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Is conservation agriculture 'climate-smart' for maize farmers in the highlands of Tanzania?

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Abstract Conservation agriculture (CA) is promoted extensively to increase the productivity and environmental sustainability of maize production systems across sub-Saharan Africa and is often listed as a climate-smart agriculture (CSA) practice. However, the impacts of CA on food security, resilience/adaptive capacity and climate change mitigation are location-dependent and it is unknown whether CA can simultaneously address CSA's multiple objectives. Here we evaluate four variations of CA: reduced tillage plus mulch (mulch), reduced tillage plus mulch and leguminous cover crop (Lablab), reduced tillage plus mulch and leguminous trees (CAWT), and reduced tillage plus mulch and nitrogen fertilizer (CA + F)—for their effect on CSA-relevant outcomes in highland Tanzania maize production. By comparison to conventional practice in the region, intensification of maize production by Lablab, CAWT, and CA + F significantly increases yields by 40, 89 and 77 %, respectively. Likewise, rainfall use efficiency was highest in these three treatments and significantly greater than conventional practices in 7 of 12 comparisons. Seasonal and annual greenhouse gas fluxes were similar across all treatments; however, yield-scaled global warming potential (Mg CO_2 eq Mg grain^{-1}) was lower in CAWT (2.1–3.1) and CA + F (1.9–2.3) than conventional practice (1.9–8.3), averaging 62 and 68 % of the emission intensity of conventional practice, respectively. The findings demonstrate that CA can deliver benefits consistent with the objectives of CSA for farmers in this region, particularly when soil nitrogen limitation is alleviated, providing other constraints to adoption are removed.

Keywords Conservation agriculture · Climate-smart agriculture · Mitigation · Tanzania

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Introduction

Soil degradation, unreliable rainfall and generally poor agronomic practices contribute to persistent food insecurity in sub-Saharan Africa and make rainfed farming a risky proposition for smallholders (Challinor

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et al. 2007; Schlenker and Lobell 2010). By 2030, there will be 120–150 million smallholder farmer households in sub-Saharan Africa. Many millions of which will rely on rainfed maize cultivation for subsistence (Dixon et al. 2001). Thus, developing and testing means to increase productivity and manage climate risks in maize-based systems is central to improving the livelihoods of farmers.

Recently, climate-smart agriculture (CSA) has been proposed to address concerns of food security and climate change in an integrated way (FAO 2013; Neufeldt et al. 2013; Harvey et al. 2014). CSA refers to land management practices that increase food security, the resilience/adaptive capacity of farmer households to climate variability and mitigate climate change by sequestering carbon in biomass and soils and/or reducing emissions when possible (FAO 2013). Support for CSA usually relies on data aggregated to levels of management measures (e.g., agroforestry) that combine multiple practices (e.g., intercropping with leguminous trees and boundary planting with timber species) from diverse agroecological and socioeconomic conditions (e.g., Branca et al. 2011). With aggregate data, it is not possible to evaluate the suitability of a specific farming practice for a specific location with much certainty.

Conservation agriculture (CA)—a combination of soil management practices that include reduced soil disturbance, permanent soil cover and crop rotation—is promoted extensively across sub-Saharan Africa and often labelled CSA (FAO 2013). CA and its derivatives that apply one or two of its three components have been found to address one or more of CSA's goals under certain conditions. Yields of maize grown under CA in Southern Africa, for instance, were higher than non-CA yields in 80 % of cases, with yield advantages of 482–1173 kg ha^{-1} depending on particulars of the CA system (Thierfelder et al. 2015). But other evidence of increased productivity with reduced and no-till practices with rainfed agriculture is mixed. Meta-analyses show higher yields under CA than conventional practice in some few cases; however, benefits were variable based on soil type, precipitation, application of nitrogen fertilizer, and implementation of the entire CA bundle (Rusinamhodzi et al. 2011; Farooq et al. 2011). Beside yield, CA can contribute to other food security objectives. For example, when leguminous crops are integrated as ground covers or intercropped as in the case with pigeonpea, CA can increase dietary diversity (Kaczan et al. 2013).

CA may also confer adaptation and mitigation advantages. Reduced soil disturbance and crop residue retention changes soil physical properties such as hydraulic conductivity and bulk density which can increase water infiltration rates and soil moisture retention helping crops cope with intra-seasonal dry spells (Thierfelder et al. 2012), reduce soil erosion (Verachtert et al. 2009) and use precipitation more efficiently. CA can affect soil fertility, sustaining or even enhancing soil carbon and nitrogen pools. Modifying nutrient stocks will affect greenhouse gas fluxes and hence determine whether CA contributes to or combats climate change through emissions or sequestration, respectively. Until recently, reduced tillage was thought to increase soil carbon content; however, the potential now appears to be somewhat negligible when considering the soil profile to depth (Baker et al. 2007; Palm et al. 2014; Powlson et al. 2014). By comparison to changes in soil carbon stocks under reduced tillage and CA, greenhouse gas emissions from soils in low-input CA systems of sub-Saharan Africa are poorly documented.

Maize is central to food security in Tanzania, and its productivity is at risk due to climate change. Maize accounts for 60 % of the dietary calories of Tanzanian consumers and more than 50 % of utilizable protein, whereas beans contribute 38 %. About 85 % of the maize produced in Tanzania is grown by small-scale farmers typically under rainfed conditions and managed under low or no input practices. Consequentially, yields are meager. By comparison to advanced agricultural production systems in Africa, yields were only 1.3 Mg grain ha^{-1} in Tanzania versus 4.3 Mg grain ha^{-1} in South Africa averaged 2009–2013 (FAOSTAT 2014). The methods of maize cultivation make maize particularly vulnerable to a changing climate. Already, the country has seen depressed maize yields due to droughts and floods (Paavola 2008). Climate predictions suggest that much of Tanzania will get 1–2 °C warmer and up to 25 % wetter by 2050 (Girvetz et al. 2009; Climate Wizard 2014). The predicted changes may cause complex and sometimes counterbalancing effects. Increases in temperature may cause an average of 19 % yield decline while increases in precipitation could increase production by an average of 6 %, but together temperature and precipitation may cause a net 11–13 % yield decline (Rowhani et al. 2011). With current and future production of an important staple crop at risk,

development of climate-smart maize production systems becomes an imperative.

The objective of this study is to evaluate CA maize for its 'climate-smartness' in the highlands of Eastern Tanzania. Therefore, we conducted a controlled experiment to compare the performance of maize under CA and three CA derivatives to conventional maize production practice based on indicators of food production (yield), resilience (rain use efficiency) and mitigation (greenhouse gas emissions and yield-scaled global warming potential) that farmers, researchers and development partners identified as important for this objective. Though caution should be taken when extrapolating these results to other locations because of the limited scope of the experiment, the approach and results of this study have broader implications. There is a dearth of information on the performance of CA for sub-humid areas of sub-Saharan Africa, no information on the greenhouse gas fluxes from CA systems in sub-Saharan Africa, and little data from co-located research efforts across the food security, adaptation and mitigation domains. This study provides a first attempt to unify empirical research agendas under the CSA umbrella.

Materials and methods

Site description and experimental design

The study was conducted over twenty-one months, October 2012 through June 2014, in the village of Kolero (37°48′E, 07°015′S), in the Uluguru Mountains of Eastern Tanzania. Elevation in the Kolero area ranges from 260 to 1250 m. Annual precipitation in the region falls within two seasons, the 'Long Rains' (approximately mid-February through June) and the 'Short Rains' (approximately mid-October through December). Temperature varies between 22 and 33 °C. Farmers cultivate maize, rice and cassava using slash and burn techniques.

Farmers and development partners' perspectives informed the research design. A 2011 survey of 333 households indicated that maize is the primary crop in the area, accounting for nearly 25 % of the cultivated land (Zagst 2011). Low yields and inter- and intra-seasonal droughts were farmers' primary concerns in maize production. Because of such concerns, local extension workers and development partners introduced CA starting

in 2008. However, adoption was oftentimes partial, with farmers only implementing one or two of the practices that constitute the full CA bundle. These concerns and farmer-adaptation of the practice informed the selection of indicators (e.g., rain use efficiency) and treatments.

The experiment was conducted at a central location in Kolero, often used as a training facility. The experiment was laid out in a completely randomized design with three replicates of five treatments. Each plot was 3 m × 5 m with 2 m unplanted buffer strips. Treatments were selected to reflect practices currently being used (#1 and 2) and those being promoted by extension services (#3, 4 and 5). Treatments were: (1) conventional cultivation (Conv), (2) reduced tillage and biomass mulch retained between rows (Mulch), (3) reduced tillage plus leguminous cover crop (Lablab), (4) reduced tillage plus mineral fertilizer (CA + F), and (5) reduced tillage intercropped with leguminous *Gliricidia sepium* trees (CAWT). Conventional cultivation reflects hand hoe cultivation, the typical mode of site preparation by farmers. Reduced tillage treatments were prepared by double-digging (within plant row) prior to the short rain season in 2012 and then were stick planted in subsequent years. Cover crop for the LabLab treatment was sown 10 days after planting maize. Seedlings of *G. sepium* were planted at a spacing of 1 m × 1 m in March 2012, 7 months prior to the start of the experiment. After 1 year (i.e., March 2013), *G. sepium* plants were pruned 2–3 times growing season^{-1} and the foliage biomass uniformly spread in the plots as green manure. At each pruning date, composite samples plot^{-1} were collected weighed fresh and taken to laboratory for oven drying and nutrient analysis. The amount of nitrogen added via green manure was then estimated as a production of dry matter and N concentration and values extrapolated on hectare^{-1} based on the plot area. The widely planted maize variety Tan250 was planted at 75 cm between rows and 30 cm within rows, leaving one plant station^{-1}. Urea was basal applied a rate of 100 kg N ha^{-1} when maize plants reached the knee height. No phosphate fertilizer was added because soils have sufficient levels of phosphorus (40 kg P ha^{-1}) for maize production in Morogoro (Marandu et al. 2013), as indicated in Table 1. Planting regimes and dates (Fig. 1) followed common practice in the area and were determined by the local county agricultural extension officer and the site was prepared according the prescribed treatments. Clean weeding was done using a hand hoe, two or three

Table 1 Soil characteristic of site

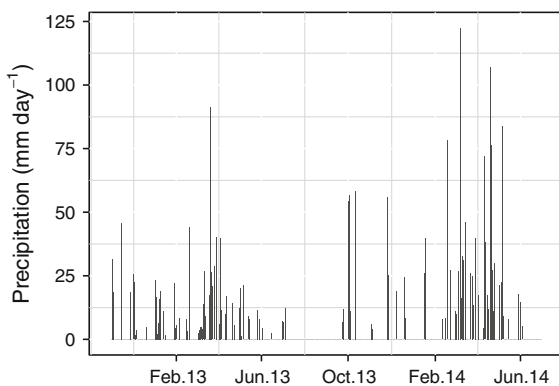| Soil parameter	Soil depth (cm)	
	0–20	20–50
Soil pH (1:2.5)	5.7	5.7
Bulk density (g cm^{-3})	1.4	1.4
Sand (%)	67.0	69.0
Silt (%)	11.0	10.0
Clay (%)	21.0	20.0
TN (%)	0.2	0.1
SOC (%)	2.7	1.8
Fe (mg kg^{-1})	59.5	59.2
Ext. P (mg kg^{-1})	38.2	15.7
ECEC (mmol$_c$ kg^{-1})	106.7	91.2
Exchangeable Ca^{2+} (mmol$_c$ kg^{-1})	66.6	52.9
Exchangeable Mg^{2+} (mmol$_c$ kg^{-1})	34.2	33.6
Exchangeable K$^+$ (mmol$_c$ kg^{-1})	31.8	14.1
Exchangeable H$^+$ (mmol$_c$ kg^{-1})	26.3	30.7
Exchangeable Al^{3+} (mmol$_c$ kg^{-1})	0.00	0.30

Fig. 1 Precipitation during the experiment. Planting-harvest dates for the four growing seasons were 15/10/2012-16/2/2013 (2012SR, 354 mm), 18/3/2013-9/7/2013 (2013LR, 485 mm), 12/10/2013-25/1/2014 (2013SR, 227 mm), and 27/1/2014-9/6/2014 (2014LR, 1256 mm). Cumulative seasonal rainfall for 2012SR represents rainfall after 1/11/2012 because of missing data

times season^{-1}, as needed. No serious pests or diseases were noted throughout the experimental period.

Soil and plant measurements

Prior to the experiment, baseline soil samples were collected at five random points to characterize the site. The samples were collected from 0 to 20 and 20 to 50 cm depths using a soil auger, mixed thoroughly and sub-sampled to obtain a composite sample. Thereafter the samples were air dried and sieved through 2 mm sieve for analysis of soil pH in 1:2.5 soil–water aqueous suspensions using a pH meter and extractable P by the Bray-1 method at Sokoine University (Morogoro, Tanzania). Ammonium acetate solution (1N) was used for the extraction of exchangeable K, Ca, and Mg and the element concentrations determined by atomic absorption spectrophotometer. Exchangeable acidity (hydrogen and aluminium) was done by leaching the soil samples with 1M KCl and measured quantitatively by titration. Cation exchange capacity was obtained by summation of exchangeable cations and exchangeable acidity. These laboratory analyses were conducted at the Sokoine University (Morogoro, Tanzania) and followed standard procedures as described by Anderson and Ingram (1993). In addition, total nitrogen and acidified carbon were determined by dry combustion at the ICRAF Soil-Plant Diagnostic Laboratory (Nairobi, Kenya).

At physiological maturity, maize grain and stover samples were harvested from the net plot areas (1.5 m by 4.5 m, 32 plants plot^{-1}), weighed and sub-sampled for oven dry weight determination at 70 °C and for the estimation of dry weight plot^{-1} based on the ratio of dry-to-fresh weights. The final maize grain and stover yields were expressed in Mg ha^{-1} based on yield sampled area^{-1}. Rain use efficiency (RUE) was expressed as the mass (kg) of grain dry matter produced hectare^{-1} precipitation^{-1} (mm) received during the rainy season and calculated by the formula RUE = yield/precipitation (Sileshi et al. 2011).

CO_2, CH_4, and N_2O measurements

Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) fluxes were measured using static chamber techniques consistent with good practice guidelines for greenhouse gas (GHG) measurements in smallholder systems (Rosenstock et al. 2013; SAMPLES 2014). Chamber base (27 × 37.2 × 10 cm) had 50 cm vents, battery operated fans, thermometers, and gas sampling ports. Chambers were made of plastic to minimize construction costs and limit financial liability due to concerns over theft and covered with reflective material. Chambers were made of two parts: a base inserted 5–10 cm into the soil and a lid (27 × 37.2 × 12 cm) that formed an

airtight seal between the two pieces when fastened with clamps. Chambers were placed in situ 1 week prior to the first measurement and then remained in place throughout the season. Each 15 m^2 plot contained two chambers, one within the row of maize (between two plants) and one between rows.

During sampling, chambers were sealed for 30 min. Samples of chamber headspace were taken at 10 min intervals (0, 10, 20, and 30 min). Gas samples were collected using a 60 mL propylene syringe with a Leurlock. Samples were immediately transferred from the syringe into a glass vial fitted with crimp seals. Vials were overpressurized to reduce the likelihood of contamination with ambient air. Samples were transferred to ICRAF and analysed as soon after collection as possible.

Concentrations of CO_2, N_2O, and CH_4 were measured using a SRI GHG gas chromatograph (model 8610C, SRI Institute). The GC was equipped with a flame ionization detector (FID) for CH_4, a ^{63}Ni electron capture detector (ECD) for N_2O, and a methanizer connected to the FID channel to measure CO_2. The GC was operated with Haysep D packed columns with oven temperature of 65 °C and flow rates of 25 mL min^{-1} on both FID and ECD lines. Gas concentrations in samples were calculated relative to the marginal concentration of peak areas measured derived from calibration gases run four times over the 8-h workday. Sample concentrations were then converted to a mass volume^{-1} basis using the Ideal Gas Law, measured chamber volume, internal air temperature, and atmospheric pressure at the site. Flux rates were based on linear regression of gas concentrations versus time. Fluxes below the minimum detection limit calculated according to the method descried by Parkin et al. (2012) were set to zero.

Soil GHG fluxes were measured for twenty-one months, October 2012 through June 2014. This period contained four growing/rainy seasons and two fallow seasons. Estimates of fluxes for each plot were calculated for each season and for the entire calendar year (annual). Both seasonal and annual estimates were based on linear interpolation between measured fluxes for the respective time period and integrated using the trapezoidal rule. Seasonal periods were determined by planting schedule, which reflected practice on-going in the area. For example, there was no fallow period between the short rains of 2013 and long rains of 2014 because early onset of rains in January 2014 stimulated farmers in the surrounding area to plant and thus the experiment followed suit. Calculations for seasonal fluxes represent 5 days prior to planting through 5 days following harvest.

Global warming potential (GWP) was calculated as CO_2 equivalents (Mg CO_2 eq) over a 100-year time horizon using a radiative forcing potential of 1 for CO_2, 298 for N_2O, and 34 for CH_4 (Myhre et al. 2013). Yield-scaled GWP (GHG intensity) was calculated as the average GWP of the three replications divided by harvested grain for the four growing seasons (Mg CO_2 eq Mg grain^{-1}).

Data analysis

The Shapiro-Wilkes test was employed to test for normality of yield and GHG data using the Statistical Analysis System (SAS Institute 2008) version 9.2. The PROC MIXED procedure in the SAS system was used to conduct the analysis of variance (ANOVA) for maize yield and rain use efficiency responses to treatments at 5 % level of significance. GHG data were also analysed using this procedure. Following ANOVA, means for significant treatments were compared using Tukey's studentized range and letter grouping done by the PDMIX procedure. Descriptive analysis of soil data for site characterization, maize and GHG data were done using the procedure MEANS provided in SAS.

Results

Seasonal patterns of yield

Overall CA improved maize grain yield compared to the conventional cultivation using a hand hoe in all seasons, except for the short rains in 2012 (Fig. 2). In the 2012 short rains, maize grain yield were similar in all treatments and ranged from 3.6 to 4.1 Mg ha^{-1}. Significant effects, however, were noted in CA treatments where reduced tillage was complemented with either nitrogen fertilizer (CA + F) or leguminous tree (CAWT) integration as noted for the long rain growing seasons in 2013 ($p = 0.016$) and 2014 ($p = 0.013$) and the short rain growing season in 2013 ($p = 0.002$). Corresponding maize grain yields for CA + F and CAWT in these seasons were 2.1 and 2.2, 2.8 and 3.2, and 2.1 and 2.3 Mg ha^{-1}, respectively. Yields were not statistically different between CA + F and CAWT in any season. Relative to the control (1.8 Mg ha^{-1})
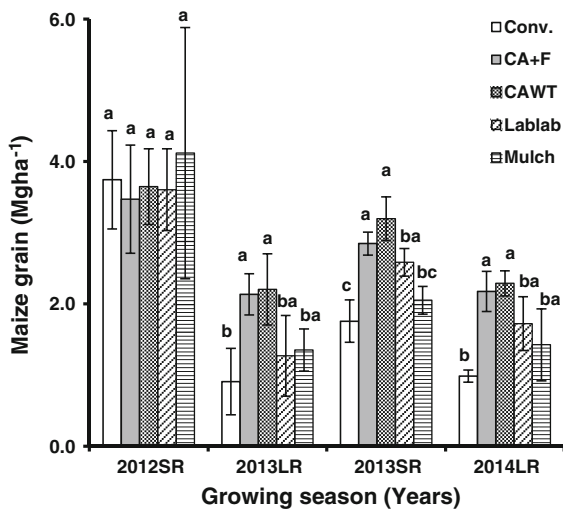
Fig. 2 Maize yields over the four growing seasons, October 2012–June 2014. *Vertical bars* are SE. *Different letters* within seasons represent significant differences ($p < 0.05$)

and CAWT (4.5 kg ha^{-1} mm^{-1}) treatments consistently recorded the highest RUE values in the long rains of 2013 and throughout the experimental period, suggesting that most of the rain water in these treatments were utilized for growth and yield increases. Relative to conventional farming average RUE in these treatments over the four growing seasons were 36 and 47 % higher, respectively. RUE during the short rain seasons of 2012 (10.5 kg ha^{-1} mm^{-1}) and 2013 (11.0 kg ha^{-1} mm^{-1}) was comparatively higher than that in the subsequent long rain seasons (3.2 and 1.4 kg ha^{-1} mm^{-1}, respectively). These RUE values are similar to those obtained by Thierfelder and Wall (2009) under CA in Zimbabwe. Though the seasons are called 'short' and 'long' by local convention, it is important to note that the two long rain seasons included in this study averaged only 8 days longer than the two short rain seasons when considering planting and harvest dates. However, the amount of precipitation received in the long seasons was three times that of the short seasons, contributing to the observed differences in the RUE.

percentage maize grain yield across the four seasons averaged 44 % (2.7 Mg ha^{-1}) for CA + F and 53 % (2.8 Mg ha^{-1}) for CAWT treatments compared to 21 % (2.2 Mg ha^{-1}) and 24 % (2.3 Mg ha^{-1}) for mulch and lablab CA-based treatments, respectively.

Rain use efficiency

Treatment effects on RUE followed a trend similar to that of maize grain yield with statically significant difference ($p < 0.05$) noted in all seasons except for the short season in 2012 (Table 2). CA + F (4.4 kg ha^{-1} mm^{-1})

Seasonal and annual patterns of GHG fluxes

Seasonal fluxes among treatments were not statistically significant from each other ($p > 0.05$), yet showed distinct patterns in terms of emissions. The vast majority of fluxes occurred during the two rainy seasons (Table 3). Seasonal fluxes in the short rains averaged from 90, 136 and 27 % of the fluxes of CO_2, N_2O, and CH_4, in the subsequent growing season. By

Table 2 Indicators of adaptive capacity, rainfall use efficiency of treatments

Treatment	Rainfall use efficiency (kg ha^{-1} mm^{-1})			
	2012–2013		2013–2014	
	Short rains	Long rains	Short rains	Long rains
Conv.	10.6 (2.0)a	1.9 (1.0)b	7.3 (1.3)c	1.5 (0.06)b
CA + F	9.8 (2.1)a	4.4 (0.6)a	12.5 (0.7)a	1.7 (0.2)a
Lablab	10.2 (1.6)a	2.6 (0.4)ab	11.4 (1.6)ab	1.4 (0.3)ab
Mulch	11.6 (4.9)a	2.9 (0.6)ab	9.0 (0.9)bc	1.1 (0.4)ab
CAWT	10.3 (1.5)a	4.5 (1.0)b	14.0 (1.4)a	1.8 (0.1)a
P > F value	0.9136	0.0055	0.0006	0.0041

Values are means (SD)

Values followed by different letters are significantly different from other treatments within column ($p < 0.05$). RUE during the short rain seasons of 2012 (10.5 kg ha^{-1} mm^{-1}) and 2013 (11.0 kg ha^{-1} mm^{-1}) was comparatively higher than corresponding values in the longer rainy seasons (3.2 and 1.4 ha^{-1} mm^{-1}, respectively)

Table 3 Annual and seasonal GHG fluxes

Treatment	Short rains (~Oct.–Jan.)			Dry fallow (~Jan.–Feb.)			Long rains (~Feb.–June)		
	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4
2012–2013									
Conv.	1.9 (0.8)	0.09 (0.02)	0.6 (0.6)	0.2 (0.02)	0.01 (0.02)	−0.06 (0.06)	2.0 (0.3)	0.3 (0.1)	−0.1 (2.1)
CA + F	2.2 (0.3)	0.2 (0.09)	1.6 (2.3)	0.2 (0.1)	0.01 (0.02)	0.01 (0.05)	1.7 (0.3)	0.2 (0.01)	1.9 (3.9)
Lablab	2.3 (0.5)	0.3 (0.1)	0.9 (2.1)	0.2 (0.04)	0.01 (0.01)	−0.03 (0.04)	2.0 (0.4)	0.2 (0.02)	3.5 (5.7)
Mulch	2.2 (0.5)	0.2 (0.04)	0.2 (0.5)	0.2 (0.1)	0.02 (0.01)	−0.01 (0.03)	2.0 (0.3)	0.2 (0.1)	−1.5 (1.8)
CAWT	2.4 (1.0)	0.3 (0.2)	1.5 (4.2)	0.2 (0.1)	0.06 (0.1)	0.05 (0.08)	1.9 (0.5)	0.2 (0.1)	−2.8 (5.1)
2013–2014									
Conv.	1.4 (0.4)	0.5 (0.09)	−0.2 (0.1)				2.2 (0.4)	0.3 (0.1)	−0.1 (0.1)
CA + F	1.4 (0.3)	0.5 (0.3)	−0.2 (0.2)				2.3 (0.4)	0.4 (0.1)	−0.1 (0.1)
Lablab	1.7 (0.4)	0.3 (0.3)	−0.7 (0.3)				2.2 (0.5)	0.2 (0.1)	−0.6 (0. 5)
Mulch	1.2 (0.1)	0.3 (0.4)	−0.2 (0.1)				2.8 ± 1.0	0.2 (0.1)	−0.2 (0.2)
CAWT	1.7 (0.1)	0.6 (0.4)	−0.2 (0.3)				2.1 (0.5)	0.2 (0.2)	−0.3 (0.3)

Treatment	Dry fallow (~June–Oct.)			Annual		
	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4
2012–2013						
Conv.	0.5 (0.1)	0.1 (0.04)	−0.1 (1.9)	4.8 (0.9)	0.4 (0.1)	0.8 (2.8)
CA + F	0.5 (0.1)	0.02 (0.01)	−0.2 (0.5)	4.8 (0.8)	0.4 (0.1)	3.3 (6.7)
Lablab	0.6 (0.1)	0.04 (0.03)	0.01 (0.9)	5.5 (0.9)	0.6 (0.1)	4.2 (3.4)
Mulch	0.5 (0.2)	0.1 (0.04)	0.1 (0.5)	5.2 (0.8)	0.5 (0.1)	−1.3 (2.6)
CAWT	0.5 (0.1)	0.1 (0.1)	0.5 (0.2)	5.4 (1.7)	0.7 (0.3)	−0.7 (0.8)
2013–2014						
Conv.						
CA + F						
Lablab						
Mulch						
CAWT						

Units are CO_2-C (Mg ha^{-1}), N_2O-N (kg ha^{-1}) and CH_4-C (kg ha^{-1})

Values are means (SD)

Table 4 Global warming potential (GWP) based on radiative forcing over a 100-year timeframe and yield-scaled GWP (GHG intensity)

Treatment	GWP (Mg CO$_2$ eq ha^{-1})					Yield-scaled GWP (Mg CO$_2$ eq Mg grain^{-1})	
	Short rains	Dry fallow	Long rains	Dry fallow	Annual	Short rains	Long rains
2012–2013							
Conv.	7.0 (2.8)	0.6 (0.1)	7.5 (1.1)	1.8 (0.1)	17.9 (3.3)	1.9	8.2
CA + F	8.0 (1.1)	0.7 (0.3)	6.5 (1.0)	1.8 (0.2)	17.9 (2.6)	2.3	3.1
Lablab	8.7 (1.8)	0.9 (0.2)	7.4 (1.5)	2.1 (0.4)	20.5 (3.3)	2.4	5.8
Mulch	8.0 (1.9)	0.9 (0.2)	7.5 (1.1)	1.9 (0.6)	19.2 (2.8)	2.0	5.6
CAWT	9.1 (3.6)	0.8 (0.3)	6.9 (1.9)	2.0 (0.4)	19.9 (6.5)	2.5	3.1
2013–2014							
Conv.	5.5 (1.6)		8.2 (1.5)			3.1	8.3
CA + F	5.3 (1.2)		8.5 (1.5)			1.9	2.4
Lablab	6.6 (1.5)		8.3 (1.8)			2.6	3.8
Mulch	4.6 (0.6)		10.4 (3.7)			2.2	3.2
CAWT	6.6 (0.6)		7.9 (1.8)			2.1	2.9

Values are means (SD)

comparison to intra-annual fluxes, inter-annual fluxes between the same seasons of subsequent years (e.g., short rains 2012 vs. short rains 2013) showed larger variations. For example, fluxes of N$_2$O-N in short rains of 2013 were between 19 % (Conv) to more than 81 % (Lablab) of that found in 2014. An opposite pattern emerged for CO$_2$-C, where fluxes were greater in the short rains of 2013 than 2014 by 31 to 78 %.

Annual emissions were not statistically significantly different across treatments. The CA + F treatment averaged the lowest CO$_2$-C emissions (4.8 Mg ha^{-1} year^{-1}) while conventional practices the lowest N$_2$O-N (0.4 kg ha^{-1} year^{-1}). All treatments emitted less the 6 Mg CO$_2$-C ha^{-1} year^{-1} and 0.7 kg N$_2$O-N ha^{-1} year^{-1}. Mulch and CAWT treatments were net sinks for CH$_4$-C while the others were sources. Annual emissions for the 2013–2014 year are uncertain because of lack of monitoring data from the 2014 fallow season following the long rains. Assuming the same emission rates as the 2013 season, we would have expected higher annual emissions of N$_2$O, with all treatments above 0.6 kg N$_2$O-N ha^{-1} year^{-1} and the CA + F and CAWT treatment-emitting equivalent to slightly less than 1 kg N ha^{-1} year^{-1}.

GWP and yield-scaled GWP

Neither GWP nor yield-scaled GWP were significantly different among treatments due to high variability between replicated plots. There was only 14 % difference in GWP between the lowest (Conv and CAWT) and the highest (lablab) (Table 4). There was a pronounced difference in mean yield-scaled GWP (GHG intensity) of the various productions in absolute terms, though. In both years, CAWT and CA + F had the lowest yield-scaled GWP, almost less than half that of the conventional practice and only between 64 and 85 % of that of lablab and mulch treatments. Given the global warming potentials of the treatments were relatively similar, the lower intensities result from the higher yields under CA + F and CAWT.

Discussion

Our results indicate that intensifying maize farming—via CA with cover crops, CAWT and CA + F—can be climate-smart for maize farmers of Kolero village. These practices increased productivity and rain use efficiency and had lower greenhouse gas intensities than conventional farming practices characteristic of the area and Tanzania more broadly. These findings add to previous results showing that CA can produce yield benefits and enhance adaptive capacity by improving soil health (Thierfelder and Wall 2009, 2010) by layering on empirical evidence of greenhouse gas emissions and mitigation and demonstrating

the triple-win characteristic of CSA (FAO 2013). Caution should be exercised when extrapolating these results to other locations, as this study was limited to a single site and CA performance is greatly influenced by edaphic, social and economic conditions (Giller et al. 2009; Rusinamhodzi et al. 2011; Rosenstock et al. 2014). Regardless, these data provide perhaps the first insight from co-located research evaluating the climate-smartness of farming practices based on participatory assessments of risks and needs.

Similar maize yields in CA + F and CAWT treatments reflect N inputs by fertilizer and trees (*G. sepium*) via the green manure additions, litter and root turnover and other biogeochemical processes (Kimaro et al. 2008). On average, application of *G. sepium* green manure added 46 kg N ha^{-1} in each season. We did not trace N transfer via other methods, but studies suggest that frequent pruning, like what was done in this trial, stimulates N transfer to intercrops via fine root and nodule turnover and root exudations and *G. sepium* can fix up to 166 kg N ha^{-1} after 9 months (Liyanage et al. 1994). The consistently higher grain yields in CA + F and CAWT treatments suggest that treatment response was driven more by nutrient inputs than biophysical advantages due to CA (e.g., improve soil moisture and root proliferations) of the double digging. These results are consistent with the argument that nutrient inputs are critical for high productivity in maize systems of sub-Saharan Africa (Sommer et al. 2014; Vanlauwe et al. 2014). The importance of nutrient additions may have been further enhanced by site selection. The study site in Kolero village is situated between two elevated areas. Soil moisture remains relatively high during most of the maize growing period perhaps dampening the effects of the soil management alone. It is not uncommon that the effects of CA on crop yield may be masked by biophysical factors like soil compaction (Brouder and Gomez-Macpherson 2014).

We found RUE in this study to be generally higher than production systems in conventional maize systems in more arid regions of sub-Saharan Africa (Thierfelder and Wall 2009; Kurwakumire et al. 2014). Though we did not monitor soil moisture level, this can likely be attributed to reduced tillage, and/or mulching applied to all plots except for the conventional farming. Mulch improves infiltration and decreases evaporation from soils and improved soil moisture retention (Thierfelder and Wall 2009), and according to Sileshi et al. (2011)

uptake and nutrient inputs contribute to increasing RUE of maize. Seasonal variations in RUE indicated that RUE was higher in short rain seasons than in the longer rain seasons (Table 2), suggesting that maize being a C4 plant was more efficient in using rain water in seasons with lower rainfalls. The highest mean values of RUE in CAWT during the short rains of 2012 and 2013 (12.2 kg ha^{-1} mm^{-1}) and across the four seasons (7.7 kg ha^{-1} mm^{-1}), may also reflect the ameliorative effects of trees (*G. sepium*) integrated in the CA. Apart from nutrient input, the presence of *G. sepium* can enhance the ability of the land to capture rainfall, store and make it available to crops through the build-up of soil organic matter (Sileshi et al. 2011). Moreover, coppicing stumps increase moisture retention in the soil by maintaining a leaf canopy during the dry season (Sileshi et al. 2011). Maize growing under these conditions is often capable of utilizing stored water for growth and yield production. Higher values of RUE in CAWT and CA + F treatments indicate that nutrient amendment by trees and/or via fertilizer also influenced RUE as noted by Kurwakumire et al. (2014).

Greenhouse gas fluxes were statistically similar across treatments and similar to that described in other maize systems in sub-Saharan Africa (Mapanda et al. 2011) supporting that N-intensification of maize farming in sub-Saharan Africa may not put climate at risk (Shcherbak et al. 2014). This is despite the relatively greater amount of N applied in this study (100 kg N ha^{-1}) when compared to average use in Tanzania (12 kg N ha^{-1}) and recommendation of 80 kg N ha^{-1}. It is important to note that the amount of N inputs, both from mineral fertilizer and *Gliricidia* litter, are half or less than that of intensive systems in developed countries. When considered within the landscape context, the lack of increased emissions from intensification and the greater yields may have significant benefits for the climate system if it reduces pressure on the surrounding forest and agricultural fallows. Fallows in the area contain considerable carbon stocks—e.g., 33 t C ha^{-1}—in aboveground biomass (Mpanda unpublished data) and thus field level intensification may avoid emissions from slash and burn and contribute to climate change mitigation (Burney et al. 2010).

The CAWT and CA + F treatments had far lower yield-scaled GWP than the others and provide further justification for intensification as a means to meet food and climate goals. Given annual GHG emissions were similar, the improved performance of these treatments

can largely be attributed to higher yields stimulated by increased nutrient availability (discussed above). The yield-scaled GWP, an indicator that internalizes multiple objectives (food production and mitigation), shows that these treatments outperform the others tested when trying to meet dual objectives. Greenhouse gas intensity is rapidly becoming the indicator selected to evaluate farming system performance on food and climate change mitigation issues and has been used extensively to assess multiple objectives in cereal production systems in Western countries and rice producing areas of Asia (van Groenigen et al. 2010; Linquist et al. 2012; Grassini and Cassman 2012). Until now, it has rarely been applied to cropping systems in sub-Saharan Africa. This indicator needs to become commonplace when investigating climate change mitigation and CSA in light of pervasive food insecurity (Rosenstock et al. 2013). When considering yield-scaled GWP, the results here suggest not only that intensification raises yields but also does so in a sustainable manner.

Conclusions

Rapid integration of CSA into the development agenda sets out a healthy challenge for scientists to provide evidence to help development partners operationalize this concept. In this study, the performance of maize under CA was explored in terms of four indicators that relate to food security, resilience and climate change mitigation based on discussions with local communities and development partners to ensure site relevance of the results. Maize grain yield under this practice was mainly enhanced by N inputs through mineral fertilizer (CA + F) or integration of leguminous tree/shrubs (CAWT) rather than biophysical advantages of reduced tillage under CA. These treatments consistently recorded the highest maize grain in three out of four growing seasons monitored. The RUE was also the highest in CA + F and CAWT, indicating high resilience on maize systems comprised of these treatments. There was no evidence of elevated GHG emissions in these treatments despite the additional N inputs relative to other treatments. Thus, the increase in yield without little or no effects on GHG emissions noted here reflect high potential for CA as a climate-smart agricultural practice for sustainable intensification smallholder farming systems in the highlands of Eastern Tanzania. However, caution should be taken when extrapolating results of this study to other locations because Kolero village was used as a case study to respond to the needs of farmers and development partners in the area. Though this study analysed indicators of locally selected CSA outcomes, it neglects other important factors of the farming system that CA may affect such as gender differentiated labor, net returns to land, changes in soil carbon, etc. These features affect the likelihood of beneficial outcomes and the probability of adoption by the farmer. Thus, positive results found here need to be balanced against the broad and dynamic socio-ecological context within which smallholders operate and recognize that the reported benefits only tell part of the story about CA, CSA and highland Tanzanian maize production.

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