent parameter of interest, for example annual biomass (kg ha^{-1}), time to pond (sec), measured maize grain yield (kg ha^{-1}).
- β_0 the intercept representing the grand mean
- *k* the number of independent variables categories (cropping systems; 1 = CA, 2 = Mbeya-fert and 3 = Maize-PP, technology; 1 = applied and 2 = control)
- β_j is the regression coefficient associated with the jth factor variable
- $\varnothing_{ij}$ represents the numerical value assigned to subject i in the jth factor variable
- ε_{ij} is the error term.

Similarly, soil chemical and yield data were subjected to analyses using the same models as above. Since there were no measured rainfall data for the sites, gridded rainfall data from NASA (https://power.larc.nasa.gov/data) were used for sites that had GPS coordinates for a 30 year period up to 2018/19. Cumulative seasonal rainfall data for the 30 years were used to compute a normal rainfall mean for the area. Using this mean, a *t* test comparing the season 2018/19 total rainfall from the known 30 years. mean was used to establish if the last season (2018/19) had significantly deviated from the mean. Finally, the analysis combined socio-economic attributes to yield to test whether there were any socio-economic variables that were associated with the observed yields and their differences relative to the conventional farmer practices.

2.6 | Economic analysis

A comparative analysis of the economic performance of the three CSA technologies and the conventional practice was done using gross margin analysis (CIMMYT,1988). The analysis was performed using labour data and prices of all applied inputs (seed, pesticides, fertilizers, etc.) from each of the plots in the 2018/2019 cropping season. Labour data (in man-days) for the CSA technologies and the conventional practice per site were obtained from standardized farmer' protocols previously recorded from the area from the Ministry of Agriculture. Labour data and prices for inputs were recorded for each technology separately. Labour was valued at prevailing local market prices for casual labour in order to avoid distortions when farmers used family labour. The value of crop residues or other plant materials used as soil cover was taken into consideration in the economic analysis (Mutenje et al., 2019). The shadow price of the crop biomass was incorporated in the economic analysis using equivalent US dollar prices. The economic performance of CSA technologies and the conventional practice were statistically compared using *t* tests.

3 | RESULTS

3.1 | Annual biomass inputs, residue cover and infiltration characteristics

Results from the studies show that the average annual biomass inputs from the CSA cropping systems amounted to 3,400, 2,900 and 3,800 kg ha^{-1} for CA, Mbeya-fert and Maize-PP intercrops, respectively (Figure 1a), and these were equivalent to 1.4, 1.2 and 1.5 t C ha^{-1} $year^{-1}$ (Table 3). There were no significant differences between the annual biomass inputs in the CA and Mbeya-fert systems compared to conventional practices. However, the Maize-PP intercrops showed significantly higher biomasses and better infiltration (higher *time to pond*) compared to the conventional monocrop systems (Figure 1b). Although positive, differences between CSA and non-CSA technologies in residue cover, and water intake were mostly not significant.

3.2 | Soil quality characteristics

T test results of the different soil quality attributes are presented in Table 2. Compared to conventionally tilled controls, fields under CA showed relatively better and statistically significant ($p < .05$) soil quality attributes except for soil pH, which remained unchanged (Table 2a). In comparison with the conventional cropping systems, the increases in these attributes because of CA varied between 39% and 201% (Table 2a). Thus, both easily degradable and protected particulate organic matter (POMR and POMP) were much higher in CA compared to conventional farmer practices and increased by 195% and 201%, respectively. Consequently,

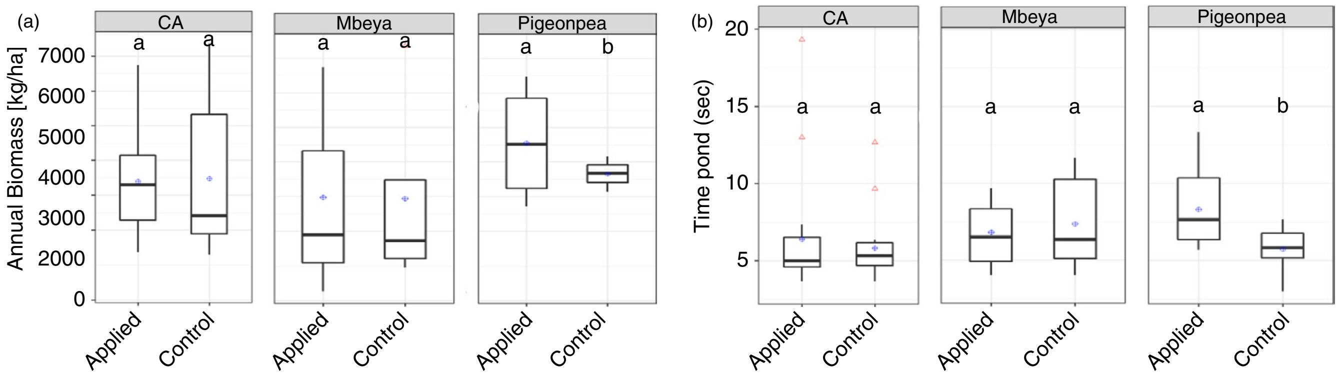

FIGURE 1 (a) Annual biomass inputs and (b) time to pond (sec) measured across three CSA practices CA, Mbeya-fert and Maize-PP intercrops in Machinga district, October 2018. N. B. Blue circles inside boxes represent means; black horizontal bar in the middle of each box represents the median. Upper and lower ends of each box represent 75% of the upper and lower quartiles

TABLE 2 Means of various soil quality attributes measured from farmer managed systems under conventional ridge/furrow farmer practice and (a) CA, (b) Mbeya-fert and (c) Maize-PP intercrops in Machinga district, Malawi, October 2018

(a) CA systems						
	N	Conventional	CA	Relative CA Advantage (%)	*p*-value from *t* test	Sig.
pH*	25	5.91	5.91	0	0.988	ns
POMR (g kg^{-1})	25	51.15	150.65	195	0.015	**
POMP (g kg^{-1})	25	31.95	96.31	201	0.003	***
Mg (cmol kg^{-1})	25	0.15	0.26	70	0.014	***
Ca (cmol kg^{-1})	25	1.97	4.24	115	0.014	**
K (cmol kg^{-1})	25	0.06	0.09	39	0.026	*
P (ppm)	25	42.41	59.21	40	0.090	
N (%)	25	0.06	0.09	44	0.010	**
OC (%)	25	0.71	1.06	48	0.001	***
OM (%)	25	1.23	1.82	48	0.059	
Compaction (kg cm^{-2})	25	2.70	1.84	−32	0.000	***
Bulk Density (g cm^{-3})	25	1.44	1.34	−7	0.000	***
(b) Mbeya-fert						
		Mbeya				
	N	**Non-Mbeya**	**Mbeya**	**Relative MBEYA Advantage (%)**	***p*-value from *t* test**	**Sig.**
pH*	14	6.12	6.10	0	0.767	ns
POMR (g kg^{-1})	14	59.0	141.9	141	0.001	***
POMP (g kg^{-1})	14	37.6	99.1	164	0.003	***
Mg (cmol kg^{-1})	14	0.20	0.33	65	0.004	***
Ca (cmol kg^{-1})	14	2.87	5.21	82	0.031	**
K (cmol kg^{-1})	14	0.08	0.13	63	0.001	***
P (ppm)	14	45.55	58.86	29	0.020	**
N (%)	14	0.10	0.13	30	0.059	*
OC (%)	14	1.07	1.58	48	0.016	**
OM (%)	14	1.85	2.73	48	0.016	**
Compaction (kg cm^{-2})	14	2.33	1.83	−21	0.001	***
Bulk Density (g cm^{-3})	14	1.33	1.28	−4	0.299	ns

(Continues)

TABLE 2 (Continued)

(c) Maize-PP intercrops						
		Maize-PP systems		Relative intercrop		
	N	Maize Monocrop	Maize-PP	Advantage (%)	*p*-value from *t* test	Sig.
pH*	14	6.03	6.09	1	0.253	ns
POMR (g kg^{-1})	14	55.96	149.40	167	0.023	**
POMP (g kg^{-1})	14	37.64	82.73	120	0.002	***
Mg (cmol kg^{-1})	14	0.18	0.27	54	0.006	***
Ca (cmol kg^{-1})	14	2.06	4.08	98	0.001	***
K (cmol kg^{-1})	14	0.06	0.11	74	0.000	***
P (ppm)	14	30.35	45.13	49	0.001	***
N (%)	14	0.08	0.11	26	0.046	*
OC (%)	14	0.93	1.32	42	0.001	***
OM (%)	14	1.60	2.27	41	0.001	***
Compaction (kg cm^{-2})	14	2.36	1.62	−31	0.003	***
Bulk Density (g cm^{-3})	14	1.38	1.37	−1	0.868	ns

Abbreviations: CA, conservation agriculture; ns, not significant; OM, organic matter (%); POMP, particulate organic matter protected by soil aggregates (g kg^{-1}); POMR, easily degradable particulate organic matter content (g kg^{-1}).

*pH = Soil pH measured based on the water standard 1:2.5 soil: water suspension (Jackson, 1973).

the soil organic carbon (SOC) measured in the top 20 cm of the soil averaged 0.71% for conventional practices compared to 1.06% under CA giving a net increase of 48%. With respect to compaction and bulk density, CA had more positive attributes. Significantly higher ($p < .0001$) compaction and bulk density was measured on conventional farmer practices compared to CA. Thus, CA had lower bulk densities of 1.34 g cm^{-3} compared to 1.44 g cm^{-3} under the conventional practices (Table 2a).

Similarly, the Mbeya-fert had positive and better soil quality characteristics than conventional till with SOC increasing from 1.07% to 1.58% (Table 2b). The highest relative advantages were noted under the POMR (141%) and POMP (164%). The Mbeya-fert fertilization strategy thus contributed to improved SOC status and better soil nutrient characteristics. The strategy was thus contributing to improved soil fertility despite the challenges of preparing this organic fertilizer. Differences in soil pH were also not significant as for the CA systems.

Maize-PP intercrop systems had significant and positive increases in SOC (42%), particulate organic matter POMR (167%), POMP (120%), magnesium (54%), Ca (98%), potassium (74%), phosphorus (49%) and nitrogen (26%) compared to conventional monocrops, while differences in soil pH were not apparent (Table 2c). Thus, in general, the Maize-PP intercrop systems also resulted in significant improvements in soil quality attributes. Bulk density differences were not significant, but there was significantly less compaction in the Maize-PP intercrop fields compared to the mono-cropped ones.

Overall, across all the practices (CA, Mbeya-fert and Maize-PP), soil pH did not show an improvement as their relative advantages were not significant ($p < .05$). The most significant relative advantages were observed with respect to POMR and POMP across all the systems. Most of the soil chemical attributes were better under the CSA practices as compared to the conventional practice. Overall, the results suggest that the three CSA systems contributed 6.5, 12 and 10.5 t C ha^{-1} from the CA, Mbeya-fert and Maize-PP intercrops systems, respectively, relative to the control farmer practices over the 2–6 years. period of implementation (Table 3). This is matched by the 1.4, 1.2 and 1.5 t C ha^{-1} $year^{-1}$ contributed by the measured annual biomass inputs (Table 3) from CA, Mbeya-fert and Maize-PP intercrops, respectively.

3.3 | Rainfall analysis and maize yield responses to CSA interventions in 2018/19

The average 30-year, total annual rainfall for the five communities amounted to 1,160 mm versus 1593 mm received in the 2018/19 season in which yields were assessed. Statistical analyses suggested no significant difference between the rainfall received between the two rainfall regime sites in 2018/19. However, the 2018/19 season was significantly wetter than the 30 years. average for the area. The rainfall analysis suggested that the in-crop rainfall total (November–April) amounted to 1,076 mm versus 1,522 mm received in 2018/19 for the same period. The major differences arose from the floods brought about by Cyclone Idai during which

TABLE 3 Soil organic carbon in the studied CSA systems and the potential organic carbon contribution relative to conventional ridge/furrow control systems measured on famers fields in Machinga district, Malawi in November 2018

	Carbon content in top 20 cm depth					Total carbon stocks in top 20 cm depth						
	CSA	Conv Control	*ΔC*	*Bulk density*		CSA	Control	*Overall C stocks Increase*	Measured Above ground biomass input	Avg Soil C increase per year	Measured C biomass input per yr.	Estimated C biomass input in 4 years
	g C kg^{-1}	g C kg^{-1}	g C kg^{-1}	g cm^{-3}	g cm^{-3}	t C ha^{-1}	t C ha^{-1}	t C ha^{-1}	t ha year^{-1}	t C ha^{-1}year^{-1}	t ha year^{-1}	t ha^{-1}
CA	10.6^a	7.6^b	*3*	1.34	1.44	28.4	21.9	*6.5*	3.4	1.6	1.4	5.4
Mbeya-Fert	15.8^a	10.7^b	*5.1*	1.28	1.33	40.4	28.5	*12.0*	2.9	3.0	1.2	4.6
Maize-PP Intercrop	13.2^a	9.3^b	3.9	1.37	1.38	36.2	25.7	*10.5*	3.8	2.6	1.5	6.1

Note:: Carbon stocks calculated for top 20 cm soil depth and respective measured mean bulk densities for each system. *Conv control* refers to the conventional ridge/furrow common farmer practice. *ΔC* = change in soil organic carbon; Measured *above ground annual biomass input* measured just before the start of next cropping season after winter livestock grazing from which *C biomass input per year* is calculated assuming 40% biomass is C (Yang & Wander, 1999). *Avg measured soil C increase per year* = Average soil organic carbon increase per year assuming observed SOC changes accrued over a 4 year period as duration of implementation varied between 2 and 6 years. C stocks calculated on the basis of a topsoil layer thickness of 0.20 m.

Different superscript letters in the same row following each CSA and control systems indicate statistically significant differences in SOC between them at $p < .05$.

470 mm was received in March 2019. Thus, there were no moisture deficits for crops since there was excessive rainfall compared to normal seasons in that area. By comparing the season onset dates to the reported dates of planting by the farmers, no delays in planting dates were apparent and hence farmers efficiently utilized the first opportunity availed by the rains to plant their crops in the 2018/19 season (Figure 2).

The three combined CSA systems significantly improved maize yields as shown in the box plots (Figure S2) compared to the conventional farmer practices. Climate smart agriculture technologies had maize grain yields averaging 3,834 kg ha^{-1} as compared to the conventional practice with 2,916 kg ha^{-1}. When compared across agro-ecologies (high and low rainfall areas), results further showed the same general pattern with CSA performing better than conventional. The CSA systems had a mean of 3,965 compared to 3,049 kg ha^{-1} under conventional in high rainfall areas, while in the low rainfall areas CSA had a mean of 3,595 kg ha^{-1} compared to 2,675 kg ha^{-1} under conventional farmer practices. The results provided solid evidence that CSA systems increased yields compared to the conventional systems at least in the 2018/19 season.

Furthermore, the yield responses under the three practices, that is CA, Mbeya-fert and Maize-PP intercrops, are shown in Figure 3. From this, the CA practice performed significantly better (p = .016) with a mean maize yield of 4,106 kg ha^{-1} compared to the conventional with a mean of 2,713 kg ha^{-1} equivalent to 51% increase. Similarly, Mbeya-fert also increased mean maize yields by 19% compared to the normal conventional fertilization (non-Mbeya) at 4,535 compared to 3,793 kg ha^{-1}, respectively, but the differences were statistically not significant (p = .571). Similarly, maize in the Maize-PP intercrop system was insignificantly higher than that from the monocrop maize (p = .735) at a mean of 3,047 versus 2,802 kg ha^{-1}, respectively, a 9% increase.

3.4 | Agronomic practices: varieties, planting density and weeding effects

Across the three CSA systems, key agronomic factors that significantly (p < .05) influenced yield included residue application (Figure 4a), plant population (Figure 4b) and number of weeding runs (Figure 4c) carried out per season. Plant population had a significant and positive linear regression effect on maize yield (p < .0000; R^2 = 0.144) with peak yields at about 44,000 plants ha^{-1} (Figure 4b). Low yields were also associated with low plant populations.

Results revealed that the number of weeding cycles per season significantly correlated with maize grain yield. Yield penalties were evident from not weeding, but weeding two or three times improved yields significantly. Most farmers weeded their crop twice per season. On average under CA, returns to weeding amounted to 1,098 kg ha^{-1} weeding-run^{-1}

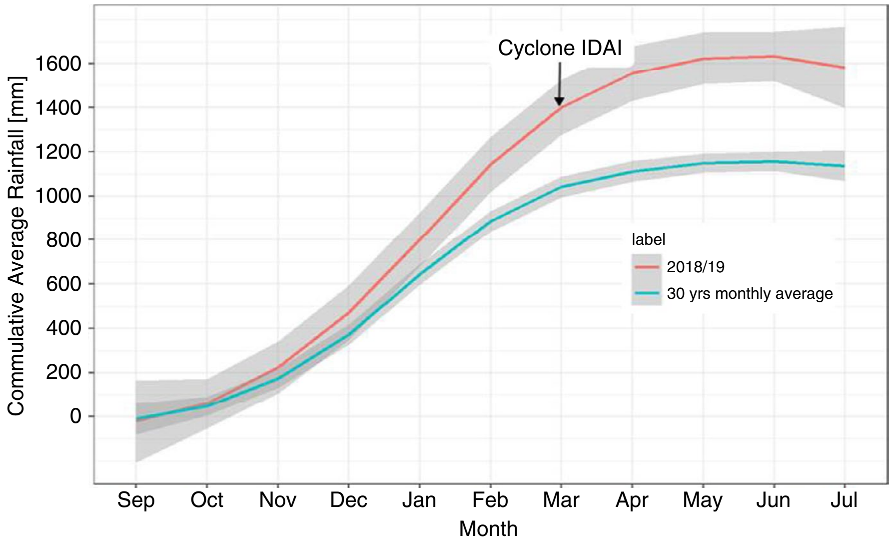

FIGURE 2 Mean cumulative seasonal rainfall distribution over a 30 year period for study sites in Machinga district, Malawi, in comparison with season 2018/19. N.B Shaded grey areas for each cumulative rainfall curve represent 95% confidence intervals

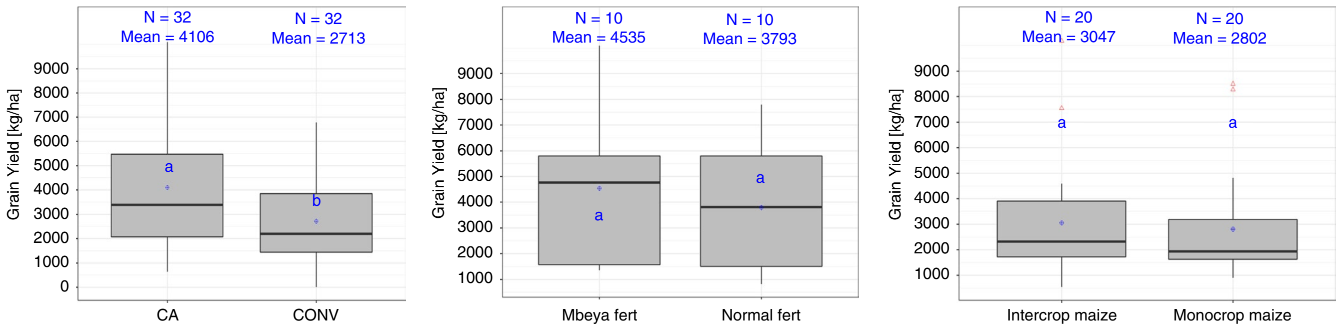

FIGURE 3 Measured mean maize yield responses to CA, Mbeya-Fert and Maize-PP intercrop systems as practised by farmers in 2018/19 in five communities of Machinga district. N. B. Blue circles inside boxes represent means; black horizontal bar in the middle of each box represents the median. Upper and lower ends of each box represent 75% of the upper and lower quartiles. $LSD_{(0.05)}$ CA = 1,122 kg ha^{-1} $LSD_{(0.05)}$ Mbeya = 2,701 kg ha^{-1}; $LSD_{(0.05)}$ Intercrop = 1,451 kg ha^{-1}

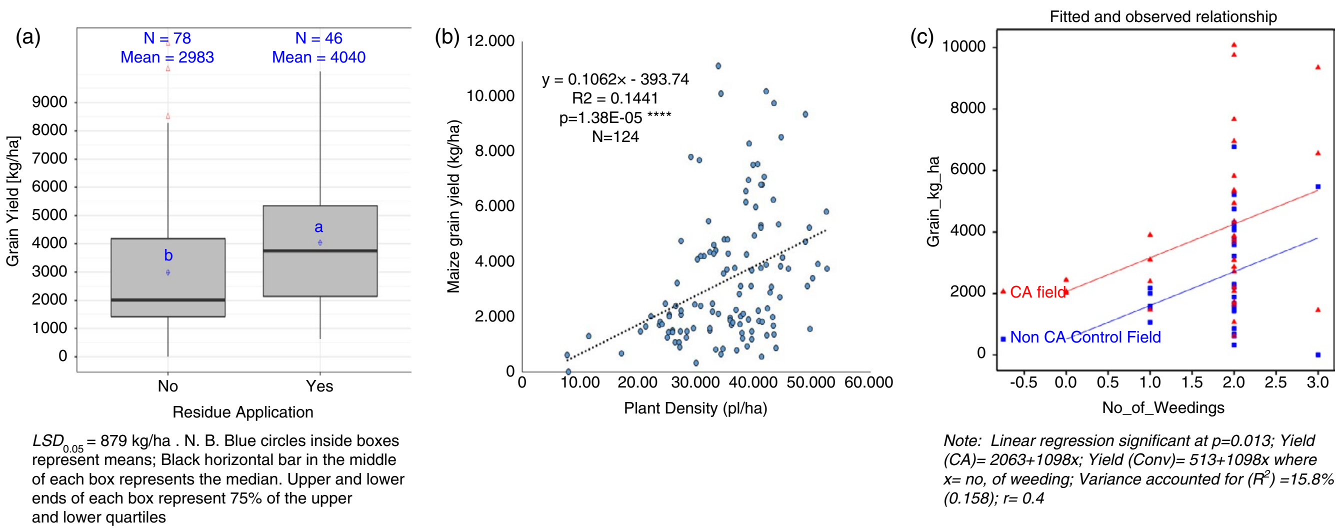

FIGURE 4 Effect of (a) residue application and (b) planting density and (c) number of weedings per season on subsequent maize yields in different CSA cropping systems in Machinga district, Malawi, in the 2018/19 season

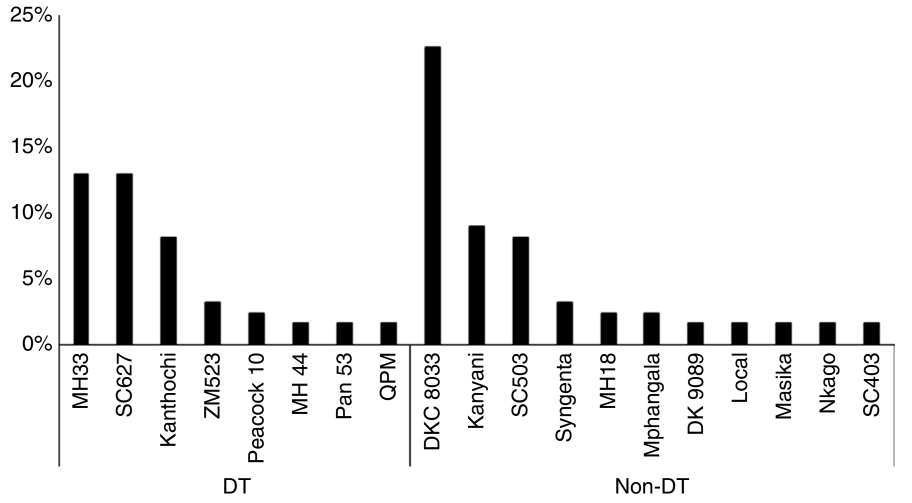

FIGURE 5 Proportion of different maize varieties grown by farmers in Machinga district in 2018/19 Note: DT = Drought tolerant varieties; Non-DT = Non-drought tolerant maize varieties

thereby suggesting that investments in weeding by farmers could give them labour returns of at least 1 tonne of grain for every weeding run (Figure 4c).

Maize varieties from more than 20 different seed companies were evident in the sites and included drought tolerant and non-drought tolerant ones (Figure 5). The most widely grown varieties were DKC8033 (non-drought tolerant), MH33 and SC627 from three different companies. The results revealed that newly released varieties like Peacock-10, ZM523 and MH26 are slowly penetrating the market compared to DKC 8,033 which has been in the market for more than 10 years (Figure 5).

3.5 | Economic analysis

The results of the economic analysis confirmed the biophysical results. All the CSA technologies were more viable compared to the conventional practice in both low rainfall and high rainfall communities (Table 4). Low rainfall areas obtained significantly higher net benefits from the use of Mbeya-fert (USD 1 675) followed by the CA (relative to the conventional practice). Similarly, in the high rainfall area, Mbeya-fert had higher net benefits (USD 1 468) followed by CA (USD 1 426) relative to the conventional practice. The results suggest that in risky environments, CSA options increase productivity whilst building resilience to climate change and variability and as such, CA and Mbeya-fert are important. These results were also supported by the focus group matrix ranks of the different CSA technologies. CA and Mbeya-fert technologies were rated highly in the high rainfall Nsanama community (Figure 6a) as well as in Lower Ntubwi (Figure 6b) community where farmers had been exposed to these for longer durations.

During the interactive discussions, farmers in all the communities emphasized the importance of integrating adaptation strategies with short- and long-term benefits (Figure 6). Among the CSA technologies promoted, combinations of CA, drought tolerant maize and rice varieties, orange fleshed sweet potatoes, natural forest regeneration, rocket stoves[2] (a wood conserving type of stove) and chicken pass-on[3] were ranked as the most important adaptation strategies by most of the communities (Figure 6). Yield performance was also evaluated based on sex of the household head. Results generally suggested male headed households had higher yields compared to female headed ones (Figure S3). Chi-square analysis also suggested a significant and positive association between resource endowment and maturity of CA implementation ($p = .013$). Experience in CA was categorized into two major groups namely junior and mature. Most of the farmers (out of a total of 19), who were mature in practicing CA technologies, were also relatively more resource endowed, while the junior CA implementers were also mostly resource constrained (Table 5). However, results also showed no significant correlations or associations between annual biomass inputs, time to pond and water intake characteristics to resource endowment or wealth status of households.

4 | DISCUSSION

The findings of this study align well with other previous studies on CSA which have shown that CSA technologies

[2]A wood fuel efficient energy saving cooking stove made from bricks and cow/ goat dung, for example https://rippleafrica.org/project/fuel-efficient-cookstoves-in-malawi-africa/

[3]Chicken pass-on was a household support scheme operated by PERFORM in which the project supported one third of the households in a village by donating 5 chickens to a household (a cock and 4 hens) from an improved breed. These households would in turn donate 5 chickens from their first generation to the next group of neighbouring households by a set date when they have reproduced. This process would continue until all the farmers in the community have benefited. The last set of beneficiaries would donate to another community in need.

TABLE 4 Gross margin analysis of CSA from the farmers, fields in Machinga

Annual rainfall classification	Low Rainfall Area						High Rainfall Area					
	Conservation Agriculture		Mbeya-fert		Maize-PP intercrops		Conservation Agriculture		Mbeya-fert		Maize-PP intercrops	
CSA Technologies	CP	CA	CP	Mbeya-fert	CP	Mz/PP intercrop	CP	CA	CP	Mbeya-fert.	CP	Mz–PP intercrop
Gross income (USD)	1,122	1,503	1,618	2,001	771	870	1,330	1,786	1,691	1,789	1,416	1,689
Input Costs												
Maize seed	65	65	65	65	65	65	65	65	65	65	65	65
Basal fertilizer	75	75	75	25	75	75	75	75	75	25	75	75
Urea fertilizer	75	75	75	25	75	75	75	75	75	25	75	75
Labour days	97	74	99	109	92	84	97	75	99	107	101	87
Labour cost	188	143	190	211	178	163	187	145	191	206	195	168
Total Variable cost	403	358	405	326	393	378	402	360	321	406	410	383
Net benefits (USD ha^{-1})	719	1,145	1,213	1,675	378	492	928	1,426	1,285	1,468	1,006	1,305
Return to labour (USD $labourday^{-1}$)	4.8	9	3.1	4	7.3	8.9	6	10.8	7.7	8.1	6.2	8.8

have significant contributions to productivity and resilience (Steward et al., 2018). For example, studies in the Southern Africa region have shown that technologies such as CSA result in yield increments of up to 50% (Nyagumbo et al., 2020). In this study where farmers implemented the technologies on their own and not as trials or experiments, the results give a close reflection of practical realities of possible achievements when farmers implement these technologies on their own. The conclusively positive soil quality benefits suggest that these CSA technologies have long-term impacts on resilience and hence yield outcomes (Michler, et al., 2019; Pittelkow et al., 2015). Some of the sampled farmers had implemented CSA technologies for more than 6 years and hence the positive soil health attributes measured. Yet surprisingly, the technologies do not seem to have any apparent effects on soil pH (Bai et al., 2018; Bayala et al., 2012). A related study in Zambia suggested CA practices increased pH over time with no significant increase over conventional ploughing after 4 years but significant beyond 7 years (Muchabi et al., 2014). The studies reported here had been running for 2–6 years and so may not have run long enough for CA to show pH increases. At 3.8 t ha^{-1} annual biomass input (estimated to contribute 1.5 t ha $year^{-1}$ of carbon), Maize-PP intercrops offered the highest potential for carbon sequestration compared to the other two CSA practices. However, soil analysis results suggested the highest SOC increase was derived from the Mbeya-fert (12 t C ha^{-1}) followed by Maize-PP intercrops (10.5 t C ha^{-1}) and CA (6.5 t C ha^{-1}). Thus, all the three CSA practices (Table 3) were contributing meaningful quantities of C that could potentially contribute to carbon sequestration in the long run (Lal, 2015; Maris et al., 2021). The results obtained here agree with literature findings suggesting increases in SOC stocks in no-till systems (Dey et al., 2020; Duval et al., 2020; Gonçalves et al., 2019; Yang & Wander, 1999) and Maris et al., (2021) who showed highly significant enrichment of SOC stocks in systems employing leguminous cover crops. Our results suggesting improvements in SOC and other soil properties under CA, also agree with findings in other studies in Malawi (Mloza-Banda et al., 2014, 2016) and on sites with CA having been implemented for up to 10 years (Simwaka et al., 2020). Yet our results contradict findings from a number of locations in southern Africa on which CA had been implemented for up to seven years where no significant differences in SOC stocks between CA and conventional till systems were observed (Cheesman et al., 2016). We attribute contradictions with the latter to the amounts of annual biomass inputs, soil types and agro-ecological conditions being key SOC influencing factors (Pittelkow et al., 2015) that may have differed between the two studies. Nonetheless averaging over a four-year period (duration of CSA implementation varied between 2 and 6 years), our results suggest the CSA practices CA, Mbeya-fert and Maize-PP intercrops resulted in SOC stocks increase

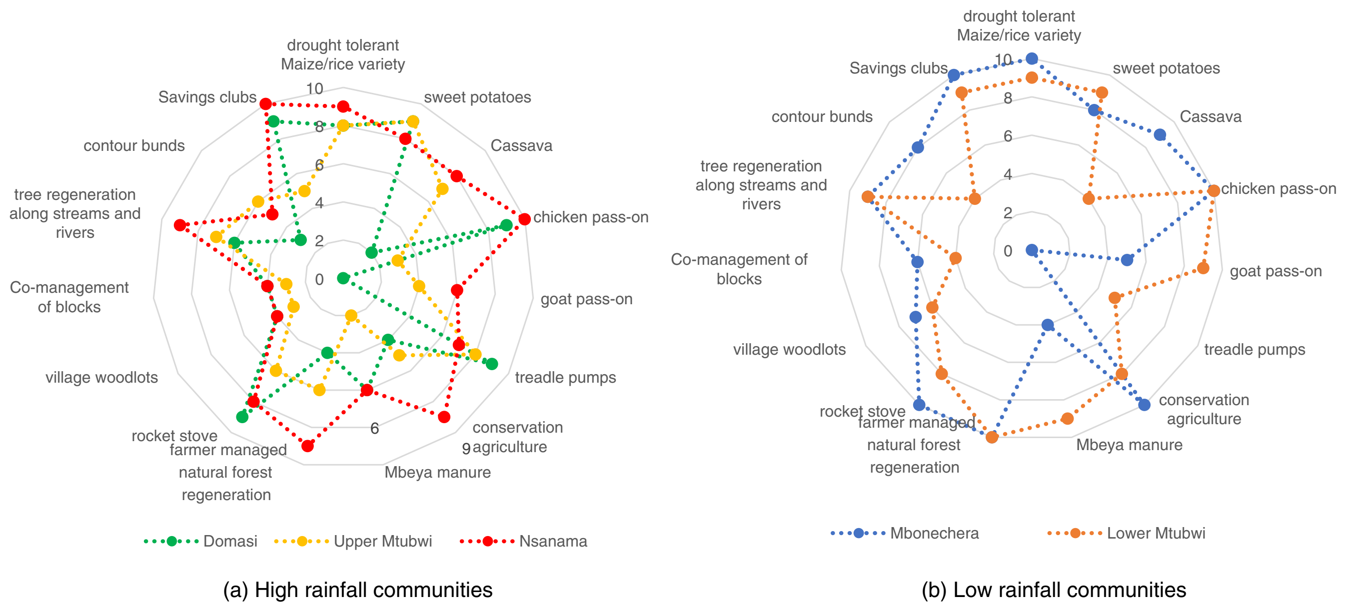

FIGURE 6 Farmer ratings of different technologies for improving agricultural resilience to climate change and variability in (a) high and (b) low rainfall communities. Note: 1 = poor capacity to addressing resilience; 10 = High capacity to address resilience challenges

TABLE 5 Chi-square association between Experience in CA and wealth status of a subset of sampled households

	Endowed	Medium	Constrained	Total
Experience in CA	Number of respondents (% of total)			
Junior (0–2 years)	2 (11%)	2 (11%)	10 (53%)	14 (74%)
Mature (3yrs +++)	4 (21%)	1 (5%)	0 (0%)	5 (26%)
Total	6 (32%)	3 (16%)	10 (53%)	19 (100%)

Note: Chi-squared = 8.6857, *df* = 2, *p*-value = 0.013.

in the top 20 cm soil depth of 1.6, 3.0 and 2.6 t C ha^{-1} yr^{-1} thereby pointing towards higher potential for carbon sequestration from these CSA systems and hence improved resilience and mitigation to climate change.

The yield increases observed from CA systems in this study amounted to 51% compared to the conventional practice and clearly show the extent to which CA practices can potentially help to address food security challenges and resilience. The newly introduced local Mbeya-fert fertilization innovation resulted in 19% yield increases but because of a small sample size (14 farms) statistically the differences were not significant. This suggests there is need to look more elaborately into this technology and properly evaluate its potential crop yield merits. Not much information was available from literature on this technology. Its popularity among cash constrained farmers who claim it reduces the cost of procured inorganic fertilizer inputs per ha, warrants further research investments on this technology.

The modest yield increases (9%) from the intercrop systems also generally agree with many other findings on intercropped maize in the region which show that maize yields tend to get depressed in intercropped systems because of the trade-off between the legume and maize (Dahmardeh et al., 2009; Ngwira et al., 2012; Nyagumbo et al., 2016; Rusinamhodzi et al., 2012, 2017). Consistent with Ngwira et al., (2012) and Rusinamhodzi et al., (2017)'s findings, the Maize-PP intercropping strategy did not provide significantly higher net yield returns relative to conventional practice. These results suggest that in drier environments, adaptation strategies that conserve soil moisture and enhance water use efficiency such as the Mbeya-fert micro-dosing and CA, are critical. Studies in five countries of ESA involving CA also suggested that maize yields in intercrop systems tended to get depressed under low rainfall conditions (<700 mm) because of moisture competition but improved considerably when seasonal rainfall increased to between 700 and 1300 mm (Nyagumbo et al., 2020).

However, the combined benefit of this intercropping practice lies in the additional legume output that also enables farmers to diversify food and income sources and so the total output from this system is usually much higher than the monocrops. However, a shortcoming of this study is that it only evaluated the performance of the CSA technologies with respect to their maize yield merits and did not measure legume yields from pigeonpea for example. Consequently, the full productivity benefits, particularly the diversification benefits, were not fully assessed in this maize yield assessment as observed from related studies in Malawi (Mutenje et al., 2019).

Generally, smallholder farmers in marginal environments integrate agricultural technologies based on their capacity to increase productivity and moderate production risks (Mutenje et al., 2019; Ngwira et al., 2012). The CSA options assessed in this study integrated at least two adaptation strategies, drought tolerant crop varieties, crop species diversification (legume intercropping, rotations) and/or fertilizer micro-dosing. The economic analysis results revealed that all the CSA practices yielded higher net-returns compared to conventional practices. These results concur with findings from other studies that CA practices offer opportunities for intensification of smallholder farming systems (Mupangwa et al., 2017; Thierfelder et al., 2016).

The results of the agronomic practices analysis also suggest that simple investments in practices such as weeding could result in large returns to the farmer, and so in this study, we found that the returns to one weeding amounted to at least 1 tonne of maize grain per ha. The importance of correct use of optimum plant populations is also apparent here and is confirmed in a meta-analysis of global maize yields (Haarhoff & Swanepoel, 2018).

The results also suggest the need to address gender inequalities as female headed households were found to be less productive compared to the male headed households across both CSA and non-CSA technologies while those with mature CA also turned out to be more resource endowed. We, however, could not establish the cause–effect relationships of this significant association to conclusively ascertain if use of the CSA technologies studied was singly responsible for the better resource endowment of those households.

Although none of the farmers using the studied CSA practices combined them together in one field for elimination of confounding effects, farmers participating in the focus group discussions emphasized the importance of integrating CSA and non-agricultural adaptation strategies as the best approach to mitigate climate change and variability impacts. For example, combinations of agricultural innovations such as the chicken pass-on scheme, CA combined with crop diversification and drought tolerant crop varieties, treddle pumps, tree regeneration along streams and non-agricultural innovations such as participating in savings clubs, and use of rocket stoves, were considered effective by farmers as contributing to building resilience and sustainability in the long run. Overall, findings from the focus group discussions emphasized the importance of diversification and multi-functional technologies as effective strategies for moderating climate risk.

All in all, the measured enhanced annual biomass inputs, increased water infiltration characteristics, soil carbon and nutrient contents observed, all point towards a more sustainable, resilient and productive cropping system. The tested CSAs all contribute to mitigating climate change and food security through GHG reductions as enunciated in the COP21 '4 per 1,000' initiative that seeks to increase global soil organic carbon (SOC) stocks by 0.4 per cent per year (Corbeels et al., 2019). Our measured increases in SOC from CSAs studied, however, still fall far short of this target as our data suggest 0.3–0.5% over the 4-year mean period (Table 3). The tested CSAs also address at least 5 of the Sustainable Development Goals namely 1 (End poverty), 2 (End hunger), 12 (sustainable consumption and production), 13 (combat climate change) and 15 (reverse land degradation).

5 | CONCLUSION

The three CSA technologies evaluated in this study positively addressed the CSA pillars in different respects. Thus, improvements in soil quality attributes were demonstrated through the use of CSA practices such as CA, Maize-PP intercrops and the combined organic and inorganic fertilizer amendment strategy locally known as Mbeya-fert. Except for soil pH, particulate organic matter, soil organic carbon, N, P, K, Ca and Mg, all significantly improved under the three CSA systems while the soil was also more friable under CSA as evidenced by the measured lower bulk densities on CSA systems. Results from the studies also confirmed higher annual biomass inputs and improved water infiltration from the Maize-PP intercrops. Overall measured increases in soil organic carbon stocks over the conventional ridge/furrow cropping practice amounted to 6, 12 and 10.5 t C ha^{-1} for CA, Mbeya-fert and Maize-PP intercrop systems, respectively. Averaging over a four-year implementation period, our results suggest the CSA practices CA, Mbeya and Maize-PP intercrops resulted in SOC stocks increase in the top 20 cm soil depth of 1.6, 3.0 and 2.6 t C ha^{-1} yr^{-1}, thereby suggesting higher potential for carbon sequestration and hence improved resilience and mitigation to climate change from these CSA systems. The results thus suggest that employing these technologies can enable farmers to be more resilient and adapt better to climate change shocks in cropping systems.

With respect to productivity, CA (51%) and the Mbeya-fert (19%) resulted in higher maize yields compared to conventional farmer practices and this could contribute to improved food security and livelihoods. Although Maize-PP intercrops did not improve maize yields compared to the monocrops, the total output from this system (maize + legume) would give the farmers higher benefits compared to the monocrop systems thereby leading to improved diversification of food sources for the households.

The results also suggest that farmers could make large steps in improving productivity by simply investing in the use of improved agronomic practices namely drought tolerant varieties, timely weeding and use of correct or optimum plant populations. Higher gross margins were also evident from the use of CSA practices compared to conventional farmer practices thus contributing to improved economic viability.

Given that the CSA technologies assessed in this study were managed by farmers on their own without any external input resources, the results show the superiority of the tested CSA technologies in terms of improving the productivity of cropping systems towards enhanced food security by small holders in a highly variable climate induced by climate change. The higher soil organic carbon in the CSA systems also suggests these systems have scope for mitigating against greenhouse gas emissions since more carbon in these systems indicate a higher potential for carbon sequestration and hence improved mitigation.

The tested CSA practices elaborately address two of the CSA pillars (productivity, resilience /adaptation), and to a moderate extent, they also address the climate change mitigation merits of the tested CSAs. Supportive policy environments are therefore required to incentivize smallholder farmers to take up and apply these CSA practices on a relatively larger scale for improved climate smartness.

Further studies are required to establish the practical economic feasibility of these CSA innovations to further provide evidence-based recommendations on perceived macro-scale benefits of their use beyond the farm.

ACKNOWLEDGEMENTS

The authors of this report gratefully acknowledge the financial contributions of the United States Department of Agriculture (USDA) that enabled CIMMYT to implement this study. We also acknowledge Tetra Tech and the rest of the PERFORM project team for the support and guidance rendered that enabled these studies to be conducted. Amos Ngwira acknowledges salary support from the CGIAR Research Program on Grain Legumes and Dryland Cereals (GLDC) which is supported by CGIAR Fund Donors (https://www.cgiar.org/funders/).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Isaiah Nyagumbo https://orcid.org/0000-0003-0180-234X

REFERENCES

Agriculture Global Practice, (2016). *CLIMATE-SMART AGRICULTURE*. Washington DC, p. 126. World Bank, http://documents1.worldbank.org/curated/en/187151469504088937/pdf/105162-WP-P132359-PUBLIC-CSAIndicatorsReportweb.pdf

Bai, Z., Caspari, T., Ruiperez, M., Batjes, N. H., Mäder, P., Bünemann, E. K., Goede, R. D., Brussaard, L., Xu, M., So, C., Ferreira, S., Reintam, E., Fan, H., & Miheli, R. (2018). Agriculture, Ecosystems and Environment Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. *Agriculture, Ecosystems & Environment*, *265*, 1–7. https://doi.org/10.1016/j.agee.2018.05.028

Bayala, J., Sileshi, G. W., Coe, R., Kalinganire, A., Tchoundjeu, Z., Sinclair, F., & Garrity, D. (2012). Cereal yield response to conservation agriculture practices in drylands of West Africa: A quantitative synthesis. *Journal of Arid Environments*, *78*, 13–25. https://doi.org/10.1016/j.jaridenv.2011.10.011

Bouyoucos, G. J. (1962). Hydrometer Method Improved for Making Particle Size Analyses of Soils 1. *Agronomy Journal*, *54*(5), 464–465. https://doi.org/10.2134/agronj1962.00021962005400050028x

Cheesman, S., Thierfelder, C., Eash, N. S., Kassie, G. T., & Frossard, E. (2016). Soil carbon stocks in conservation agriculture systems of Southern Africa. *Soil and Tillage Research*, *156*, 99–109. https://doi.org/10.1016/j.still.2015.09.018

Chianu, J. N., Chianu, J. N., & Mairura, F. (2012). Mineral fertilizers in the farming systems of sub- Saharan Africa. A review. *Agronomy for Sustainable Development*, *32*, 545–566. https://doi.org/10.1007/s13593-011-0050-0

Chilimba, A. D. C., Mughogho, S. K., & Wendt, J. (1999). Mehlich 3 or modified olsen for soil testing in Malawi. *Communications in Soil Science and Plant Analysis*, *30*(7-8), 1231–1250. https://doi.org/10.1080/00103629909370280

Chinsinga, B., Chasukwa, M., & Naess, L. O. (2012). *Climate change and agricultural policy processes in Malawi*.Working Paper August 2012(1–26). Brighton, UK: University of Sussex, UK Department for International Developmentg. https://www.future-agricultures.org

Chirwa, E., Matita, M., Mvula, P., & Dorward, A. (2011). *Evaluation of Malawi Farm Input Subsidy Programme. School of Oriental and African Studies, University of London Impacts of the Farm Input Subsidy Programme in Malawi*. Paper prepared for Malawi Government / DFID Evaluation of Malawi Farm Input Subsidy Prog. London, UK.

Chowaniak, M., Głąb, T., Klima, K., Niemiec, M., Zaleski, T., & Zuzek, D. (2020). Effect of tillage and crop management on runoff, soil erosion and organic carbon loss. *Soil Use and Management*, *36*, 581–593. https://doi.org/10.1111/sum.12606

CIMMYT (1988). *From Agronomic Data to Farmer Recommendations: An Economics Training Manual*. Completely revised edition. Mexico: CIMMYT.

Corbeels, M., Cardinael, R., Naudin, K., Guibert, H., & Torquebiau, E. (2019). The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. *Soil and Tillage Research*, *188*, 16–26. https://doi.org/10.1016/j.still.2018.02.015

Dahmardeh, M., Ghanbari, A., Syahsar, B. A., & Ramrodi, M. (2009). The role of intercropping maize (*Zea mays* L.) and Cowpea (*Vigna unguiculata* L.) on yield and soil chemical properties.

African Journal of Agricultural Research, *5*, 631–636. https://doi.org/10.5897/AJAR09.607

Denning, G., Kabambe, P., Sanchez, P., Malik, A., Flor, R., Harawa, R., Nkhoma, P., Zamba, C., Banda, C., & Magombo, C. (2009). Input subsidies to improve smallholder maize productivity in Malawi: Toward an African green revolution. *PLoS Biology*, *7*(1), e1000023. https://doi.org/10.1371/journal.pbio.1000023

Descheemaeker, K., Oosting, S. J., Homann-Kee Tui, S., Masikati, P., Falconnier, G. N., & Giller, K. E. (2016). Climate change adaptation and mitigation in smallholder crop–livestock systems in sub-Saharan Africa: A call for integrated impact assessments. *Regional Environmental Change*, *16*(8), 2331–2343. https://doi.org/10.1007/s10113-016-0957-8

Dey, A., Dwivedi, B. S., Bhattacharyya, R., Datta, S. P., Meena, M. C., Jat, R. K., Gupta, R. K., Jat, M. L., Singh, V. K., Das, D., & Singh, R. G. (2020). Effect of conservation agriculture on soil organic and inorganic carbon sequestration and lability: A study from a rice–wheat cropping system on a calcareous soil of the eastern Indo-Gangetic Plains. *Soil Use and Management*, *36*(3), 429–438. https://doi.org/10.1111/sum.12577

Duval, M. E., Martinez, J. M., & Galantini, J. A. (2020). Assessing soil quality indices based on soil organic carbon fractions in different long-term wheat systems under semiarid conditions. *Soil Use and Management*, *36*, 71–82. https://doi.org/10.1111/sum.12532

FAO (2005). The importance of soil organic matter, key to drought resistant soil and sustained food production. *Soils Bullettin*, *80*, 1–78.

Faurès, J. M., Bartley, D., Bazza, M., Burke, J., Hoogeveen, J., Soto, D., & Steduto, P. (2017). *Climate smart agriculture sourcebook*. Rome, Italy.

Gonçalves, D. R. P., Sá, J. C. D. M., Mishra, U., Fornari, A. J., Furlan, F. J. F., Ferreira, L. A., Inagaki, T. M., Romaniw, J., de Oliveira Ferreira, A., & Briedis, C. (2019). Conservation agriculture based on diversified and high-performance production system leads to soil carbon sequestration in subtropical environments. *Journal of Cleaner Production*, *219*, 136–147. https://doi.org/10.1016/j.jclepro.2019.01.263

Govaerts*, B., Verhulst*, N., Castellanos-Navarrete, A., Sayre, K. D., Dixon, J., & Dendooven, L. (2009). Conservation agriculture and soil carbon sequestration: Between myth and farmer reality. *Critical Reviews in Plant Sciences*, *28*, 97–122. https://doi.org/10.1080/07352680902776358

Haarhoff, S. J., & Swanepoel, P. A. (2018). Plant population and maize grain yield: A global systematic review of rainfed trials. *Crop Science*, *58*, 1819–1829. https://doi.org/10.2135/cropsci2018.01.0003

Hayati, D., Ranjbar, Z., & Karami, E. (2010). Measuring agricultural sustainability. In: E. Lichtfouse (Ed.), *Biodiversity, Biofuels, Agroforestry and Conservation Agriculture* (pp. 73–100). Springer.

Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*, 543–555. https://doi.org/10.1098/rstb.2007.2169

Jackson, M. (1973). *Soil Chemical Analysis*. Prentice-Hall of India Pvt. Ltd.

Kaczan, D., Arslan, A., & Lipper, L. (2013). *Climate-smart agriculture? A review of current practice of agroforestry and conservation agriculture in Malawi and Zambia*.

Kassam, A., Friedrich, T., Shaxson, F., & Pretty, J. (2009). The spread of Conservation Agriculture: Justification, sustainability and uptake. *International Journal of Agricultural Sustainability*, *7*, 292–320. https://doi.org/10.3763/ijas.2009.0477

Kell, D. B. (2011). Breeding crop plants with deep roots: Their role in sustainable carbon, nutrient and water sequestration. *Annals of Botany*, *108*, 407–418. https://doi.org/10.1093/aob/mcr175

Lal, R. (2015). Sequestering carbon and increasing productivity by conservation agriculture. *Journal of Soil and Water Conservation*, *70*, 55–62. https://doi.org/10.2489/jswc.70.3.55A

Maris, S. C., Fiorini, A., Boselli, R., Santelli, S., & Tabaglio, V. (2021). Cover crops, compost, and conversion to grassland to increase soil C and N stock in intensive agrosystems. *Nutrient Cycling in Agroecosystems*, *9*, 83–101. https://doi.org/10.1007/s10705-020-10110-9

Michler, J. D., Baylis, K., Arends-Kuenning, M., & Mazvimavi, K. (2019). Conservation agriculture and climate resilience. *Journal of Environmental Economics and Management*, *93*, 579–620. https://doi.org/10.1016/jeem.2018.11.008

Mloza-Banda, H. R., Makwiza, C. N., & Mloza-Banda, M. L. (2016). Soil properties after conversion to conservation agriculture from ridge tillage in Southern Malawi. *Journal of Arid Environments*, *127*, 7–16. https://doi.org/10.1016/j.jaridenv.2015.11.001

Mloza-Banda, M. L., Cornelis, W. M., Mloza-Banda, H. R., Makwiza, C. N., & Verbist, K. (2014). Soil properties after change to conservation agriculture from ridge tillage in sandy clay loams of mid-altitude Central Malawi. *Soil Use and Management*, *30*, 569–578. https://doi.org/10.1111/sum.12139

Muchabi, J., Lungu, O. I., & Mweetwa, A. M. (2014). Conservation Agriculture in Zambia: Effects on Selected Soil Properties and Biological Nitrogen Fixation in Soya Beans (Glycine max (L.) Merr). *Sustainable Agriculture Research*, *3*, 28. https://doi.org/10.5539/sar.v3n3p28

Muoni, T., Koomson, E., Öborn, I., Marohn, C., Watson, C. A., Bergkvist, G., Barnes, A., Cadisch, G., & Duncan, A. (2019). Reducing soil erosion in smallholder farming systems in east Africa through the introduction of different crop types. *Experimental Agriculture*, *56*(2), 183–195. https://doi.org/10.1017/S0014479719000280

Mupangwa, W., Thierfelder, C., & Ngwira, A. (2017). Fertilization strategies in conservation agriculture systems with maize-legume cover crop rotations in Southern Africa. *Experimental Agriculture*, *53*, 288–307. https://doi.org/10.1017/S0014479716000387

Mutenje, M. J., Farnworth, C. R., Stirling, C., Thierfelder, C., Mupangwa, W., & Nyagumbo, I. (2019). A cost-benefit analysis of climate-smart agriculture options in Southern Africa: Balancing gender and technology. *Ecological Economics*, *163*, 126–137. https://doi.org/10.1016/j.ecolecon.2019.05.013

Ngwira, A. R., Aune, J. B., & Mkwinda, S. (2012). On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. *Field Crops Research*, *132*, 149–157. https://doi.org/10.1016/j.fcr.2011.12.014

Ngwira, A. R., Aune, J. B., & Thierfelder, C. (2014). DSSAT modelling of conservation agriculture maize response to climate change in Malawi. *Soil and Tillage Research*, *143*, 85–94. https://doi.org/10.1016/j.still.2014.05.003

Nyagumbo, I., Mkuhlani, S., Pisa, C., Kamalongo, D., Dias, D., & Mekuria, M. (2016). Maize yield effects of conservation agriculture based maize–legume cropping systems in contrasting agro-ecologies of Malawi and Mozambique. *Nutrient Cycling in Agroecosystems*, *105*, 275–290. https://doi.org/10.1007/s10705-015-9733-2

Nyagumbo, I., Mupangwa, W., Chipindu, L., Rusinamhodzi, L., & Craufurd, P. (2020). A regional synthesis of seven-year maize yield responses to conservation agriculture technologies in Eastern and Southern Africa. *Agriculture, Ecosystems & Environment*, *295*, 106898. https://doi.org/10.1016/j.agee.2020.106898

Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., & Grace, P. (2014). Conservation agriculture and ecosystem services: An overview. *Agriculture, Ecosystems & Environment*, *187*, 87–105. https://doi.org/10.1016/j.agee.2013.10.010

Pauw, K., Thurlow, J., & Van Seventer, D. (2010). Droughts and floods in Malawi: Assessing the economywide effects. Washington, DC 20005-3915 USA. Discussion Paper 2020, 134. Washington, DC: International Food Policy Research institute. http://ebrary.ifpri.org/utils/getfile/collection/p15738coll2/id/1370/filename/1371pdf

Pittelkow, C. M., Liang, X., Linquist, B. A., Groenigen, K. J. V., Lee, J., Lundy, M. E., Gestel, N. V., Six, J., Venterea, R. T., & Kessel, C. V. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature*, *517*, 365–368. https://doi.org/10.1038/nature13809

Rusinamhodzi, L., Corbeels, M., Nyamangara, J., & Giller, K. E. (2012). Maize – grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. *Field Crops Research*, *136*, 12–22. https://doi.org/10.1016/j.fcr.2012.07.014

Rusinamhodzi, L., Makoko, B., & Sariah, J. (2017). Field Crops Research Ratooning pigeonpea in maize-pigeonpea intercropping : Productivity and seed cost reduction in eastern Tanzania. *Field Crops Research*, *203*, 24–32. https://doi.org/10.1016/j.fcr.2016.12.001

Shelton, D. P., & Jasa, P. J. (1995). Estimating Percent Residue Cover Using the Photo-Comparison Method. Hist. Mater. from Univ. Nebraska-Lincoln Ext. 782. Historical Materials from University of Nebraska-Lincoln Extension, 78A1-9), USA. University of Nebraska. https://digitalcommons.unl.edu/extensionhist/7822

Simwaka, P., Tesfamariam, E., Ngwira, A., & Chirwa, P. (2020). Carbon sequestration and selected hydraulic characteristics under conservation agriculture and traditional tillage practices in Malawi. *Soil Research*, *58*, 759–769. https://doi.org/10.1071/SR20007

Six, J., Elliott, E. T., & Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, *32*, 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6

Smith, A., Snapp, S., Chikowo, R., Thorne, P., Bekunda, M., & Glover, J. (2017). Measuring sustainable intensification in smallholder agroecosystems: A review. *Global Food Security*, *12*, 127–138. https://doi.org/10.1016/j.gfs.2016.11.002

Steward, P. R., Dougill, A. J., Thierfelder, C., Pittelkow, C. M., Stringer, L. C., Kudzala, M., & Shackelford, G. E. (2018). Agriculture, Ecosystems and Environment The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments : A meta-regression of yields. *Agriculture, Ecosystems & Environment*, *251*, 194–202. https://doi.org/10.1016/j.agee.2017.09.019

Thien, S. J. (1979). A flow diagram for teaching texture-by-feel analysis. *Journal of Agronomic Education*, *8*(1), 54–55. https://doi.org/10.2134/jae.1979.0054

Thierfelder, C., Matemba-Mutasa, R., Bunderson, W. T., Mutenje, M., Nyagumbo, I., & Mupangwa, W. (2016). Evaluating manual conservation agriculture systems in southern Africa. *Agriculture, Ecosystems & Environment*, *222*, 112–124. https://doi.org/10.1016/j.agee.2016.02.009

UN, (2015). *United Nations Transforming Our World: The 2030 Agenda for Sustainable Development*. A/RES/70/1, United Nations.

USAID. (2015). *Protecting Ecosystems and Restoring Forests in Malawi (Perform)*. 1–44.

Verhulst, N., Carrillo-García, A., Moeller, C., Trethowan, R., Sayre, K. D., & Govaerts, B. (2011). Conservation agriculture for wheat-based cropping systems under gravity irrigation: Increasing resilience through improved soil quality. *Plant and Soil*, *340*, 467–479.

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science*, *37*, 29–38.

Wang, Q., Li, Y., & Wang, Y. (2011). Optimizing the weight loss-on-ignition methodology to quantify organic and carbonate carbon of sediments from diverse sources. *Environmental Monitoring and Assessment*, *174*, 241-257. https://doi.org/10.1007/s10661-010-1454-z

Yang, X. M., & Wander, M. M. (1999). Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois. *Soil and Tillage Research*, *52*, 1–9. https://doi.org/10.1016/S0167-1987(99)00051-3

Young, M. D., Ros, G. H., & de Vries, W. (2020). A decision support framework assessing management impacts on crop yield, soil carbon changes and nitrogen losses to the environment. *European Journal of Soil Science*. https://doi.org/10.1111/ejss.13024

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Nyagumbo I, Mutenje M, Setimela P, et al. Evaluating the merits of climate smart technologies under smallholder agriculture in Malawi. *Soil Use Manage*. 2021;00:1–17. https://doi.org/10.1111/sum.12715