Agricultural Systems 190 (2021) 103117

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Conservation agriculture improves adaptive capacity of cropping systems to climate stress in Malawi

Adam M. Komarek [a,b,*], Christian Thierfelder [c], Peter R. Steward [d,e]

[a] International Food Policy Research Institute, Washington, DC, USA
[b] The University of Queensland, School of Agriculture and Food Sciences, Gatton, Qld 4343, Australia
[c] International Maize and Wheat Improvement Center (CIMMYT), P.O. Box MP 163, Mount Pleasant, Harare, Zimbabwe
[d] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom
[e] World Agroforestry (ICRAF), United Nations Avenue, Gigiri, PO BOX 30677, Nairobi 00100, Kenya

ARTICLE INFO

Editor name: Mark van Wijk

Keywords:
Heat stress
Intercropping
Maize
Malawi
No tillage
Rotation

ABSTRACT

Context: Adaptation to climate stress is an unprecedented challenge facing cropping systems. Most adaptation assessments focus on how adaptation options affect yields of a single crop under different weather or climate conditions. Yet, cropping systems often comprise more than one crop, and holistic assessments should consider all crops grown in a cropping system. One adaptation option is Conservation Agriculture that is commonly defined around a set of three principles: minimum mechanical soil disturbance, permanent soil organic cover, and crop species diversification.
Objective: Here we estimated the statistical effect of Conservation Agriculture on cropping-system yields under historical climate conditions.
Methods: The cropping-system yields considered all crops grown including maize (*Zea mays* L.) and legumes in intercropping or rotation, or both. The climate conditions included conditions of heat stress for maize and precipitation balances during the maize growing season. Heat stress for maize was studied using growing degree days over 30 °C. Precipitation balance was the difference between precipitation and reference evapotranspiration. Data included 6296 yield observations from on-farm trials in farmer plots conducted over 14 seasons (2005–2006 to 2018–2019) in ten communities in Malawi. These yield data were coupled with daily weather data. We studied three treatments: (1) a Control Practice treatment where the soil was tilled, crop residues were removed, and there was no crop species diversification, (2) a No-Tillage treatment where the soil was not tilled, crop residues were retained, and there was no crop species diversification, and (3) a Conservation Agriculture treatment where the soil was not tilled, crop residues were retained, and there was crop species diversification through legume intercropping. The use of maize varieties and legume rotation changed over time; however, the treatments studied remained the same over the entire length of the on-farm trials period in all individual communities.
Results and conclusions: Results of our study showed that heat stress for maize had a negative effect on cropping-system yields for non-stress-tolerant maize varieties and no legume rotation, although the Conservation Agriculture treatment reduced this negative effect compared with the Control Practice treatment. With the use of stress-tolerant maize varieties and legume rotation and Conservation Agriculture, our results suggest that heat stress for maize did not have a negative effect on cropping-system yields.
Significance: Our results demonstrate how Conservation Agriculture can improve the adaptive capacity of cropping systems and this provides urgently needed evidence on how farmers can adapt to climate stress.

1. Introduction

Humanity faces an unprecedented challenge in meeting growing demand for food and improving environmental sustainability (Godfray and Garnett, 2014) whilst adapting agriculture to an increased severity and frequency of climate stresses (Challinor et al., 2014; Thornton et al.,

* Corresponding author at: International Food Policy Research Institute, Washington, DC, USA.
E-mail address: a.komarek@uq.edu.au (A.M. Komarek).

https://doi.org/10.1016/j.agsy.2021.103117
Received 9 September 2020; Received in revised form 16 February 2021; Accepted 22 February 2021
Available online 7 March 2021

2014; Challinor et al., 2016). As such, we urgently need better evidence showing how cropping systems can adapt to climate stresses (Cooper et al., 2008; Conway et al., 2019), especially in Southern Africa (Challinor et al., 2007; Thierfelder et al., 2018; Nyagumbo et al., 2020). To address these challenges one adaptation option is Conservation Agriculture that is commonly defined around three management principles: minimum mechanical soil disturbance, permanent soil organic cover, and crop species diversification through varied crop sequences and associations (FAO, 2019). In addition to the three principles, the functioning of Conservation Agriculture can be enhanced by using good agricultural practices, some of which include planting stress-tolerant crop varieties and appropriate nutrient supply (Sommer et al., 2014; Thierfelder et al., 2018).

The objective of our study was to test if changes in crop management (based on Conservation Agriculture) can make cropping systems more adaptive to climate stress. From on-farm trials in ten communities in the Central and Southern Region of Malawi we combined 14 seasons of yield data with daily weather data from geo-spatial datasets to answer the following question: what is the statistical effect of a No-Tillage or Conservation Agriculture treatment on cropping-system yields (considering all crops grown) compared to a Control Practice treatment given growing season precipitation balance (precipitation minus reference evapotranspiration) and given growing season heat stress for maize (*Zea mays* L.)? The Control Practice treatment (CP) included tillage with crop residue removal and no legume intercropping, the No-Tillage treatment (NT) included no tillage with crop residue retention and no legume intercropping, and the Conservation Agriculture (CA) treatment included no tillage with crop residue retention and legume intercropping. We estimated this statistical effect separately for three crop management strategies that were practiced during different seasons: 1) a crop management strategy of non-stress-tolerant maize and without a legume rotation, 2) a crop management strategy of non-stress-tolerant maize and with a legume rotation, and 3) a crop management strategy of stress-tolerant maize and with a legume rotation.

Two main types of studies have examined adapting cropping systems to climate stress at the plot scale, including studies that have analyzed Conservation Agriculture. First, several meta-analyses have positioned the yield effect of Conservation Agriculture (or at least two of its principles) into different contexts such as soil texture, precipitation, or a level of aridity (Rusinamhodzi et al., 2011; Pittelkow et al., 2015; Corbeels et al., 2020). These studies have highlighted where yield response ratios are higher, such as in dry climates and on well-drained soils. Climate is typically considered in these studies by using average growing season (or annual) precipitation (Rusinamhodzi et al., 2011; Corbeels et al., 2020) or by using an aridity index (mean annual precipitation divided by potential evapotranspiration) (Pittelkow et al., 2015). Second, the vulnerability of maize (or wheat, *Triticum aestivum* L.) yields to climate stress has also been quantified (Barnabás et al., 2008; Lobell et al., 2011; Lobell et al., 2012; Cairns et al., 2013b; Bowles et al., 2020; Shew et al., 2020). Evidence also suggests that Conservation Agriculture can provide adaptive capacity to maize under interactive water and heat stress for maize (Thierfelder et al., 2017; Steward et al., 2018). Some of these studies have coupled yield data from trials with daily weather data (Lobell et al., 2011; Lobell et al., 2012; Steward et al., 2018; Shew et al., 2020). The studies listed in this paragraph reported the yield of individual crops, even if the cropping systems studied included multiple crops.

Our study takes an alternative approach to the two main types of studies listed before. First, the existing studies in the preceding paragraph consider the yield of one crop even if this crop is embedded in a multi-crop system. We provide additional insights by examining cropping-system yield, considering all crops grown, namely maize and legumes, with legumes either grown as an intercrop or rotation or both. Studying cropping-system yield is important because multiple cropping is a widespread land management strategy in tropical and subtropical agriculture (Waha et al., 2020). Second, we examined how weather directly interacts with treatment in a statistical model using daily weather data (converted into seasonal indicators of precipitation balance and heat stress for maize) as an explanatory variable, rather than using weather variables as a contextual factor. Existing studies have tended to use more aggregate measures of climate (such as annual growing season precipitation). Our study provides an alternative approach to studying weather and treatment interactions by using daily weather data over the growing season to calculate explanatory variables for climate conditions during the maize growing season. We combined the use of cropping-system yields and climate stress indicators from daily weather data into one study.

2. Methods

2.1. Experimental design

2.1.1. Overview

Yield data for our study came from rainfed (non-irrigated) on-farm trials conducted between the years 2005 (season 2005–2006) and 2019 (season 2018–2019) in ten communities across six districts in the Central Region and Southern Region of Malawi (Table 1). Across the ten communities, average elevation was 691 m above sea level (range 491–1166) and average annual precipitation averaged 999 mm (range 739–1352). Soils were mostly Luvisols or Lixisols. We used yield data from 118 community-season combinations, because the start date of the on-farm trials varied by community. Table 1 reports additional contextual details for each community.

In each community, six trial replicates were established on six farmers' fields in any one season, set up in walking distance to be a maximum of 2 km apart. In any one season there were between 18 and 60 farmers in total across all communities participating in the on-farm trials. There was a range in the number of farmers participating because communities joined the on-farm trials in different seasons (Table 4). As part of the on-farm trials, each farmer had one field with a land area of 3000 m^2. This one field was divided into three adjacent (side-by-side) plots and each plot had a land area of 1000 m^2. Each plot contained one of the three treatments. Therefore, each farmer was a replicate in the on-farm trials as they managed all three treatments in one farm. Table 2 provides the summary features of the treatment-strategies and Fig. 1 provides a general layout of the on-farm trials.

Maize was the primary crop in the on-farm trials and Table 3 reports the legume planted as part of intercropping or rotation. In the Conservation Agriculture treatment, maize was intercropped with either pigeonpea (*Cajanus cajan* (L.) Millsp) or cowpea (*Vigna unguiculata* (L.) Walp). If in rotation, maize was rotated with either groundnuts (*Arachis hypogaea* L.), pigeonpea, or cowpea.

Each treatment was defined around the management of tillage, residue, and intercropping. Each farmer simultaneously managed three treatments in every season but over the time sequence of the on-farm trials the use of maize varieties and legume rotation changed (Table 4). To organize our analysis into comparable time sequences that captured the evolution of the use of maize varieties and legume rotation we defined three crop management strategies. In a specific season all treatments were in one of three crop management strategies and each strategy was defined around two management options: (1) the maize variety planted and (2) if legume rotation was used. The three strategies in our study included (columns 5 and 6 of Table 2):

1. A crop management strategy based on using non-stress-tolerant maize varieties without a legume rotation.
2. A crop management strategy based on using non-stress-tolerant maize varieties with a legume rotation.
3. A crop management strategy based on using stress-tolerant maize with a legume rotation.

Our study entailed a side-by-side (paired) comparison for the

Table 1
Contextual details of each community in the on-farm trials.

Region	Community	District	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Elevation (masl)	Soil texture (0–30 cm)	Soil group	Köppen climate	Annual precipitation (mm)
Southern	Malula	Balaka	−14.96	34.99	605	Loamy sand	Luvisols	Cwb	747 (247)
Southern	Lemu	Balaka	−14.80	35.02	720	Sandy loam	Luvisols	Cwb	809 (231)
Southern	Herbert	Balaka	−14.88	35.05	635	Sandy loam	Luvisols	Cwb	739 (257)
Southern	Matandika	Machinga	−15.18	35.28	688	Sandy loam	Luvisols	Cwa	1168 (401)
Southern	Songani	Zomba	−15.34	35.39	788	Clay loam	Lixisols	Cwa	1132 (390)
Central	Chipeni	Dowa	−13.76	34.05	1166	Sandy loam	Luvisols	Cwa	820 (184)
Central	Chinguluwe	Salima	−13.69	34.24	657	Sandy clay loam	Lixisols	Cwb	798 (184)
Central	Mwansambo	Nkhotakota	−13.29	34.13	632	Sandy clay loam	Lixisols	Cwb	1178 (210)
Central	Zidyana	Nkhotakota	−13.23	34.26	535	Sandy clay loam	Luvisols	Cwb	1352 (300)
Central	Linga	Nkhotakota	−12.75	34.20	491	Sandy loam	Lixisols	Cwb	1256 (283)

Notes: Elevation, soil texture, and precipitation values adapted from Thierfelder et al. (2013). Precipitation values are average with standard deviation in parenthesis. For Köppen climate, Cwb is temperate climate, dry winter, and hot summer, and Cwa is temperate climate, dry winter, and warm summer (Peel et al., 2007). Elevation is in meters above sea level (masl). Soil group is the most probable Reference Soil Group based on the World Reference Base for Soil Resources (IUSS, 2006) using each community's latitude and longitude in SoilGrids (Hengl et al., 2017).

Table 2
Summary features of treatments and crop management strategies.

Treatment	Tillage?	Retain residues?	Legume intercrop?		
Strategy				Stress-tolerant maize variety?	Legume rotation?
Control practice	Yes	No	No	No	No
No tillage	No	Yes	No	No	No
Conservation agriculture	No	Yes	Yes	No	No
Control practice	Yes	No	No	No	Yes
No-tillage	No	Yes	No	No	Yes
Conservation agriculture	No	Yes	Yes	No	Yes
Control practice	Yes	No	No	Yes	Yes
No-Tillage	No	Yes	No	Yes	Yes
Conservation agriculture	No	Yes	Yes	Yes	Yes

Notes: Tillage was based on the ridge and furrow system where annual ridges were formed approximately 75 cm apart. For the intercrop column, "No" means maize was not intercropped with a legume, and "Yes" means maize was intercropped with a legume. For the rotation column, "No" means maize was not rotated with a legume (i.e., maize in one season then maize again in the following season) and "Yes" means maize was rotated with a legume (i.e., maize in one season then a legume in the following season, using a phased rotation).

treatments (Control Practice, No-Tillage, and Conservation Agriculture), but no side-by-side (paired) comparison for rotation.

2.1.2. Treatments

There were three treatments in the experiment: Control Practice (CP) treatment, No-Tillage (NT) treatment, and Conservation Agriculture (CA) treatment. The two treatments that include some or all the three principles of Conservation Agriculture include 1) a No-Tillage treatment with no intercropping, and 2) a Conservation Agriculture maize-legume intercrop treatment. Both the No-Tillage and Conservation Agriculture treatments had crop residues retained in the plot as a surface mulch. The definition of treatment in our study is unrelated to rotation (Section 2.1.4).

The Control Practice treatment refers to the use of tillage, based on the ridge and furrow system, where annual ridges were formed approximately 75 cm apart, and there was no intercropping. For the Control Practice treatment, crop residues were typically grazed, burned or removed from the plot for other uses such as composting, with some remaining crop residues placed in the furrow before forming the ridges in September or October of each year. The ridges were then re-built on top of the few buried residues. The row spacing was 75 cm and the in-row spacing was 25 cm to achieve a target plant population of approximately 53,333 plants ha^{-1} following the Sasakawa Global 2000 plant spacing recommendation (Ito et al., 2007). Planting was done with a hand hoe or pointed stick on the ridges. Weed control was achieved by reforming the ridge, locally called banking, which scrapes the weeds off during this action. Weeding was limited to two, seldom three, operations and stopped when maize reached the tasseling/silking stage, so final weed emergence and proliferation was often not fully controlled.

For the No-Tillage treatment, maize was direct-seeded into untilled soil with a pointed stick (dibble stick) in rows spaced 75 cm apart and an in-row spacing of 25 cm to achieve a target plant population of approximately 53,333 plants ha^{-1}. Previous ridges were not maintained and subsided over time. In the first season, crop residues were applied in the form of maize stalks at a rate of 2500 kg ha^{-1}. From there onwards, the crop residues were retained in the plot and manually spread evenly over the soil surface (i.e., retained in the plot in situ). Initially, weed control was achieved through an application of a mixture of 2.5 l ha^{-1} glyphosate (N-(phosphono-methyl) glycine) and 6 l ha^{-1} of Bullet® (25.4% Alachlor (2-chloro-N-(2,6-diethylphenyl)-N-(methoxymethyl) acetamide) and 14.5% atrazine (2-Chloro-4-ethylamino-6-iso-propylamino-1,3,5-triazine). This was applied as a pre-emergence herbicide after planting. In 2010, Bullet was replaced by the more environmentally benign herbicide Harness® (acetochlor (2-ethyl-6-methylphenyl-d11)) at a rate of 1 l ha^{-1} in the five communities in the Central Region and from 2017 onwards in all communities. Weeds were further hoe weeded when they reached 10 cm height or 10 cm in circumference.

For the Conservation Agriculture treatment, maize was planted and managed in the same way as in the No-Tillage treatment with the same maize planting density but in the Conservation Agriculture treatment maize was intercropped with either pigeonpea (Southern Region of Malawi) or cowpea (Central Region of Malawi) (Table 3). In the Conservation Agriculture treatment, intercropping occurred when there was the simultaneous presence of maize and a legume in a plot with the legume planted between maize rows. The intercropped legumes were planted between the maize rows at an in-row spacing of 40 cm for cowpea or 50 cm for pigeonpea. For intercropped cowpea, 2 to 3 seeds were normally planted per station and this was thinned to a single plant (target population 33,333 plants ha^{-1}). For intercropped pigeonpea, 5 to 7 seeds were normally planted per station and this was thinned to a

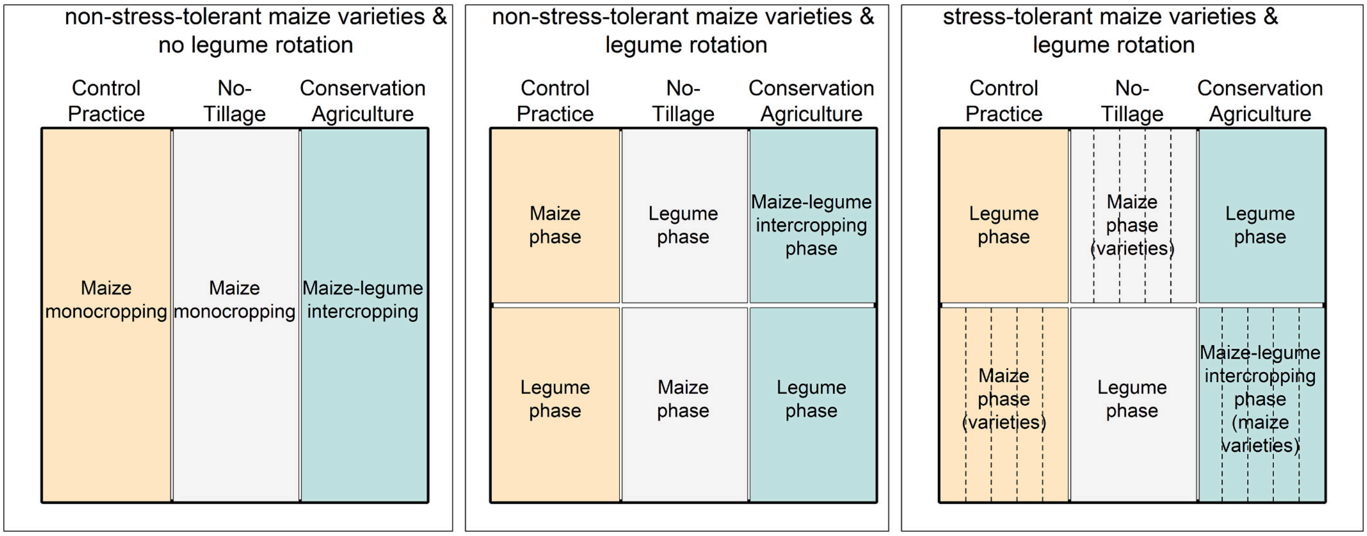

Fig. 1. General layout of the on-farm trials conducted over 14 seasons (2005–2006 to 2018–2019) in ten communities in the Central Region and Southern Region of Malawi. The three treatments of Control Practice, No-Tillage, and Conservation Agriculture were maintained across the entire period of the on-farm trials in different crop management strategies (combinations of maize varieties and rotation). The start season and end season of each strategy differed by community (Table 4). Control Practice = tillage and residue removal, No-Tillage = no tillage and residue retention, and Conservation Agriculture = no tillage, residue retention, and maize-legume intercropping.

Table 3
Intercropping and rotation crops planted in on-farm trials.

Community	Intercropped legume	Rotational legume
Malula	Pigeonpea	Pigeonpea
Lemu	Pigeonpea	Groundnuts
Herbert	Pigeonpea or cowpea	Cowpea
Matandika	Pigeonpea	Pigeonpea
Songani	Pigeonpea	Pigeonpea
Chipeni	Cowpea	Groundnuts
Chinguluwe	Cowpea	Groundnuts
Mwansambo	Cowpea	Groundnuts
Zidyana	Cowpea	Groundnuts
Linga	Cowpea	Groundnuts

Notes: Farmers in Herbert rejected the pigeonpea after the first rotational season due to limited selling options and a lack of interest in the crop. They opted for cowpea thereafter.

single plant (target population 26,666 plants ha^{-1}). Table 3 reports the crop planted as the intercrop in each community. As in the No-Tillage treatment a pointed stick was used to plant by making two small holes for the seed and fertilizer at each planting station. Weed control was achieved through the application of glyphosate at 2.5 l ha^{-1} post-planting followed by manual weeding as in the No-Tillage treatment. No residual herbicide (bullet) was initially applied to these plots. In later seasons, the post emergence herbicide harness was also applied (as in the No-Tillage treatment) to the Conservation Agriculture treatment as it does not affect legumes.

The management of the three treatments has remained the same since the on-farm trials commenced (apart from any minor changes mentioned in this Section 2.1.2) and is based on the initial experimental design (Thierfelder et al., 2013). We maintained the specific treatment labels in this study although strictly speaking, when regular annual rotations started in 2011, the No-Tillage treatment can also be regarded as "Conservation Agriculture" according to the FAO (2019) definition. The Control Practice is considered a control treatment so we could estimate the statistical effect of the No-Tillage and Conservation Agriculture treatments on cropping-system yields.

In all three treatments the quantity of crop residues that were either retained in No-Tillage or Conservation Agriculture or removed in the Control Practice from the plot were the quantity that was produced by the farmer in situ. It was actively discouraged each season for farmers to transfer crop residues from their Control Practice plot to their plots with No-Tillage or Conservation Agriculture. But given that farmers managed the day-to-day operations of the trials, it was inevitable that these transfers occurred occasionally – one reason being that mice hunters burned crop residues in the No-Tillage and Conservation Agriculture

Table 4
Start and end season for each crop management strategy in on-farm trials.

	Stress-tolerant maize variety?	No	No	No	No	Yes	Yes
	Legume rotation?	No	No	Yes	Yes	Yes	Yes
Community		Start season	End season	Start season	End season	Start season	End season
Malula		2008–2009	2011–2012	2012–2013	2018–2019	2013–2014	2018–2019
Lemu		2005–2006	2010–2011	2011–2012	2018–2019	2013–2014	2018–2019
Herbert		2007–2008	2011–2012	2012–2013	2018–2019	2013–2014	2018–2019
Matandika		2006–2007	2011–2012	2012–2013	2018–2019	2013–2014	2018–2019
Songani		2008–2009	2012–2013	2013–2014	2017–2018	2013–2014	2017–2018
Chipeni		2007–2008	2011–2012	2012–2013	2018–2019	2013–2014	2018–2019
Chinguluwe		2006–2007	2012–2013	2013–2014	2018–2019	2013–2014	2018–2019
Mwansambo		2005–2006	2010–2011	2011–2012	2018–2019	2013–2014	2018–2019
Zidyana		2007–2008	2012–2013	2013–2014	2018–2019	2013–2014	2018–2019
Linga		2005–2006	2010–2011	2011–2012	2018–2019	2013–2014	2018–2019

Notes: strategy is a combination of maize variety planted and use of legume rotation.

treatments in search of mice, and these crop residues were then replaced to not leave the plots in the No-Tillage and Conservation Agriculture treatments uncovered. These occasional transfers were within the same farm only and always in accordance with the principles of Conservation Agriculture.

All three treatments received a uniform fertilizer application rate of 69 kg N ha^{-1} which was supplied as 100 kg of N:P:K ha^{-1} (23:21:0 + 4S) at planting and 100 kg urea ha^{-1} (46% N) at approximately three weeks after planting (total nutrient content applied was 69 kg N ha^{-1}: 21 kg P_2O_5 ha^{-1}: 0 kg K_2O ha^{-1}: 4 kg S ha^{-1}) to the maize. The rotated legumes received a basal fertilization of 100 kg of N:P:K ha^{-1} (23,21:0 + 4S) at planting only. This application rate followed the general recommendations of the Malawian Government at the time the on-farm trials commenced and was maintained in every season. Intercropped legumes did not receive an extra dose of fertilizer, and therefore competed with maize for the fertilizer applied to the treatment.

2.1.3. *Varieties planted*

The maize variety planted was the first management option that defined each of the three crop management strategies studied. The on-farm trials included both stress-tolerant and non-stress-tolerant maize varieties. Before the 2013–2014 season only non-stress-tolerant maize varieties were planted, and from the 2013–2014 season onwards both stress-tolerant and non-stress-tolerant maize varieties were planted (Table 4). From the 2013–2014 season onwards, all subplots in the maize phase of the rotation were allocated one of five varieties, four stress-tolerant maize varieties and one non-stress-tolerant maize variety. A land area of 100 m^2 was planted to each of the five varieties (Fig. 1). In each of the three strategies, each farmer used the same maize varieties on all plots in a season. The maize varieties planted were the result of the rapid-cycle breeding program at CIMMYT that aims to deliver improved varieties with tolerance to drought stress, heat stress, and low-nitrogen stress to the Southern African region (Cairns et al., 2013a; Masuka et al., 2017a; Masuka et al., 2017b; Setimela et al., 2017; Setimela et al., 2018).

In total 11 maize varieties were part of the on-farm trials (Table 5). In general, the four hybrids of PAN53, MH30, MH31, and SC719 have some tolerance to both water and heat stress, the medium maturing PAN53 has been tested for water and heat stress. SC719 is a medium to long-season hybrid from Seed Co selected under drought. The medium maturing MH30 and MH31 have two parental lines that also went through screening for water and heat stress. ZM523 and ZM309 are Open Pollinated Varieties which are made up of many parental lines and they went through screening for water stress before being released. In general, the selected hybrids used are considered more tolerant to heat and water stress than the Open Pollinated Varieties.

Legume varieties planted in the on-farm trials for both the intercropped legume and the legume in the rotation included the CG7 variety for groundnuts, pigeonpea variety ICEAP 00557, and cowpea variety Sudan.

2.1.4. *Rotation*

The use of legume rotation was the second management option that defined each of the three crop management strategies studied. Table 3 and Table 4 provide details on rotation management, including crop planted and year started. For plots in rotation, there were two phases of the rotation: (1) a maize phase where the crop planted in the current season was maize and the crop planted in the subsequent season was a legume, and (2) a legume phase where the crop planted in the current season was a legume and the crop planted in the subsequent season was maize. All phases of the rotation were present in each season. For the plots in rotation, all plots were divided into two subplots and both subplots had a land area of 500 m^2. One subplot was for the maize phase of the rotation and one subplot was for the legume phase of the rotation.

The planting density for the sole crop legume in the maize-legume rotations was as follows. Rotated groundnuts (in Linga, Mwansambo, Zidyana, Chipeni, Chiguluwe, and Lemu) were planted on ridges in the Control Practice treatment with rotation on 75 cm row spacing and 20 cm in-row spacing (target population 66,666 plants ha^{-1}). Rotated groundnuts in the No-Tillage and Conservation Agriculture treatments were planted on the flat at half row spacing of 37.5 cm × 20 cm (target population 133,333 plants ha^{-1}). For groundnuts, one seed was planted per station. Rotated pigeonpea (Malula, Matandika and Songani) had a row spacing of 75 cm by 50 cm in-row spacing (target population 26,666 plants ha^{-1}) for all three treatments with one seed planted per station. Finally, rotated cowpea (Herbert) were seeded at 75 cm row by 20 cm in-row spacing (target population 66,666 plants ha^{-1}) in the Control

Table 5
Maize varieties planted by community and crop management strategy in the on-farm trials.

	Stress-tolerant maize variety?	No	No	Yes
	Legume rotation?	No	Yes	Yes
Community				
Malula		DK8033, DKC8053	DKC8053	MH30, PAN53, ZM523, MH31, ZM309
Lemu		DK8033, DKC8053	DKC8053	MH30, PAN53, ZM523, MH31, ZM309
Herbert		DK8033, DKC8053	DKC8053	MH30, PAN53, ZM523, MH31, ZM309
Matandika		DK8033, DKC8053, DKC9089, SC627	DKC8053	MH30, PAN53, ZM523, MH31, SC719
Songani		DK8033, DKC8053, DKC9089	DKC8053	MH30, PAN53, ZM523, MH31, SC719
Chipeni		DK8033, DKC8053, SC627	DKC8053, DKC9053, DKC9089	MH30, PAN53, ZM523, MH31, SC719
Chinguluwe		DKC8053, DKC9089	DKC8053, DKC9053, DKC9089	MH30, PAN53, ZM523, MH31, SC719
Mwansambo		DK8033, DKC8053, SC627	DKC8053, DKC9053, DKC9089	MH30, PAN53, ZM523, MH31, SC719
Zidyana		DK8033, DKC8053, SC627	DKC8053, DKC9053, DKC9089	MH30, PAN53, ZM523, MH31, SC719
Linga		DKC8053, DKC9089	DKC8053, DKC9053, DKC9089	MH30, PAN53, ZM523, MH31, SC719

Notes: Strategy is a combination of maize variety planted and use of legume rotation.

Practice treatment and were seeded at 37.5 cm row by 20 cm in-row spacing (target population 133,333 plants ha^{-1}) in the No-Tillage and Conservation Agriculture treatments. For cowpea, one seed was planted per station. Flat planting in the No-Tillage and Conservation Agriculture treatments tended to allow for a higher plant population for groundnuts and cowpea whereas pigeonpea cannot increase its population due to its growth habit.

2.1.5. Grain measurements

Maize yield was estimated from ten subsamples per treatment, each subsample was taken from a land area of 7.5 m^2 (total harvest from a land area of 75 m^2). In later seasons, two subsamples were harvested per maize variety. All maize was harvested separately at physiological maturity and the fresh cobs and biomass weighed in the field. A subsample was taken and weighed, dried, shelled, re-weighed and a grain moisture measurement taken. The yield data was then converted into maize grain yield in kg ha^{-1} at 12.5% moisture content. Intercropped and rotated groundnuts and cowpea were harvested at physiological maturity (usually March–May of each year). Sometimes a second cowpea crop could be seeded in Herbert if there was enough soil moisture. Pigeonpea grain was harvested in August or September once pods reached physiological maturity. Crop residues of both legumes were maintained in the field.

All on-farm trials were managed on a day-to-day basis by the farmers based on the study protocol regarding on-farm management, and this was done in coordination with resident extension officers, either from the Governmental extension services or from the non-profit, non-government regional organization Total LandCare. Researchers from the Department of Research Services and the International Maize and Wheat Improvement Center (CIMMYT) provided scientific oversight throughout the whole duration of the on-farm trials. Maize planting was done after the first effective rains in each community, which usually occurred between the last week of November and mid-December in each season. In some seasons, maize planting occurred only at the beginning of January due to the late onset of the season or insufficient initial precipitation. Maize was typically harvested in April or May of each season.

2.2. Cropping-system yield calculation

For each treatment-strategy in Table 2, we calculated the annual grain yield for all crops (kg dry matter ha^{-1}) and an annual cropping-system yield in energy (gigajoules (GJ) ha^{-1}). The cropping-system yield was defined as the per hectare total grain yield from all crops grown (maize or maize and legumes, depending on the treatment-strategy) in a treatment-strategy-season. In plots under maize-legume rotation, each phase of the rotation was represented simultaneously in subplots (of equal land area) for either the maize phase or the legume phase. And the cropping-system yield was calculated by summing the yield across both subplots, either maize plus rotation legume, or maize and intercropped legume plus rotation legume. Table SI.1 provides additional details on the calculation of cropping-system yield. Existing studies have also used gigajoules for cropping-system yield (Parihar et al., 2016; Guilpart et al., 2017; Silva et al., 2017). The energy content per 100 g of each crop equaled 353 kcal for maize, 316 kcal for cowpea, 301 kcal for pigeonpea, and 578 kcal for groundnuts (Smith et al., 2016).

2.3. Climate stress data and calculations

To examine how climate stress affected yields, we first obtained weather data from two sources for each of the ten communities. Our study used the word stress to describe a situation that may lead to decreases in crop growth and reproduction below the crop's yield potential (Osmond et al., 1987).

Daily precipitation data (in mm) between January 1st 2005 and August 31st 2019 was sourced from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset (Funk et al., 2015) that has a spatial resolution of 0.05 degree × 0.05 degree. These CHIRPS data have been compared with rain gauge data across the globe (Funk et al., 2015) and specifically in Eastern and Southern Africa including in Malawi (Dinku et al., 2018; Muthoni et al., 2019). In Africa, CHIRPS data have been used in existing studies to test how yields respond to changes in weather (Steward et al., 2018; Michler et al., 2019; Mutuku et al., 2020).

Six weather parameters for each day between January 1st 2005 and August 31st 2019 were sourced from the NASA Prediction Of Worldwide Energy Resources (POWER) dataset (NASA, 2020) that has a spatial resolution of 0.5 degree × 0.5 degree. The six parameters were: 1) relative humidity (%), 2) atmospheric pressure at surface (kPa), 3) daily minimum air temperature (°C), 4) daily maximum air temperature (°C), 5) wind speed at 2 m height, (m per second), and 6) incoming solar radiation, based on daily MJ m^2. The NASA POWER data have been compared to daily data from ground stations across the globe (Stackhouse Jr, 2019), and specifically in Eastern and Southern Africa (Van Wart et al., 2015). Data from NASA POWER have been previously used in the study of yields and weather (Komarek et al., 2019; Nyagumbo et al., 2020).

We computed precipitation balance and heat stress for maize using the weather data to examine how they affect cropping-system yield. Extension officers recorded planting and harvest dates in all 118 community-season combinations of data. The average days to maturity for maize (length of growing season, days between planting and harvest) was 137 days (range 104–190). The planting and harvest dates were used to determine if a daily weather observation was part of the growing season for calculating precipitation balance and heat stress for maize over the growing season. We examined precipitation balances and heat stress for maize over the growing season.

We calculated the precipitation balance for the growing season as precipitation minus reference evapotranspiration using the Penman-Monteith method (Zotarelli et al., 2010). Precipitation outside the maize growing season was minimal (Fig. SI.2). Precipitation data came from CHIRPS and all non-precipitation weather data came from NASA POWER. Elevation data came from Thierfelder et al. (2013) and was collected in each community. We computed precipitation balance as the sum of all daily precipitation balances during the growing season. Our precipitation balance is similar to the Standardized Precipitation Evapotranspiration Index that uses the monthly (or weekly) difference between precipitation and reference evapotranspiration (Vicente-Serrano et al., 2010), but we use daily weather data. Reference evapotranspiration was calculated using a uniform surface of actively growing vegetation (Zotarelli et al., 2010). Crops can experience several types of water-related stress in response to the water balance or soil water availability or both at different stages of crop growth and reproduction, for brevity we use the phrase precipitation balance hereinafter to refer to the range of precipitation balance values in our entire dataset across all treatment-strategy combinations.

We calculated heat stress for maize using the sum of growing degree days (GDD) above 30 °C during the maize growing season (Lobell et al., 2011; Steward et al., 2018), labelled GDD_{30+}. In our results, heat stress refers to heat stress for maize. Growing degree days were estimated from daily minimum and maximum temperatures at each community over the growing season using eq. (1):

$$GDD_{base,opt} = \sum_{t=1}^{N} DD_t, \quad DD = \left\{ \begin{array}{ll} 0 & \text{if } T < T_{base} \\ T_t - T_{base} & \text{if } T_{base} \leq T_t \leq T_{opt} \\ T_{opt} - T_{base} & \text{if } T_t > T_{opt} \end{array} \right\} \quad (1)$$

In Eq. (1) t is an individual time step (hour) within the growing season, T_t is the average temperature during this time step (determined by interpolating between the minimum and maximum temperature with a sin curve) and N is the number of hours between planting and harvest. Using eq. (1) we calculated GDD_{30+} that corresponds to $T_{base} = 30$ °C, and $T_{opt} = \infty$. All temperature data for calculating heat stress for maize came from NASA POWER. GDD_{30+} is a measure of exposure to temperatures above a threshold at which warming can be quite harmful to the growth and reproductive processes of maize (Schlenker and Lobell, 2010), and this measure has been used in existing studies (Lobell et al., 2011; Steward et al., 2018).

2.4. Statistical analyses

We used linear mixed-effects models to examine the effect of each treatment on cropping-system yield, and how these treatment effects depend on precipitation balance and heat stress for maize. We performed the statistical analyses using the lmer function in the 'lme4' package (Bates et al., 2015) in R version 3.6.1 (R, 2020). We first specified a global model that included all explanatory variables and their interactions that we suspected may affect cropping-system yields (eq. 2).

$$sqrt(sysYld)=tmnt\times poly(PB,2)\times log_e(GDD_{30+}+1)+tmnt\times log_e(duration)+(1|community/farmer)+(1|mzVar) \quad (2)$$

In Eq. (2), sysYld = annual cropping-system yield in GJ ha^{-1} and is a numerical variable (sqrt = square root), tmnt = fixed effect for treatment and is a nominal categorical variable with three classes (Control Practice, No-Tillage, and Conservation Agriculture), PB = precipitation balance (precipitation minus reference evapotranspiration) over the growing season in mm and is a numerical variable, poly(PB,2) = a second-degree orthogonal polynomial for precipitation balance, GDD_{30+} = our measure of heat stress for maize calculated as the sum of growing degree days over 30 °C for the growing season and is a numerical variable, duration = the total number of seasons a plot has been in the on-farm trials and is a numerical variable, community = name of community (nominal categorical variable), farmer = anonymized farmer identification (nominal categorical variable), and mzVar = maize variety planted (nominal categorical variable). We specified a random effect for each community and the effect of farmer was nested in community to control for spatial auto correlation within the dataset. We also included a random effect for the maize variety planted. We undertook variable transformation and standardization to avert issues of model scaling and non-symmetric distributions of variables, and to improve convergence of the model's fitting algorithm (Zuur et al., 2009). We transformed numerical variables in eq. (2) using either a square root or natural logarithm, based on the magnitude of the variable's positive skewness (Tabachnick and Fidell, 2007) (Fig. SI.1). We standardized all numerical variables to have a zero mean and standard deviation of one (i.e. $\mu = 0$ and $\sigma = 1$) across the entire dataset. The standardization was done by pooling all observations for each variable across the entire dataset. For the variables that we transformed we standardized the transformed version of the variable.

Variable choices and their interaction terms in the global model were made a priori based on existing research and our understanding of Conservation Agriculture and climate within the on-farm trials. For variable choice, maize-based studies in Southern Africa have shown that precipitation balance and heat stress for maize interact (Steward et al., 2018). An inverted U-shaped relationship can exist between yields and precipitation (Rusinamhodzi et al., 2011). We therefore included a quadratic term for precipitation balance using a second-degree orthogonal polynomial. The variable GDD_{30+} (as a linear term) has been used to study heat stress for maize (Lobell et al., 2011). Duration was included as existing research has shown that crop yield performance under conservation agriculture can improve over time (Corbeels et al., 2014; Thierfelder et al., 2015; Corbeels et al., 2020). Although we suspected the variables in Eq. (2) may affect cropping-system yields in our dataset, this suspicion needed testing. We estimated models separately for each of the three crop management strategies (Section 2.1.1). One regression was run for each strategy, i.e., the regression for each strategy was considered by taking a subset of the entire dataset based on the type of maize variety and rotation.

Model selection aimed to identify a suitable and parsimonious approximating model for predicting cropping-system yield. This selection involved trade-offs between model bias and model precision (Zuur et al., 2009). Model selection involved estimating eight candidate models with Maximum Likelihood. Candidate models included combinations of the global model: (1) a 2-way interaction between climate (precipitation balance and heat stress for maize) and treatment, or a 3-way interaction between climate and treatment, (2) a linear or quadratic specification of precipitation balance, and (3) with or without duration (and its interaction with treatment). We included candidate models based on our understanding of Conservation Agriculture and how it may interact with climate, rather than using an all-subset approach of the global model. We used multi-model inference and compared candidate models within each the three strategies based on each model's Akaike information criterion (AIC) with a correction for finite sample sizes (AICc) (Akaike, 1974; Burnham and Anderson, 2002). Supplementary Information: statistical analyses provides additional information on model selection. We generated a 95% confidence set of models from the candidate models based on a cumulative Akaike weight ≤ 0.95. From the candidate models we retained the model with the lowest AICc within each of the three strategies. We used Restricted Maximum Likelihood to estimate the retained models. Parametric bootstrapping procedures with the 'lmeresampler' package were used to generate 95% confidence intervals for estimated coefficients in the retained models using 10,000 iterations (Loy and Steele, 2016). Estimated coefficients were considered significant if the 95% confidence intervals did not overlap with zero and if the *P* value was <0.05 using the Kenward-Roger approximation of the degrees of freedom (Kenward and Roger, 1997). For model assumptions, we inspected the normality of residuals with quantile-quantile plots and inspected residual versus predicted values for the homogeneity assumption (Zuur et al., 2009).

3. Results

Summary descriptive (non-inferential) statistics suggest that across all communities and seasons average cropping-system yield and maize yield was higher in the No-Tillage and Conservation Agriculture treatments than in the Control Practice treatment (Table 6). The total energy content of the cropping-system yield under rotation was on average 73% maize and 27% legumes (range by treatment-strategy in Table SI.3). Cropping-system yields displayed substantial variation among community-season. Cropping-system yields in the Control Practice treatment had a higher coefficient of variation than in the No-Tillage or Conservation Agriculture treatments. Average growing season precipitation balance across all communities and seasons was −28 mm (range − 401 to 431) (range across community-season in Fig. SI.3). Average growing season GDD_{30+} across all communities and seasons was 3.0 (range 0–33.5) (range across community-season in Fig. SI.4). The non-inferential statistics in Table 6 highlight considerable variation in cropping-system yield among the treatments. Although statistical analyses are needed to test if treatment (and its interaction with climate) had a significant effect on cropping-system yield.

For the statistical analyses, one candidate model was the suitable and parsimonious approximating model in the strategy with non-stress-tolerant maize and no rotation and in the strategy with stress-tolerant maize and rotation. In other words, only one model was in the 95% confidence set for these two crop management strategies. For the strategy with non-stress-tolerant maize and rotation, there were four models in the 95% confidence set of models and in this strategy we retained the model with the lowest AICc (Table SI. 4). The proportion of variance explained by the fixed effects (marginal R^2) and random effects (conditional R^2 − marginal R^2) was 0.216 and 0.378 in the strategy with non-stress-tolerant maize and no rotation, was 0.168 and 0.316 in the strategy with non-stress-tolerant maize and rotation, and was 0.187 and 0.347 in the strategy with stress-tolerant maize and rotation.

Table 6
Descriptive summary (non-inferential statistics) for annual cropping-system yields and maize yields.

	Stress-tolerant maize variety?	No	No	No	No	No	No	Yes	Yes	Yes
	Legume rotation?	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
	Treatment	CP	NT	CA	CP	NT	CA	CP	NT	CA
Yield	Summary statistic									
Cropping system (GJ ha^{-1})	N	285	285	285	457	458	458	1356	1356	1356
	Average	54.0	72.6	75.2	33.4	47.1	48.3	33.2	44.3	47.0
	Minimum	8.1	22.6	26.3	5.3	8.5	8.0	6.2	6.0	6.1
	Maximum	135.2	138.5	147.2	101.6	130.1	94.7	103.8	126	112.8
	CV	0.47	0.35	0.33	0.45	0.41	0.38	0.45	0.42	0.39
Maize (kg ha^{-1})	N	281	281	281	457	458	458	1356	1356	1356
	Average	3654	4896	4857	3327	4377	4215	3347	4131	4080
	Minimum	545	1531	1669	285	613	317	121	291	232
	Maximum	9148	9372	9959	9111	10,044	10,061	12,569	13,986	14,134
	CV	0.47	0.35	0.34	0.49	0.44	0.45	0.53	0.47	0.48

Notes: CP = Control Practice (tillage and residue removal), NT = No-Tillage (no tillage and residue retention), and CA = Conservation Agriculture (no tillage, residue retention, and maize-legume intercropping). N is number of observations. CV is coefficient of variation defined as the average for all communities and seasons divided by standard deviation for all communities and seasons. Table SI1.2 reports yields for the individual legume crops.

Unexplained variance existed in our estimation of cropping-system yields (Supplementary Information: statistical analyses).

Predicted cropping-system yields in the No-Tillage and Conservation Agriculture treatments were significantly greater than in the Control Practice treatment (Table 7). Precipitation balance had a significant positive effect on cropping-system yield if under rotation (Fig. 2). But a point occurred where cropping-system yields started to plateau or even decline as precipitation balance increased. These points were significant

Table 7
Linear mixed-effects model results for predicted cropping-system yield.

Stress-tolerant maize variety?	No			No			Yes		
Legume rotation?	No			Yes			Yes		
Variable	Coefficient	95% confidence interval	*P* value	Coefficient	95% confidence interval	*P* value	Coefficient	95% confidence interval	*P* value
CP:intercept	0.104	−0.396–0.623	0.707	−0.439	−0.747 to −0.129	0.016**	−0.567	−0.891 to −0.241	0.004***
NT	0.762	0.635–0.888	<0.001***	0.690	0.593–0.789	<0.001***	0.595	0.531–0.659	<0.001***
CA	0.877	0.753–1.003	<0.001***	0.796	0.697–0.893	<0.001***	0.735	0.671–0.800	<0.001***
PB	−0.274	−3.738–3.118	0.876	0.135	0.053–0.216	0.001***	15.297	11.211–19.478	<0.001***
GDD_{30+}	−0.255	−0.346 to −0.163	<0.001***	0.072	−0.023–0.166	0.136	0.153	0.099–0.206	<0.001***
NT:PB	−2.228	−5.999–1.608	0.257	0.028	−0.080–0.134	0.612	1.416	−4.056–6.790	0.615
CA:PB	0.021	−3.763–3.933	0.991	0.151	0.044–0.260	0.006***	6.464	0.918–12.004	0.022**
NT:GDD_{30+}	0.210	0.101–0.317	<0.001***	0.040	−0.084–0.163	0.526	0.017	−0.054–0.088	0.633
CA:GDD_{30+}	0.256	0.147–0.364	<0.001***	0.171	0.046–0.295	0.007***	0.065	−0.007–0.136	0.073*
PB:GDD_{30+}	−3.117	−5.512 to −0.742	0.011**	0.112	0.029–0.193	0.006***	11.307	6.026–16.502	<0.001***
NT:PB:GDD_{30+}				0.029	−0.079–0.135	0.595	4.795	−2.300–11.729	0.181
CA:PB:GDD_{30+}				0.122	0.016–0.228	0.026**	7.153	0.195–14.306	0.046**
PB2	−5.367	−8.152 to −2.548	<0.001***				−6.575	−10.104 to −3.065	<0.001***
PB2:GDD_{30+}	−5.299	−7.947 to −2.691	<0.001***				2.545	−0.295–5.386	0.076*
NT:PB2	−0.345	−3.903–3.268	0.851				5.075	0.394–9.662	0.033**
NT:PB2:GDD_{30+}							−1.749	−5.530–2.089	0.367
CA:PB2	−0.323	−3.890–3.251	0.860				3.031	−1.633–7.762	0.203
CA:PB2:GDD_{30+}							−0.277	−4.154–3.578	0.886
duration	−0.305	−0.431 to −0.182	<0.001***						
NT:duration	0.017	−0.121–0.159	0.812						
CA:duration	0.131	−0.009–0.269	0.070*						
Random effects									
σ^2		0.50			0.54			0.52	
τ_{00}		$0.14_{\text{farmer:community}}$ $0.17_{\text{community}}$ 0.16_{mzVar}			$0.11_{\text{farmer:community}}$ $0.20_{\text{community}}$ 0.02_{mzVar}			$0.12_{\text{farmer:community}}$ $0.21_{\text{community}}$ 0.05_{mzVar}	
ICC		0.48			0.38			0.43	
N		91_{farmer} $10_{\text{community}}$ 4_{mzVar}			97_{farmer} $10_{\text{community}}$ 4_{mzVar}			96_{farmer} $10_{\text{community}}$ 6_{mzVar}	
Total observations		855			1373			4068	
Marginal R^2 / Conditional R^2		0.216 / 0.594			0.168 / 0.484			0.187 / 0.534	

Notes: CP = Control Practice (tillage and residue removal), NT = No-Tillage (no tillage and residue retention), and CA = Conservation Agriculture (no tillage, residue retention, and maize-legume intercropping). PB = precipitation balance, PB2 = (precipitation balance)^2, GDD_{30+} = sum of growing degree days above 30 °C, and duration is number of seasons in on-farm trials. All numerical variables are standardized to $\mu = 0$ and $\sigma = 1$ across entire dataset. **P* < 0.1; ***P* < 0.05; ****P* < 0.01. Nakagawa et al. (2017) conditional and marginal R^2 reported. Figs. SI.5–SI.6 are plots for normality of residuals and homogeneity.

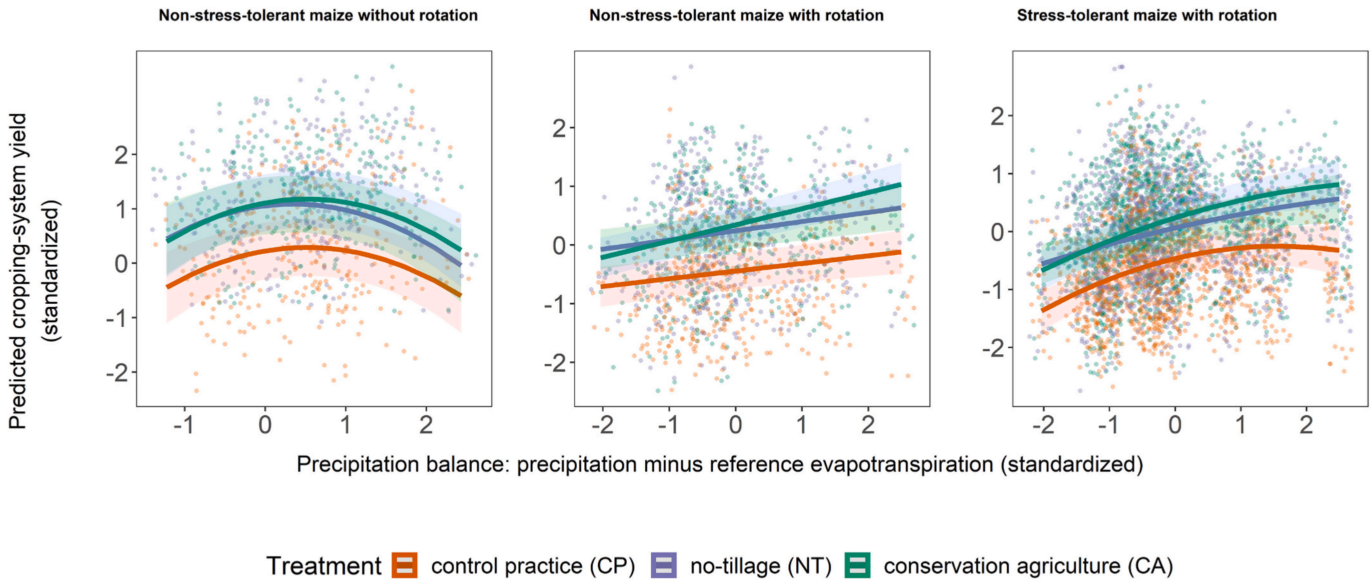

Fig. 2. Predicted effect of growing season precipitation balance on cropping-system yield. Standardized units: $\mu = 0$ and $\sigma = 1$, and the zero average translates to −28 mm for precipitation balance. Lines are for the predicted values of cropping-system yield for the retained models. Precipitation balance used a linear specification in the strategy of non-stress-tolerant maize with rotation, and a quadratic specification (a second-degree orthogonal polynomial) in the other two strategies. Markers are the raw data. All other numerical explanatory variables held constant at their average. Shading around each line is the 95% confidence interval.

in the strategies with non-stress-tolerant maize and no rotation and with stress-tolerant maize and rotation. Heat stress for maize had a significant negative effect on cropping-system yield in the strategy of non-stress-tolerant maize and no rotation (Fig. 3). However, in this strategy the negative effect of heat stress for maize was significantly less in the No-Tillage and Conservation Agriculture treatments. For stress-tolerant maize under rotation, cropping-system yields showed a significant increase as heat stress for maize increased.

Fig. 4 and Table 7 report how precipitation balance and heat stress for maize simultaneously affected predicted cropping-system yields. For non-stress-tolerant maize and no rotation, heat stress for maize had a significant negative effect on cropping-system yield. This negative effect was more pronounced at higher and lower levels of precipitation balance. For non-stress-tolerant maize and no rotation (top row of Fig. 4), the interaction between precipitation balance and heat stress for maize was significantly negative. Under rotation (middle and bottom row of Fig. 4) heat stress for maize did not reduce cropping-system yields, and legume yields appeared less effected by heat stress for maize than maize yields (Figs. SI.7–SI.8). In the strategy of stress-tolerant maize and rotation, as heat stress for maize increased cropping-system yields increased, but heat stress for maize had no effect on cropping-system yields in the strategy of non-stress-tolerant maize and rotation. With rotation, there was an interaction effect where cropping-system yields increased as heat stress for maize and precipitation balance increased simultaneously. With rotation, the positive interaction effect between heat stress for maize and precipitation

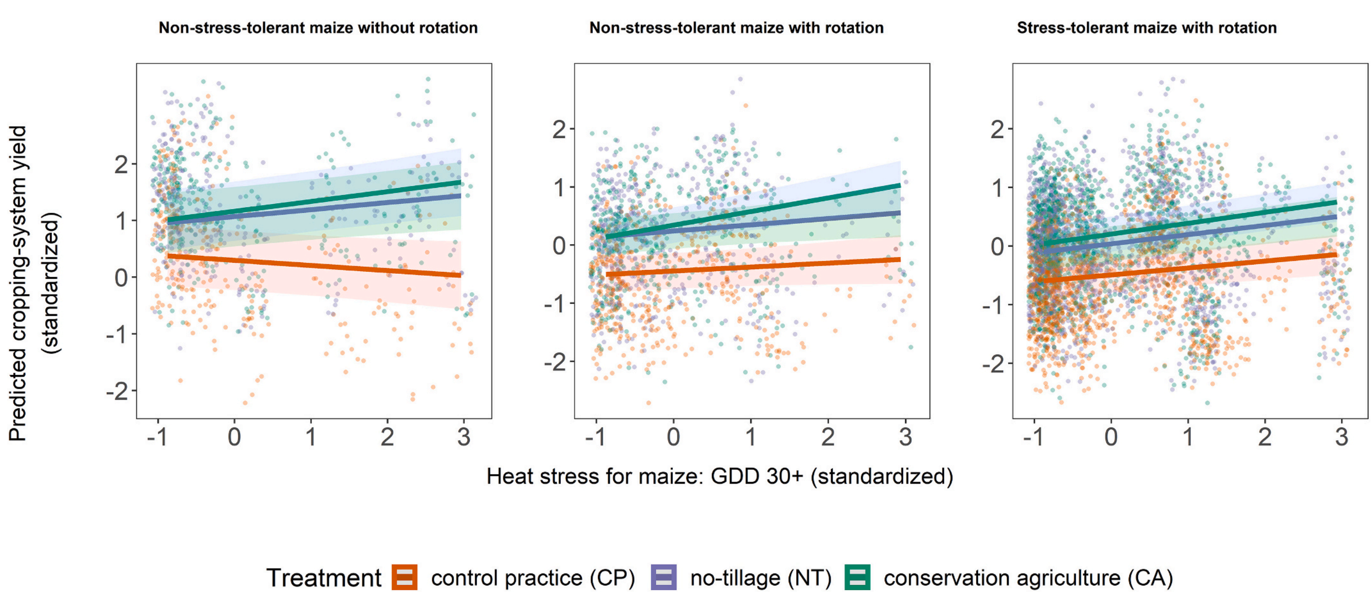

Fig. 3. Predicted effect of heat stress for maize on cropping-system yield. Heat stress for maize is the sum of growing degree days above 30 °C for the growing season (GDD_{30+}). Standardized units: $\mu = 0$ and $\sigma = 1$, and the zero average translates to 3 GDD_{30+}. Lines are for the predicted values of cropping-system yield for the retained models, with GDD_{30+} using a linear specification in all three strategies. Markers are the raw data. All other numerical explanatory variables held constant at their average. Shading around each line is the 95% confidence interval.

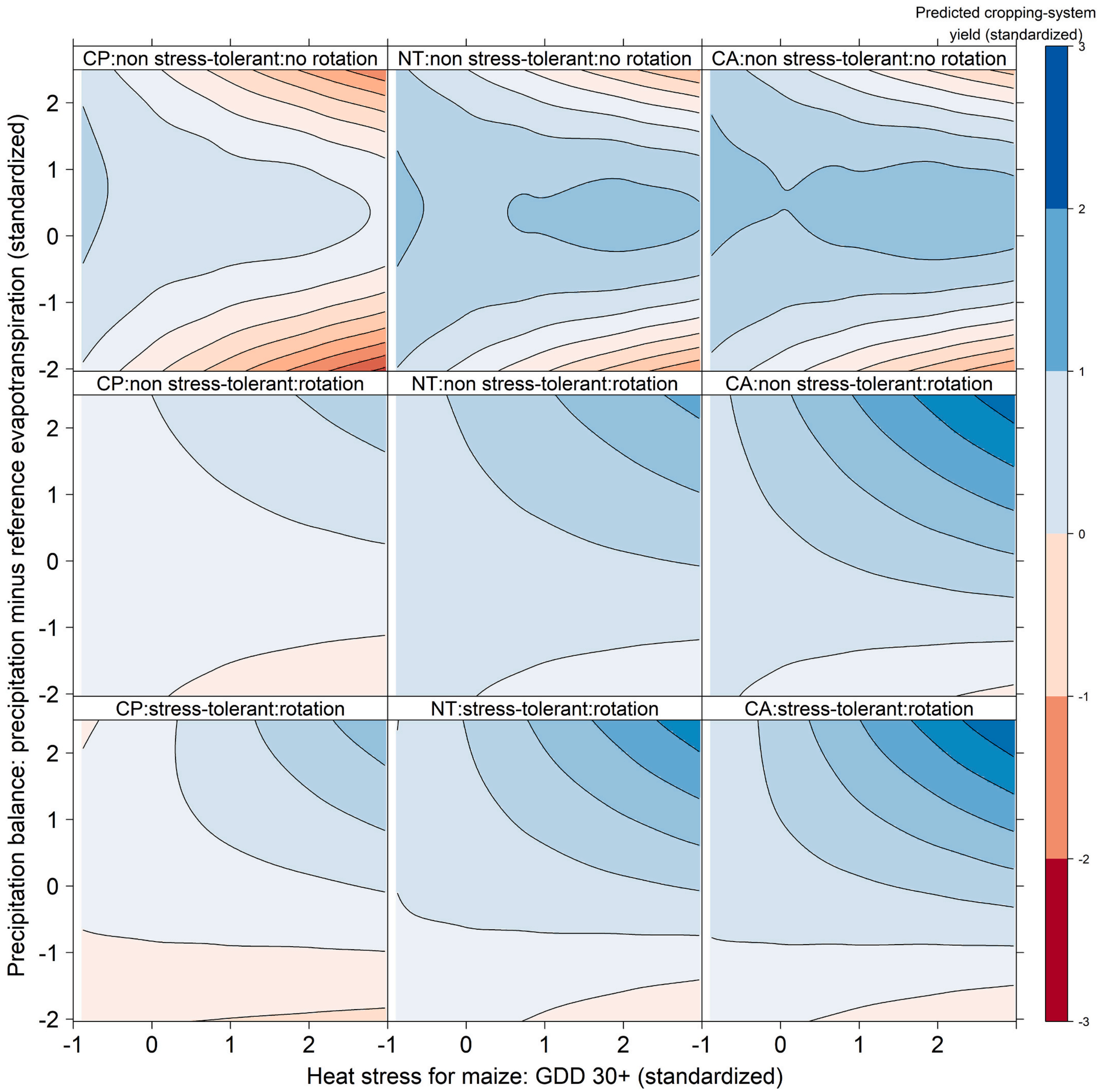

Fig. 4. Predicted effect of growing seasons precipitation balance and heat stress for maize on cropping-system yield (energy). Heat stress for maize is the sum of growing degree days above 30 °C for the growing season. CP = Control Practice (tillage and residue removal), NT = No-Tillage (no tillage and residue retention), and CA = Conservation Agriculture (no tillage, residue retention, and maize-legume intercropping). Stress tolerant refers to type of maize variety. Rotation refers to a maize-legume rotation. All variables are in standardized units with $\mu = 0$ and $\sigma = 1$ across the entire dataset, and the zero average translates to −28 mm for precipitation balance and 3 GDD_{30+} for heat stress for maize.

balance was significantly greater in Conservation Agriculture compared with the Control Practice treatment.

4. Discussion

We examined how Conservation Agriculture affected cropping-system yields given variation in growing season precipitation balance (precipitation minus reference evapotranspiration) and heat stress for maize. Related to the treatments, we found two main results: (1) the No-Tillage and Conservation Agriculture treatments reduced the detrimental effect of heat stress for maize on cropping-system yields, compared to the Control Practice treatment (tillage and residue removal), and (2) with rotation, as heat stress for maize and precipitation balance simultaneously increased, cropping-system yields increased at a faster rate in the Conservation Agriculture treatment than in the Control Practice treatment.

Existing studies have shown that heat stress for maize can have a negative effect on maize grain yields (Schlenker and Lobell, 2010; Lobell et al., 2011; Steward et al., 2018). Existing studies have also shown that Conservation Agriculture can reduce some of these negative effects for maize grain yields (Steward et al., 2018). Our results complement these existing studies by showing that, with non-stress-tolerant maize varieties and no rotation, the No-Tillage and Conservation Agriculture treatments can reduce the negative effect of heat stress for maize on cropping-system yields. Retaining maize residues as a mulch (in the No-Tillage and Conservation Agriculture treatments) has been previously shown to reduce soil temperatures and improve soil water content, compared to no mulch (Lal, 1974; Doran et al., 1984; Horton et al., 1996). In addition, the Conservation Agriculture treatment included maize being intercropped with a legume. Existing research has shown that intercropping can reduce diurnal soil temperatures compared with maize monocropping (Ghuman and Lal, 1992; Olasantan et al., 1996). The studies mentioned above have shown that the reduced soil temperature is beneficial for enhancing root growth and water and nutrient uptake during heat stress for maize, thereby reducing some of the negative yield effects of heat stress for maize.

With rotation, we found that cropping-system yields increased as heat stress for maize increased, and this effect was stronger as precipitation balance increased. We offer some possible reasons underlying this finding. Because our study focused on directly measuring grain yield, our possible reasons are based primarily on evidence for existing studies. Our heat stress calculation was a calculation of heat stress for maize.

Legumes tend to have a greater tolerance to heat stress than maize (Farooq et al., 2017; Sita et al., 2017). Our calculation of heat stress for maize used a threshold of 30 °C as the base temperature (Section 2.3). This calculation used the threshold that is specific to maize even though most treatment-strategy combinations included one or more legumes. The optimum temperature range for grain legume crops has been reported as 10 °C to 36 °C, above which severe losses in grain yield can occur (Farooq et al., 2017). For example, the heat stress threshold temperature range for groundnuts has been reported as 30 °C to 35 °C (Sita et al., 2017). In our study, the cropping systems that included legumes have greater within-plot crop species diversity than those that did not include legumes. This greater diversity may mean that the cropping systems that included legumes can better maintain their functioning under heat stress.

Existing studies have shown that incorporating legumes into maize-based systems can improve soil physical, chemical and biological properties, such as increased soil organic matter (Snapp et al., 1998), improved soil nitrogen content through biological nitrogen fixation (Snapp et al., 2010), improved soil carbon and aggregate stability (Thierfelder and Wall, 2010b), and improved soil structure (Eze et al., 2020). More generally, improved nutrient management can alleviate heat stress (Waraich et al., 2012). Improvements in soil properties associated with changes in tillage and residue management have also been measured for other crops and regions (beyond maize in Southern Africa), such as residue retention and no tillage significantly enhance enzyme activity, nutrient availability and uptake at different growth stages of wheat as compared to conventional tillage for wheat in India (Jat et al., 2020a). More generally, combining crop rotation with no tillage promotes a more extensive network of root channels and macropores in the soil (Hobbs et al., 2008). Legume intercropping has also been shown to increase root biomass (Arihara et al., 1991). All these improvements can increase the water holding capacity of soil and helps water infiltrate to deeper depths. Related to improved soil properties, Conservation Agriculture has also been shown to improve water-use efficiency in South Asia (Gathala et al., 2015; Jat et al., 2020b). Therefore, given the mixture of maize and legumes grown in the cropping systems, the threshold temperature used, the role of stress-tolerant maize varieties, and nutrient management, it may be plausible that cropping-system yields in our study increased even as our measure of heat stress for maize increased.

We also found that with rotation cropping-system yields were more responsive to a simultaneous increase in precipitation balance and heat stress for maize in the Conservation Agriculture treatment than in the Control Practice treatment. The surface area exposed to heat and evapotranspiration was higher in the Control Practice treatment than in the No-Tillage or Conservation Agriculture treatments. This greater exposure was because the use of planting ridges in the Control Practice treatment exposed the soil to more sunlight and wind. The predominant practice in Malawi is to use planting ridges (Thierfelder et al., 2013) and they have a bell-shaped structure. This greater exposure, in response to a greater soil surface area, typically increases the drying of soil and magnifies declines in precipitation balance because of greater evaporation. If there are higher precipitation balances, soils in the Control Practice treatment may also drain faster. This faster drainage may expose crops to increased heat stress and means that the Control Practice has insufficient soil moisture content to help the crop recover after heat stress has ended. Existing studies have shown that practicing the principles of Conservation Agriculture can slow down drainage and improve infiltration rates (Thierfelder and Wall, 2010a; Eze et al., 2020). This may mean that the onset of the negative consequences of heat stress are faster in the Control Practice treatment than in the Conservation Agriculture treatment. Furthermore, in the Control Practice treatment the formation of ridges and the annual shift of the ridge to the furrow area in the next year implies that there is no possibility that the soil can develop a continuous soil pore structure, unlike in no tillage. Often, the soil develops a hoe pan underneath the ridges which further impedes root proliferation. This reduces capillary uptake and slows water infiltration rates (Thierfelder and Wall, 2009). In the No-Tillage and Conservation Agriculture treatments, more soil moisture would most likely be conserved under greater heat stress for maize. These responses will differ by soil type and other contextual factors (Steward et al., 2018), but across the ten communities our results suggest that the No-Tillage and Conservation Agriculture treatments coped better with heat stress for maize.

5. Conclusion

We examined how cropping-system yields were affected by the principles of Conservation Agriculture, and the interaction of these principles with precipitation balance (precipitation minus reference evapotranspiration) and heat stress for maize under different combinations of maize variety and rotation. Our study used data from on-farm trials in ten communities and 14 seasons in the Central Region and Southern Region of Malawi. Our study has two main conclusions. First, practicing some or all the principles of Conservation Agriculture reduces the negative effect of heat stress for maize on cropping-system yield. This complements existing evidence that Conservation Agriculture can improve the adaptive capacity of maize to heat stress. Second, a positive interaction existed between precipitation balance and heat stress for maize when maize was rotated with a legume. We examined all crops grown in the cropping system rather than yields of only one crop (such as maize) per se as ultimately we must consider how the whole cropping system may contribute to climate adaptation. Our results suggest that Conservation Agriculture can reduce some of the detrimental effects of heat stress for maize on cropping-system yields, which is pertinent to the looming challenges of climate stress facing farmers.

Data and code availability statement

The raw yield data and R scripts used in this study are available online: http://hdl.handle.net/11529/10823.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Acknowledgements

This study was undertaken as part of, and funded by, Africa Research in Sustainable Intensification for the Next Generation (Africa RISING) with generous support from USAID's Feed the Future Initiative. The International Fund for Agriculture Development (IFAD) provided financial support from 2008 to 2012 and the Gesellschaft für Internationale Zusammenarbeit (GIZ) from 2004 to 2007 and from 2017 to 2019 financed and co-financed the on-farm trials. The International Maize and Wheat Improvement Center (CIMMYT) and Total LandCare filled jointly funding gaps when no projects could fund the on-farm trials. We acknowledge the long-term commitment of management and field staff from Total LandCare and Machinga ADD, in particular, Trent Bunderson, Zwide Jere, Richard Museka and Mphatso Gama, who assisted in funding and management of long-term on-farm trials and data collection throughout the whole period of the on-farm trials. The time of Thierfelder was provided by the MAIZE CRP and its donors (www.maize.org) whose generous support is highly acknowledged. Andrew Challinor and Andrew Dougill provided helpful comments on an earlier version of this study.

Appendix A. Supplementary data

Supplementary information to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103117. This includes Tables SI.1–SI.4, Figs. SI.1–SI.8, and Supplementary Information: statistical analyses.

References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Autom. Control 19, 716–723.
Arihara, J., Ae, N., Okada, K., 1991. Root development of pigeonpea and chickpea and its significance in different cropping systems. In: Johansen, C., Lee, K.K., Sahrawat, K.L. (Eds.), Phosphorous Nutrition of Grain Legumes in the Semi-arid Tropics, pp. 183–194.
Barnabás, B., Jäger, K., Fehér, A., 2008. The effect of drought and heat stress on reproductive processes in cereals. Plant Cell Environ. 31, 11–38.
Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67, 1–48.
Bowles, T.M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M.A., Culman, S.W., Deen, W., Drury, C.F., Garciay Garcia, A., Gaudin, A.C.M., Harkcom, W.S., Lehman, R.M., Osborne, S.L., Robertson, G.P., Salerno, J., Schmer, M.R., Strock, J., Grandy, A.S., 2020. Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. One Earth 2, 284–293.
Burnham, K.P., Anderson, D.R., 2002. A Practical Information-Theoretic Approach. Model Selection and Multimodel Inference, 2nd ed. Springer, New York.
Cairns, J.E., Crossa, J., Zaidi, P.H., Grudloyma, P., Sanchez, C., Araus, J.L., Thaitad, S., Makumbi, D., Magorokosho, C., Bänziger, M., Menkir, A., Hearne, S., Atlin, G.N., 2013a. Identification of drought, heat, and combined drought and heat tolerant donors in maize. Crop Sci. 53, 1335–1346.
Cairns, J.E., Hellin, J., Sonder, K., Araus, J.L., MacRobert, J.F., Thierfelder, C., Prasanna, B.M., 2013b. Adapting maize production to climate change in sub-Saharan Africa. Food Security 5, 345–360.
Challinor, A., Wheeler, T., Garforth, C., Craufurd, P., Kassam, A., 2007. Assessing the vulnerability of food crop systems in Africa to climate change. Clim. Chang. 83, 381–399.
Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Chang. 4, 287–291.
Challinor, A.J., Koehler, A.K., Ramirez-Villegas, J., Whitfield, S., Das, B., 2016. Current warming will reduce yields unless maize breeding and seed systems adapt immediately. Nat. Clim. Chang. 6, 954–958.
Conway, D., Nicholls, R.J., Brown, S., Tebboth, M.G.L., Adger, W.N., Ahmad, B., Biemans, H., Crick, F., Lutz, A.F., De Campos, R.S., Said, M., Singh, C., Zaroug, M.A.H., Ludi, E., New, M., Wester, P., 2019. The need for bottom-up assessments of climate risks and adaptation in climate-sensitive regions. Nat. Clim. Chang. 9, 503–511.
Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., Twomlow, S., 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change? Agric. Ecosyst. Environ. 126, 24–35.
Corbeels, M., de Graaff, J., Ndah, T.H., Penot, E., Baudron, F., Naudin, K., Andrieu, N., Chirat, G., Schuler, J., Nyagumbo, I., Rusinamhodzi, L., Traore, K., Mzoba, H.D., Adolwa, I.S., 2014. Understanding the impact and adoption of conservation agriculture in Africa: a multi-scale analysis. Agric. Ecosyst. Environ. 187, 155–170.
Corbeels, M., Naudin, K., Whitbread, A.M., Kühne, R., Letourmy, P., 2020. Limits of conservation agriculture to overcome low crop yields in sub-Saharan Africa. Nat. Food 1, 447–454.
Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., Ceccato, P., 2018. Validation of the CHIRPS satellite rainfall estimates over eastern Africa. Q. J. R. Meteorol. Soc. 144, 292–312.
Doran, J.W., Wilhelm, W.W., Power, J.F., 1984. Crop residue removal and soil productivity with no-till corn, Sorghum, and soybean. Soil Sci. Soc. Am. J. 48, 640–645.
Eze, S., Dougill, A.J., Banwart, S.A., Hermans, T.D.G., Ligowe, I.S., Thierfelder, C., 2020. Impacts of conservation agriculture on soil structure and hydraulic properties of Malawian agricultural systems. Soil Tillage Res. 201, 104639.
FAO, 2019. Conservation Agriculture. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/conservation-agriculture/en/ [accessed September 4, 2020].
Farooq, M., Nadeem, F., Gogoi, N., Ullah, A., Alghamdi, S.S., Nayyar, H., Siddique, K.H.M., 2017. Heat stress in grain legumes during reproductive and grain-filling phases. Crop Pasture Sci. 68, 985–1005.
Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations–a new environmental record for monitoring extremes. Sci Data 2, 150066.
Gathala, M.K., Timsina, J., Islam, M.S., Rahman, M.M., Hossain, M.I., Harun-Ar-Rashid, M., Ghosh, A.K., Krupnik, T.J., Tiwari, T.P., McDonald, A., 2015. Conservation agriculture based tillage and crop establishment options can maintain farmers' yields and increase profits in South Asia's rice–maize systems: evidence from Bangladesh. Field Crop Res. 172, 85–98.
Ghuman, B.S., Lal, R., 1992. Comparative evaluation of some inter-cropping Systems in the Humid Tropics of southern Nigeria. J. Sustain. Agric. 2, 59–73.
Godfray, H.C.J., Garnett, T., 2014. Food security and sustainable intensification. Philosoph. Transac. Royal Soc. B: Biol. Sci. 369.
Guilpart, N., Grassini, P., Sadras, V.O., Timsina, J., Cassman, K.G., 2017. Estimating yield gaps at the cropping system level. Field Crop Res. 206, 21–32.
Hengl, T., Mendes de Jesus, J., Heuvelink, G.B.M., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M.N., Geng, X., Bauer-Marschallinger, B., Guevara, M.A., Vargas, R., MacMillan, R.A., Batjes, N.H., Leenaars, J.G.B., Ribeiro, E., Wheeler, I., Mantel, S., Kempen, B., 2017. SoilGrids250m: global gridded soil information based on machine learning. PLoS One 12, e0169748.
Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philosoph. Transac. Royal Soc. Lond B: Biol. Sci. 363, 543–555.
Horton, R., Bristow, K.L., Kluitenberg, G.J., Sauer, T.J., 1996. Crop residue effects on surface radiation and energy balance — review. Theor. Appl. Climatol. 54, 27–37.
Ito, M., Matsumoto, T., Quinones, M.A., 2007. Conservation tillage practices in sub-Saharan Africa: the experience of Sasakawa Global 2000. Crop Prot. 26, 417–423.
IUSS, 2006. World reference base for soil resources 2006. In: World Soil Resources Reports No. 103. IUSS Working Group WRB. FAO, Rome. http://www.fao.org/tempref/docrep/fao/009/a0510e/a0510e00.pdf [accessed November, 2020].
Jat, H.S., Choudhary, M., Datta, A., Yadav, A.K., Meena, M.D., Devi, R., Gathala, M.K., Jat, M.L., McDonald, A., Sharma, P.C., 2020a. Temporal changes in soil microbial properties and nutrient dynamics under climate smart agriculture practices. Soil Tillage Res. 199, 104595.
Jat, M.L., Chakraborty, D., Ladha, J.K., Rana, D.S., Gathala, M.K., McDonald, A., Gerard, B., 2020b. Conservation agriculture for sustainable intensification in South Asia. Nat. Sustain. 3, 336–343.
Kenward, M.G., Roger, J.H., 1997. Small sample inference for fixed effects from restricted maximum likelihood. Biometrics 53, 983–997.
Komarek, A.M., Kwon, H., Haile, B., Thierfelder, C., Mutenje, M.J., Azzarri, C., 2019. From plot to scale: ex-ante assessment of conservation agriculture in Zambia. Agric. Syst. 173, 504–518.
Lal, R., 1974. Soil temperature, soil moisture and maize yield from mulched and unmulched tropical soils. Plant Soil 40, 129–143.
Lobell, D.B., Bänziger, M., Magorokosho, C., Vivek, B., 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. Nat. Clim. Chang. 1, 42–45.
Lobell, D.B., Sibley, A., Ivan Ortiz-Monasterio, J., 2012. Extreme heat effects on wheat senescence in India. Nat. Clim. Chang. 2, 186–189.
Loy, A., Steele, S., 2016. lmeresampler: Bootstrap methods for nested linear mixed-effects models. https://cran.r-project.org/package=lmeresampler.
Masuka, B., Atlin, G.N., Olsen, M., Magorokosho, C., Labuschagne, M., Crossa, J., Bänziger, M., Pixley, K.V., Vivek, B.S., von Biljon, A., Macrobert, J., Alvarado, G., Prasanna, B.M., Makumbi, D., Tarekegne, A., Das, B., Zaman-Allah, M., Cairns, J.E., 2017a. Gains in maize genetic improvement in eastern and southern Africa: I. CIMMYT hybrid breeding pipeline. Crop Sci. 57, 168–179.
Masuka, B., Magorokosho, C., Olsen, M., Atlin, G.N., Bänziger, M., Pixley, K.V., Vivek, B.S., Labuschagne, M., Matemba-Mutasa, R., Burgueño, J., Macrobert, J., Prasanna, B.M., Das, B., Makumbi, D., Tarekegne, A., Crossa, J., Zaman-Allah, M., van Biljon, A., Cairns, J.E., 2017b. Gains in maize genetic improvement in eastern and southern Africa: II. CIMMYT open-pollinated variety breeding pipeline. Crop Sci. 57, 180–191.
Michler, J.D., Baylis, K., Arends-Kuenning, M., Mazvimavi, K., 2019. Conservation agriculture and climate resilience. J. Environ. Econ. Manag. 93, 148–169.
Muthoni, F.K., Odongo, V.O., Ochieng, J., Mugalavai, E.M., Mourice, S.K., Hoesche-Zeledon, I., Mwila, M., Bekunda, M., 2019. Long-term spatial-temporal trends and variability of rainfall over eastern and southern Africa. Theor. Appl. Climatol. 137, 1869–1882.
Mutuku, E.A., Roobroeck, D., Vanlauwe, B., Boeckx, P., Cornelis, W.M., 2020. Maize production under combined conservation agriculture and integrated soil fertility

management in the sub-humid and semi-arid regions of Kenya. Field Crop Res. 254, 107833.
Nakagawa, S., Johnson, P.C., Schielzeth, H., 2017. The coefficient of determination R 2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. J. R. Soc. Interface 14, 20170213.
NASA, 2020. Prediction of Worldwide Energy Resource (POWER) (Higher Resolution Daily Time Series by Location).
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. Agric. Ecosyst. Environ. 295, 106898.
Olasantan, F.O., Ezumah, H.C., Lucas, E.O., 1996. Effects of intercropping with maize on the micro-environment, growth and yield of cassava. Agric. Ecosyst. Environ. 57, 149–158.
Osmond, C.B., Austin, M.P., Berry, J.A., Billings, W.D., Boyer, J.S., Dacey, J.W.H., Nobel, P.S., Smith, S.D., Winner, W.E., 1987. Stress physiology and the distribution of plants. BioScience 37, 38–48.
Parihar, C.M., Jat, S.L., Singh, A.K., Kumar, B., Yadvinder, S., Pradhan, S., Pooniya, V., Dhauja, A., Chaudhary, V., Jat, M.L., Jat, R.K., Yadav, O.P., 2016. Conservation agriculture in irrigated intensive maize-based systems of North-Western India: effects on crop yields, water productivity and economic profitability. Field Crop Res. 193, 104–116.
Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633–1644.
Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365–368.
R, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
Rusinamhodzi, L., Corbeels, M., Wijk, M.T., Rufino, M.C., Nyamangara, J., Giller, K.E., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agron. Sustain. Dev. 31, 657–673.
Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5, 014010.
Setimela, P.S., Magorokosho, C., Lunduka, R., Gasura, E., Makumbi, D., Tarekegne, A., Cairns, J.E., Ndhlela, T., Erenstein, O., Mwangi, W., 2017. On-farm yield gains with stress-tolerant maize in eastern and southern Africa. Agron. J. 109, 406–417.
Setimela, P., Gasura, E., Thierfelder, C., Zaman-Allah, M., Cairns, J.E., Boddupalli, P.M., 2018. When the going gets tough: performance of stress tolerant maize during the 2015/16 (El Niño) and 2016/17 (La Niña) season in southern Africa. Agric. Ecosyst. Environ. 268, 79–89.
Shew, A.M., Tack, J.B., Nalley, L.L., Chaminuka, P., 2020. Yield reduction under climate warming varies among wheat cultivars in South Africa. Nat. Commun. 11, 4408.
Silva, J.V., Reidsma, P., van Ittersum, M.K., 2017. Yield gaps in Dutch arable farming systems: analysis at crop and crop rotation level. Agric. Syst. 158, 78–92.
Sita, K., Sehgal, A., HanumanthaRao, B., Nair, R.M., Vara Prasad, P.V., Kumar, S., Gaur, P.M., Farooq, M., Siddique, K.H.M., Varshney, R.K., Nayyar, H., 2017. Food legumes and rising temperatures: effects, adaptive functional mechanisms specific to reproductive growth stage and strategies to improve heat tolerance. Front. Plant Sci. 8.
Smith, M.R., Micha, R., Golden, C.D., Mozaffarian, D., Myers, S.S., 2016. Global expanded nutrient supply (GENuS) model: a New method for estimating the global dietary supply of nutrients. PLoS One 11, e0146976.
Snapp, S.S., Mafongoya, P.L., Waddington, S., 1998. Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. Agric. Ecosyst. Environ. 71, 185–200.
Snapp, S.S., Blackie, M.J., Gilbert, R.A., Bezner-Kerr, R., Kanyama-Phiri, G.Y., 2010. Biodiversity can support a greener revolution in Africa. Proc. Natl. Acad. Sci. 107, 20840–20845.
Sommer, R., Thierfelder, C., Tittonell, P., Hove, L., Mureithi, J., Mkomwa, S., 2014. Fertilizer use should not be a fourth principle to define conservation agriculture: response to the opinion paper of Vanlauwe et al. (2014) 'a fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity'. Field Crop Res. 169, 145–148.
Stackhouse Jr., P., 2019. POWER Data Methodology: Validation Overview (Version: 1.0). https://power.larc.nasa.gov/docs/methodology/validation/.
Steward, P.R., Dougill, A.J., Thierfelder, C., Pittelkow, C.M., Stringer, L.C., Kudzala, M., Shackelford, G.E., 2018. The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: a meta-regression of yields. Agric. Ecosyst. Environ. 251, 194–202.
Tabachnick, B.G., Fidell, L.S., 2007. Using Multivariate Statistics, 5th ed. Allyn & Bacon/ Pearson Education, Boston, MA.
Thierfelder, C., Wall, P.C., 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil Tillage Res. 105, 217–227.
Thierfelder, C., Wall, P.C., 2010a. Investigating conservation agriculture (CA) Systems in Zambia and Zimbabwe to mitigate future effects of climate change. J. Crop Improv. 24, 113–121.
Thierfelder, C., Wall, P.C., 2010b. Rotation in conservation agriculture systems of Zambia: effects on soil quality and water relations. Exp. Agric. 46, 309–325.
Thierfelder, C., Chisui, J.L., Gama, M., Cheesman, S., Jere, Z.D., Bunderson, W.T., Eash, N.S., Rusinamhodzi, L., 2013. Maize-based conservation agriculture systems in Malawi: long-term trends in productivity. Field Crop Res. 142, 47–57.
Thierfelder, C., Matemba-Mutasa, R., Rusinamhodzi, L., 2015. Yield response of maize (Zea mays L.) to conservation agriculture cropping system in southern Africa. Soil Tillage Res. 146, 230–242.
Thierfelder, C., Chivenge, P., Mupangwa, W., Rosenstock, T.S., Lamanna, C., Eyre, J.X., 2017. How climate-smart is conservation agriculture (CA)? – its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa. Food Security 9, 537–560.
Thierfelder, C., Baudron, F., Setimela, P., Nyagumbo, I., Mupangwa, W., Mhlanga, B., Lee, N., Gérard, B., 2018. Complementary practices supporting conservation agriculture in southern Africa. A review. Agron. Sustain. Dev. 38, 16.
Thornton, P.K., Ericksen, P.J., Herrero, M., Challinor, A.J., 2014. Climate variability and vulnerability to climate change: a review. Glob. Chang. Biol. 20, 3313–3328.
Van Wart, J., Grassini, P., Yang, H., Claessens, L., Jarvis, A., Cassman, K.G., 2015. Creating long-term weather data from thin air for crop simulation modeling. Agric. For. Meteorol. 209-210, 49–58.
Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J. Clim. 23, 1696–1718.
Waha, K., Dietrich, J.P., Portmann, F.T., Siebert, S., Thornton, P.K., Bondeau, A., Herrero, M., 2020. Multiple cropping systems of the world and the potential for increasing cropping intensity. Glob. Environ. Chang. 64, 102131.
Waraich, E., Ahmad, R., Halim, A., Aziz, T., 2012. Alleviation of temperature stress by nutrient management in crop plants: a review. J. Soil Sci. Plant Nutr. 12, 221–244.
Zotarelli, L., Dukes, M.D., Romero, C.C., Migliaccio, K.W., Morgan, K.T., 2010. Step by step calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method). http://edis.ifas.ufl.edu/ae459 (accessed March 30, 2020).
Zuur, A., Ieno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R. Springer Science & Business Media.