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Conservation agriculture enhances resistance of maize to climate stress in a Malawian medium-term trial

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ABSTRACT

Smallholder farming in southern African needs climate-smart agricultural approaches to adapt to current climate stress and climate variability, and increasing risk of these under future global climate change. There are a range of climate-smart systems that have been proposed and conservation agriculture (CA) based on minimum soil disturbance, crop residue retention and crop rotation is one of them. A CA trial established in 2007 in Malawi was used during cropping -seasons 2015–2016 (El Niño) and 2016–2017 (La Niña) to assess the performance and resistance of different CA maize systems under climate-related stress at anthesis, a climate sensitive growth stage. Large *in-situ* rainout shelters were used to simulate increased daytime temperatures and in-season droughts of 18–19 days and 27 days. CA systems better resisted climate stress around anthesis than conventional tillage practices as CA systems showed greater resistance to drought than conventional practice. This was expressed by higher CA maize grain yields, biomass yields or harvest index under conditions of natural (El Niño) or 19 day simulated drought. However, under 27 day drought simulation the resistance benefit of CA was no-longer significant. Crop diversification improved the resistance of CA systems to climate stress, more so when diversification was over time (rotation) than in space (intercropping). In all years CA systems substantially outyielded conventional practice, this highlights the benefits of medium-term (eight years) CA management before the rainout shelter experiment started. Our results from natural and simulated drought conditions confirm that CA systems can increase adaptive capacity to an increased risk of climate stress associated with projected global climate change. We show that large-scale rainout shelters are a useful means of accelerating our understanding of how long-term agricultural management practices can enhance resistance to climate stresses.

1. Introduction

Global food security is increasingly affected by declining soil fertility and the impact of climate variability (Wheeler and von Braun, 2013). This is particularly the case for sub-Saharan Africa (Lobell et al., 2008) where increasing temperatures and more erratic rainfall are predicted by 2050 (Cairns et al., 2013; Tesfaye et al., 2015). Already, around 40% of maize-producing regions in sub-Saharan Africa experience occasional drought stress leading to yield reductions of 10–25% with 25% of maize production suffering from frequent drought that causes losses of up to 50% of the harvest (Fisher et al., 2015). Temperatures in southern Africa are likely to rise by an average of 2.6 °C (Cairns et al., 2012) and rainfall seasons are predicted to start later, shortening the cropping seasons that will be characterized by stronger and more irregular rainfall events, although there is considerable variability in change impacts predicted between input levels, regions and maize mega environments (Tesfaye et al., 2015)

In response to current and future climate risk, the concept of climate-smart agriculture (CSA) has been developed, acknowledging the need to adapt current farming systems to the impacts of climate-related stresses (Campbell et al., 2014; Lipper et al., 2014). Climate-smart agriculture is a concept that aims to: a) increase productivity and profitability of farming while b) enhancing the adaptation (resilience) to climate related stresses and c) reducing the negative side effects of climate by sequestering more carbon and reducing greenhouse gas emissions (FAO, 2013). The concept of CSA is not a technology *per se* but a suite of technologies, approaches and management practices that together make a landscape climate-smart (Scherr et al., 2012). This framework has been embraced by many countries in sub-Saharan Africa and an increasing level of investment is expected within the next

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decade (Bell et al., 2018). Organizations such as the New Partnership for Africa's Development (NEPAD) have formulated a target to reach 25 million farmers by 2025 with climate-smart agriculture technologies and approaches through its Alliance for Climate-smart Agriculture (ACSA). However, there is very limited direct data available to show how increased climate risk (*e.g.* drought and heat stress) will affect specific cropping system performance in Africa and there is urgent need to generate such evidence.

Conservation agriculture (CA) is one cropping system highlighted under the umbrella of CSA which is based on the three principles of a) minimum soil disturbance; b) crop residue retention and c) crop diversification through rotations and intercropping systems (Kassam et al., 2009; Thierfelder et al., 2017). CA has been tested in southern Africa in on-station and on-farm long-term trials to better understand the mechanisms that could underpin its resistance to climate-related stresses (Thierfelder and Wall, 2010a; Thierfelder et al., 2017). Regional results from on-farm and on-station studies of soil infiltration, moisture, aggregation and biological activity show that CA systems have significant benefits over conventional tillage based practices (Mupangwa et al., 2007; Thierfelder and Wall, 2009; Nyamangara et al., 2014). Longer term benefits in crop yields have been monitored after 2–5 cropping seasons (Thierfelder et al., 2015; Mupangwa et al., 2016) and increases in soil carbon have been observed in some cases (González-Sánchez et al., 2012; Ligowe et al., 2017) while questioned in others (Cheesman et al., 2016; Piccoli et al., 2016; Powlson et al., 2016). A recent meta-analysis of maize yield response ratios using a large number of trials has shown that there is an increase in the adaptive capacity of CA systems over conventional control treatments especially on sandy and loamy soils (Steward et al., 2018).

Both on-farm and on-station field trials have significant limitations in relation to detailed research on climate related effects, droughts and heat stresses cannot be simulated well *in vivo* or predicted. This means that currently research gaps persist on how CA systems adapt to the effects of climate change at critical stages of plant development (*e.g.* germination, flowering, tassling, silking and grain filling). One strategy to artificially create moisture limiting conditions within a standing crop is to use rainout shelters to shield the crop from rainfall at critical times during the cropping season (Yahdjian and Sala, 2002; Lucas et al., 2008; Kant et al., 2017). Building physical structures to "generate" or "simulate" drought and heat stress has the advantage that climate stress can be induced at times when it is physiologically critical for crops during the growing season. For maize, this is during the period of anthesis and silking (also referred to as the anthesis silking interval) when maize is particularly sensitive to climate-related stresses (Cairns et al., 2012, 2013). Rainout shelters have the advantage that they can be put on and being removed to "switch on" a drought and "switch it off" again simulating an in-season dry-spell.

Previous work has often focused on shelters that are small (3.76 m^2, Yahdjian and Sala, 2002; 4 m^2, Aanderud et al., 2011) manipulating only the upper surface of the soil profile (*e.g.*, 0–30 cm, Yahdjian and Sala, 2002; 2 cm, Aanderud et al., 2011). Larger rainout shelters are required to effectively manipulate the soil moisture profile for crops such as maize which can have maximum root depths of 89–157 cm (Ordóñez et al., 2018) because soil moisture will increasingly penetrate from the sides with increasing depth.

The aim of this study was to monitor the effects of climate-related stress factors *in-situ* with rainout shelters that are big enough to allow for realistic field monitoring. Our hypotheses are: a) CA systems better resist climate related stress around anthesis than conventional tillage practices as expressed by greater yields and/or harvest index; and b) CA systems are more resistant to climate stress when they incorporate crop diversification in time (rotation) or space (intercropping).

Table 1
Soil properties at the Chitedze medium-term conservation agriculture trial as measured at the end of the 2011–12 cropping season (see Ligowe et al., 2017, note for some parameters presented here data were collected but not published). OM = organic matter, pH = pH determined in water (1 soil: 2.5 H_2O), P = available phosphorous, N = mineralizable nitrogen and K, M and Ca = exchangeable potassium magnesium and calcium.

OM g kg^{-1}	pH	P ug g^{-1}	N g kg^{-1}	K cmol kg^{-1}	Mg cmol kg^{-1}	Ca cmol kg^{-1}	Clay %	Silt %	Sand %
40.53	5.96	33.01	2.09	0.58	3.25	15.95	37.5	6.9	55.7
35.32	5.83	22.48	1.78	0.42	2.50	11.49	39.6	5.9	54.6
32.15	5.69	14.60	1.53	0.35	1.99	10.09	39.6	7.1	53.2
24.14	5.64	7.79	0.85	0.26	1.65	8.50	38.1	8.4	53.6
17.56	5.54	4.04	0.56	0.22	1.39	6.39	37.4	7.7	54.9
31.23	4.68	9.25	1.56	0.45	1.85	7.83	37.0	7.5	55.5
24.62	4.68	8.15	1.33	0.23	1.58	7.33	39.5	6.0	54.5
22.9	4.63	6.98	1.02	0.18	1.40	6.60	36.8	10.5	52.8
15.72	4.45	3.68	0.65	0.15	1.30	6.43	41.8	6.5	51.8
8.13	4.45	2.83	0.25	0.10	1.18	6.25	39.3	6.5	54.3

2. Methods

2.1. Location and experimental design

A long-term CA trial was established in 2007 at Chitedze Research Station (CRS), Malawi (latitude -13.9738°, longitude 33.6527°, altitude 1147 m.a.s.l.) on a sandy clay loam soil (Chromic Luvisol, for more details see Table 1) where rainfed cropping is standard practice. The site was under maize (*Zea mays* L.)- pigeonpea (*Cajanus cajan* (L.) Millsp.) trials prior to cropping season 2005/2006. In cropping season 2006/2007 it was planted to a uniform fertilized maize crop, before it was converted into the conservation agriculture long-term trial in 2007.

Rainfall at Chitedze follows a unimodal distribution typically starting in November and ending in March. Annual rainfall, beginning with the growing season in November, over the period 2005–2015 has a mean value of 828 ± 119.9 (SD) mm with a minimum of 578 mm and maximum of 1016 mm. This study took place across two growing seasons 2015–2016, a very strong El Niño year with 463 mm rainfall, and 2016–2017, a weak La Niña year with 861 mm rainfall.

The experiment consisted of eight management treatment plots in a randomized complete block design with four replications. Plots were 24 m × 12.75 m, accommodating 18 rows of maize.

The management treatments manipulated with rainout shelters in this study were:

1) *CP (conventional control plot):* Maize was planted as a continuous monocrop in a ridge and furrow system prepared by hand hoes with no surface crop residues (Fig. A.1A in Supplementary material);
2) *NT (no-tillage, crop residue mulching and maize monoculture):* Maize was direct-seeded as a continuous monocrop using dibble sticks with crop residues retained from the previous season (Fig. A.1B in Supplementary material);
3) *CArot (no-tillage, crop residue retention and crop rotation):* Maize was direct-seeded as a continuous monocrop using dibble sticks with crop residues retained from the previous season. Maize rotated with cowpea, both phases of the rotation alternated annually across two plots in each replicate block (Fig. A.1C in Supplementary material); and
4) *CAint (no-tillage, crop residue retention and intercropping):* Maize and cowpea were direct-seeded using dibble sticks with crop residues retained from the previous season. The cowpea intercrop was seeded between maize rows (Fig. A.1D in Supplementary material).

We consider maize monoculture as an undiversified cropping system with only maize planted in both space and time, intercropping to be a diversified system in space and rotation to be a diversified system in time.

2.2. *Crop management*

The commercial maize variety DKC 90-89 was planted in both seasons. The variety is a flint type, early to medium maturity hybrid (115–120 days to harvest) with yield potential of up to 10 tons ha^{-1} and tolerance to disease (grey leaf spot (*Pyricularia grisea* Sacc.), maize streak virus, blights, rust and cob rot). Maize was planted in 24 m long rows spaced at 75 cm with 25 cm between planting stations. Two seeds were planted per station and thinned to a single plant when seedlings were approximately 10 cm tall. The target maize population was 53,000 plants ha^{-1}. Maize was planted when 30–50 ml of rainfall was received over a two day period after the 15th November, in both seasons this was December (Table A.1 in Supplementary material).

Legumes in rotation were cowpea, variety Sudan, planted at one seed per station in rows spaced at 75 cm with stations spaced at 10 cm (target population 133,333 plants ha^{-1}). Groundnuts, ICRISAT variety CG 7, were planted one seed per station in rows spaced at 37.5 cm with stations spaced at 15 cm (177,777 plants ha^{-1}). The cowpea variety Sudan, was also planted in the intercropped treatment in 75 cm rows between maize lines, two seed per station, and 50 cm between stations (53,333 plants ha^{-1}).

All treatments received top-dressings of 100 kg ha^{-1} basal N-P-K fertilizer (23-21-0 + 4S) approximately two weeks after planting and 100 kg ha^{-1} urea approximately five weeks after planting based on the recommended fertilizer rate for Malawi.

Weeds were removed three times per season across all treatments using shallow hoeing or hand removal. No herbicides were applied on the trial in both cropping seasons. The insecticides, Cypermethrin 200EC and Dimethoate, were applied using knapsack sprayers to control aphid outbreaks on cowpeas only, no other chemicals were sprayed during in the duration of the trial.

As per treatment, all crop residues were retained and spread over the surface of experimental treatments at the end of the growing season. They were re-distributed before planting as some had been moved by strong winds during the dry winter season.

2.3. *Rainout shelter construction, timing and climate*

In August to September 2015 management treatments were divided into two sub-plots, in one of each sub-plot pair a rainout shelter was erected giving a total of four shelters per treatment and 16 in total. The following season in September 2016 a further four shelters were built in the alternate phase of the *CArot* treatment.

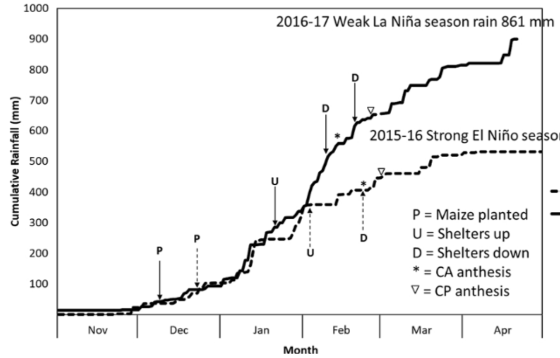

Fig. 2. Cumulative rainfall and major events for the strong 2015–16 El Niño (dotted line) and weak 2016–17 La Niña (solid line) experimental growing seasons.

Rainout shelters were 24.5 m long by 3.7 m wide (90 m^2) and 2–2.5 m tall (Fig. 1) accommodating five rows of maize. Shelters were covered by transparent polythene sheets used in commercial horticultural polytunnels.

To simulate a pre-anthesis drought in the 2015–16 shelter covers were erected for 19 days beginning 43–62 days after planting (DAP) maize (Fig. 2), then removed again. In 2016–17, to increase the effect size of the drought simulation on soil moisture, rain shelters were split into two equal halves (45 m^2 split sub-plots), one half was erected for 19 days between 43 and 62 DAP and the other half erected for 27 days between 43 and 70 DAP.

Soil moisture was measured using monitoring tubes installed at depths of 0.1, 0.2, 0.5 and 1.0 m with 16 replicates of each depth in open areas and 20 replicates within rainshelters. Soil moisture was recorded using a ML3 ThetaProbe (AT Delta-T Devices, Cambridge) 18 and 19 days after rainout shelters were erected in 2016 and 2017 respectively. The location of monitoring tubes within shelters caused issues for the 2016–17 split-plot design, so soil moisture was determined by oven drying 100 g soil samples at 105 °C until weight remained constant.

Temperature and humidity were recorded in open areas and shelters at a height of 1.25 m using shaded and naturally aspirated DS1921 G Thermochron and DS1923 Hygrochron iButtons. Climate data were compared for a 13 day period after rainout shelters were erected. Two measures of growing degree days, $GDD_{8,30}$ ($T_{base} = 8\,^{\circ}C$ and $T_{opt} = 30\,^{\circ}C$) and GDD_{30+} ($T_{base} = 30\,^{\circ}C$ and $T_{opt} = \infty$) were used to calculate temperature as relevant to maize production using the formula:

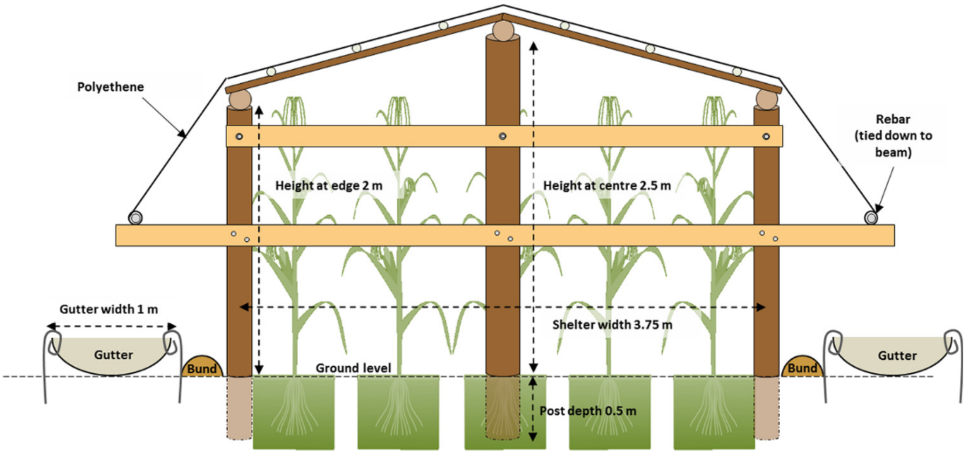

Fig. 1. Cross-sectional diagram of a rainout shelter. Length is 24.5 m. Crop measurements were only taken from the central three rows of the shelter. Photographs of shelters are provided in Fig. A.2 in Supplementary material.

$$GDD_{base,opt} = \sum_{t=1}^{N} DD_t,\ \mathrm{DD} = \begin{Bmatrix} 0 & \text{if } T_t < T_{base} \\ T - T_{base} & \text{if } T_{base} < T_t < T_{opt} \\ T_{opt} - T_{base} & \text{if } T_T > T_{opt} \end{Bmatrix}$$

where *t* is an individual time step (hour), T_t is the average temperature during this time step and *N* is the number of hours in day. The former, $GDD_{8,30}$, predicts maize development rates (Kiniry and Bonhomme, 1991), whereas GDD_{30+} presents a risk of heat stress to maize by exposure to temperatures which are considered harmful to growth and reproductive processes (Schlenker and Roberts, 2009).

2.4. Maize performance

Mean anthesis date was taken as 50% tasseling in maize crops. At physiological maturity, maize yield samples were harvested from three rows by 6 m from each sub- and/or split-sub plot. To minimize edge effects in drought simulation sub-plots, maize samples were taken from the central three maize rows and 2 m from the end of rows. In-keeping with the design of long-term performance monitoring at the trial, an additional nine samples of 5 m × 2 rows were collected from open sub-plots (without rainout shelters). These samples had to be 2 m or two rows from the edge of the sub-plot. A sub-sample of 10 cobs per plot was dried and shelled to calculate grain moisture and yield at 12.5% moisture content. Dried maize stalks were weighed at harvest without maize cobs and recorded as above ground maize biomass. The harvest area of samples was used to extrapolate yields to an area basis. Yields were averaged across all sub-samples for each sub-plot. The biomass values used in harvest index calculations included cob stones, cob leaves and biomass stovers.

2.5. Statistical analyses

The interaction of simulated anthesis drought (rainout shelters) and soil depth on soil moisture were analyzed using linear mixed-effects (LME) models with a nested random effect of treatment within replicate. The effects of drought simulation on temperature and humidity variables were analyzed using LME models with a random effect for replicate block. In LME models parameter 95% confidence intervals were bootstrap estimated using 10,000 replicates.

Linear models were used to test for differences between days to anthesis between treatments and for interactions between drought simulation and management treatments on biomass and grain yields, harvest index (HI) and response ratios (yields or HI of treatment divided by control within replicates). Dependent variables were transformed to correct residual heteroscedacity between treatments if required.

Posthoc contrasts between open and covered treatments were performed using bootstrapped Welch two-sample *t*-tests with 10,000 replications, p-values were adjusted for multiple testing using the false discovery rate (FDR) correction.

3. Results

3.1. Management effects on maize anthesis timing

An incidental, but important, result of the experiment was that we found “CA” treatments (*NT, CAint* and *CArot*) reached anthesis significantly earlier than *CP* treatments (Fig. 2, Table A.2). Mean maize anthesis date in *“CA”* compared to *CP* was 6.2 days earlier in 2015–16 (64.3 *vs.* 70.5 DAP) and 9.2 days earlier in 2016–17 (69.8 *vs.* 79.0 DAP).

3.2. Drought simulation effects on soil moisture, temperature and humidity

Drought simulation significantly reduced available soil moisture with increasing depth (Table A.3 in Supplementary material). The effect of drought simulation was weaker in the 18 day 2015–16 El Niño season where conditions were drier, compared to the 19 day drought simulation in the weak 2016–17 La Niña.

Growing season rainfall in El Niño was low at 463 mm (Table A.5 in Supplementary material), thisis 55.9% of the 2005–2015 average and 115 mm lower than any other year in this period. Rainfall was 111.8 mm in the week before shelters went up (35–42 DAP) and 48.0 mm was diverted away from covered plots. After 18 days the drought simulation had significantly reduced soil moisture compared to open controls at depths 0–50 cm with percentage soil moisture reductions of 19.0–36.0% corresponding to absolute soil moisture reductions of 3.5–7.1%. However, drought simulation did not significantly reduce soil moisture at 100 cm where mean absolute values were only 0.2% different.

In La Niña growing season rainfall was 858.8 mm with 41.2 mm falling in the week before shelters went up (35–42 DAP) and diverted rainfall was 199.8 mm was 19 day split sub-plots and 308.6 mm for 27 day split sub-plots. The 19 day drought simulation significantly reduced soil moisture compared to open controls at depths of 0–100 cm with percentage reductions in soil moisture of 54.5% at the surface and 18.7% at 100 cm corresponding to absolute soil moisture reductions of 14.1% and 4.3% respectively. After 27 days of drought simulation gravimetric readings of soil moisture showed significant reductions at depths of 0–100 cm with percentage reductions in soil moisture of 54.5% at 0–5 cm and 18.7% at 95–100 cm corresponding to absolute soil moisture reductions of 14.1% and 4.3% respectively.

During drought simulation periods maize exposure to daily maximum temperatures was typically within the range 30 °C–40 °C (Fig. A.3 in Supplementary material) with shelters increasing daily temperature maxima by 2.7 °C; mean by 1.9 °C and minima by 0.7 °C (Table A.6 in Supplementary material). Drought simulators approximately doubled daily exposure to growing degree days above 30 °C (GDD_{30+}), but the effect size was small, an increase of 0.7 (Table A.6 in Supplementary material). Drought simulation effects on growing degree days between 8 °C and 30 °C ($\mathrm{GDD}_{8,30}$) were also significant, again with a small effect size increasing daily $\mathrm{GDD}_{8,30}$ by 0.4.

3.3. Maize yields under drought simulation

In the 2015–2016 El Niño, pre-anthesis drought simulation had no significant effect on maize performance indicators (Figs. 3A, 4 A). In open sub-plots the average maize grain yield of the *CP* control was 1555 kg ha^{-1}, this was substantially and significantly lower than any of the treatments (*NT* = 4627 kg ha^{-1}, *CArot* = 4850 kg ha^{-1} and *CAint* = 5671 kg ha^{-1}; Tables 2 and A.7). When considering response ratios, all treatments outperformed *CP* under open or drought simulation conditions (Fig. 4A), but this was not significant in linear regression models (Table 3) and in posthoc tests only *CArot* under 18 day drought simulation was significantly higher than parity with the control (Fig. 4).

El Niño maize biomass yield for open *CP* was 2021 kg ha^{-1}, significantly lower than any of the open treatments (*NT* = 4345 kg ha^{-1}, *CArot* = 4879 kg ha^{-1} and *CAint* = 4330 kg ha^{-1}; Tables A.7 and A.8 in Supplementary material). Posthoc tests showed under 18 day drought simulation maize biomass yields were significantly higher in *CArot* compared to *NT* (Fig. 3C). Considering response ratios, all treatments outperformed the control under open or drought simulation conditions (Fig. 4C). In linear regression models this was significant for *CArot* and *CAint*, but not *NT* (Table A.9 in Supplementary material) and posthoc tests showed only biomass yields in the *CAint* 18 day drought simulation and *CArot* open treatments were significantly higher than parity with the control (Fig. 3C).

The maize harvest index (HI) for *CP* in open and drought simulation conditions was significantly lower than in any CA treatment plots. There were no differences in HI between treatments within open or drought simulation treatments.

In La Niña the 19 day pre-anthesis drought simulation had no statistically significant effect on maize grain yields, but the 27 day drought

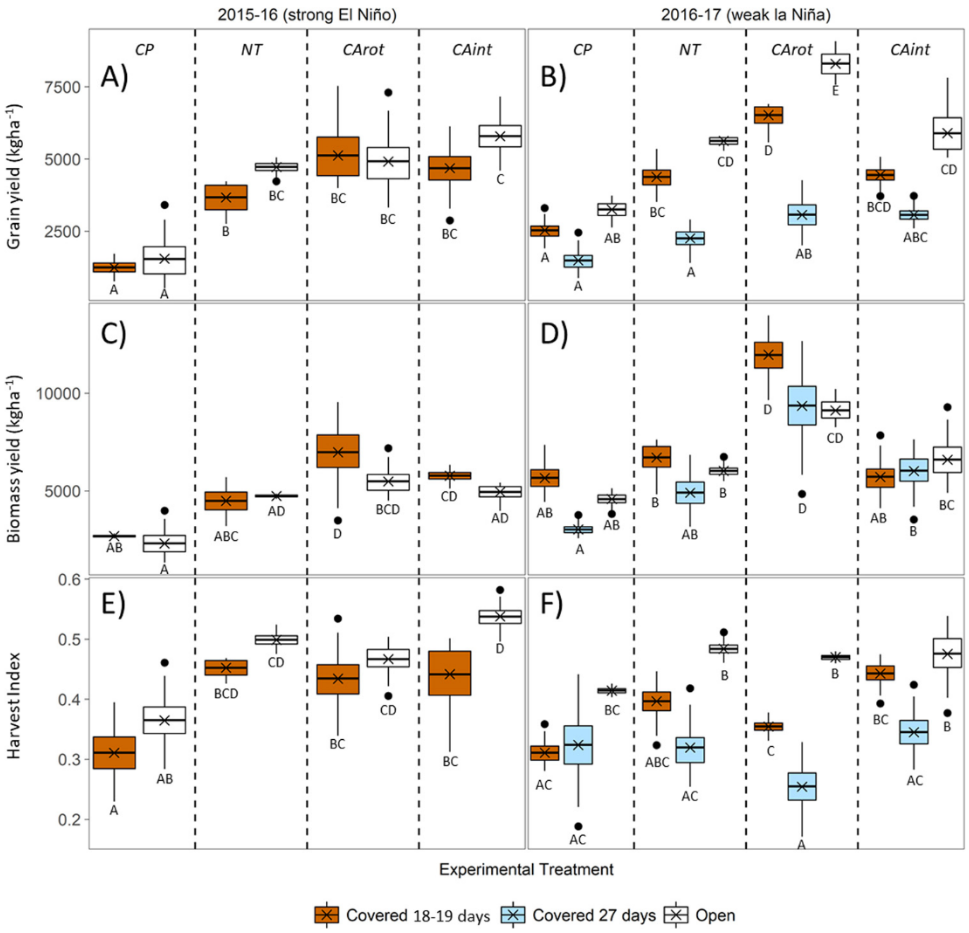

Fig. 3. Treatment effects (groups separated by vertical dashed lines) on maize performance indicators (grain yield A & B, biomass yield C & D, and harvest index E & F) under open (white boxes) and drought simulated conditions (orange/blue boxes) for the 2015–16 strong El Niño (left panels A, C & E) and 2016–17 weak El Niña events (right panels B, D & F). Boxplots were generated using bootstrapping with 10,000 replications, the central line of the plot is the is median, "x" is the mean, the upper and lower hinges of boxes are the interquartile range (IQR), whiskers extend to the largest value no further than 1.5 times the IQR and outliers beyond the whiskers are plotted as points. Letters compare treatments within a panel, if treatments share the same characters they are not significantly different according to pairwise *t*-tests ($p < 0.05$, FDR adjusted), $n = 4$ per treatment (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

simulation significantly reduced grain yields by 1788 kg ha^{-1} (Fig. 3B, Table 2). This was reflected in the response ratio of grain yields across treatments which were significantly higher under 19 day, but not 27 day, drought simulation (Table 3). Posthoc tests showed all treatments under 19 day drought simulation performed significantly better than *CP* with the open *CArot* treatment outperforming all others (Fig. 3B). Treatments in the open condition also significantly outperformed *CP* (Fig. 3B, Table 2). There were no significant differences between treatments or between treatments and control under the 27-day drought simulation.

La Niña Biomass yields were significantly higher in the *CArot* treatment under both 19 and 27 day drought simulations compared to *CP*, *CAint* and *NT* whereas yields under *CAint* and *NT* did not differ from *CP* (Fig. 3; Table A.8).

Whilst there was no difference maize HI between *CP* compared to treatment plots (Tables 2 and A.7), the response ratios of HI were significantly higher than parity in both *NT* and *CAint* (Table 3). Only HI under *CArot* showed a significant interaction with drought simulation declining by −0.14 after 27 days (note that this treatment maintained high biomass production under drought simulation). Posthoc tests showed the harvest indexes in open treatments were significantly higher than *CArot* and *CP* under 19 day drought simulation and all treatments and *CP* under 27 day droughts simulation (Fig. 3F).

4. Discussion

Drought simulations at the Chitedze CA medium-term trial in the two cropping season 2015–2016 (El Niño) and 2016–2017 (La Niña) had significant effects on available soil moisture, moisture distribution in the soil profile and exposure to temperatures above 30 °C (heat stress) between open and covered areas. The effect of 18–19 day drought simulation was much greater in La Niña due to large differences in rainfall between seasons. Very low grain yields observed in some of the 29 day drought simulation yield samples suggest that this level of moisture stress was nearing a threshold beyond which yields collapse.

To discuss the resistance of maize yields to climate stress we focus on the final yield because this experiment was designed to only reliably detect difference in soil moisture within and outside the shelters and not smaller differences between different treatments. We assume that effects on yields from treatment interactions with drought simulation are due to known mechanisms including greater infiltration and available soil moisture, common in CA systems with rotation and residue cover (Mupangwa et al., 2008; Govaerts et al., 2009; Thierfelder and Wall, 2009, 2010b; Castellanos-Navarrete et al., 2012; TerAvest et al., 2015). Data from eastern and southern Africa ($n = 39$ datasets) showed CA systems increase infiltration rates by 67% compared to conventional controls (Wall et al., 2014). Continous organic soil cover (*i.e.* crop residues) is critical to achieving enhanced water inflitration rates and no-till soils without cover can have lower infiltration rates (Wall, 1999; Govaerts et al., 2005; McHugh et al., 2007). Continous organic soil cover can also buffer soils against extreme temperatures minimizing another potential cause of yield limitation related to climate stress (Kassam et al., 2012). Greater infiltration rates are complemented by a greater soil mositure holding capacity in CA soils compared to tilled soils (see a review of the literature in Verhulst et al., 2010). Enhanced soil moisture availability under CA systems, due to increase soil moisture infiltration rates and holding capacity, results in greater resistance to in-seasonal dry-spells and this translates into increased grain yield at harvest (Mupangwa et al., 2008; Thierfelder and Wall, 2009, 2010b).

Whilst all experimental plots received adequate NPK fertilizer,

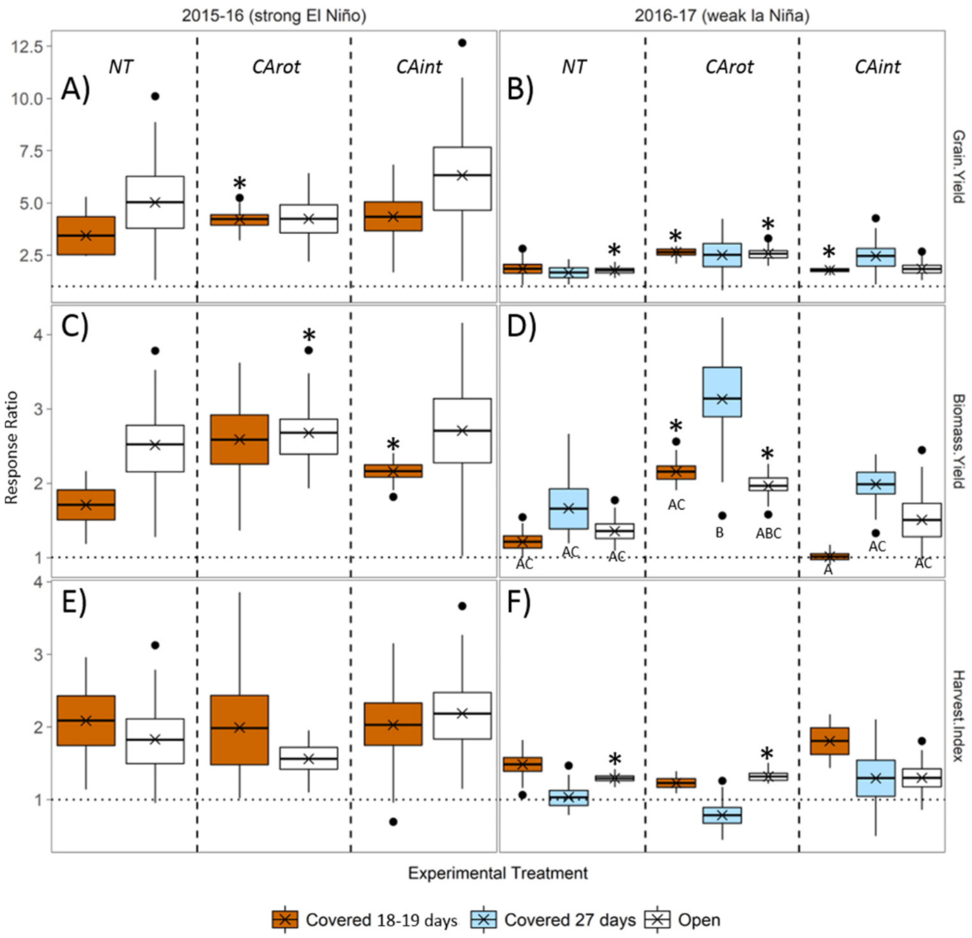

Fig. 4. Treatment effects (groups separated by vertical dashed lines) on the response ratios of maize performance indicators (grain yield A & B, biomass yield C & D, and harvest index E & F) under open (white boxes) and drought simulated conditions (orange/blue boxes) for the 2015–16 strong El Niño (left panels A, C & E) and 2016–17 weak El Niña events (right panels B, D & F). Boxplots were generated using bootstrapping with 10,000 replications (see Fig. 3 for interpretation of boxplots). Letters compare treatments within a year, if treatments share the same characters they are not significantly different according to posthoc pairwise *t*-tests ($p < 0.05$, FDR adjusted), if there are no letters in a plot panel then there was no significant difference between treatments. Asterisks “*” above a boxplot indicate the treatment was significantly different from parity with the control (*i.e.*, one) in posthoc tests, n = 4 per treatment (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

effects on yield stress resistance at the Chitedze long-term trial could arise from increased available P (Table 1) in CA systems (Waraich et al., 2011). In 2010–11 available P was three times higher in the upper soil profile in CA systems compared to the conventional control where available P was low (unpublished data collected by Ligowe et al., 2017). A non-target finding of this experiment was that the time to anthesis was shorter in CA and delayed in CP systems (6.2 and 9.2 days less under CA in 2015–16 and 2016-17, respectively). This is likely due to plants under CA systems making optimal use of soil moisture and finalizing all physiological growth stages without moisture stress induced delays, which was previously found for maize and sorghum (Craufurd et al., 1993; Craufurd and Peacock, 1993; Otegui and Bonhomme, 1998). There is limited published literature available on the interaction of drought and CA management on crop events, but studies of no-till effects on cotton production found a better resistance to dry-spells with cotton plants flowering for longer and producing higher yields under water stress compared to tilled plots (Naudin et al., 2010). A lower maize grain yield under conventional tillage might be a result of stress at anthesis, which influenced kernel number development after anthesis and ultimately the expression of grain yield (Otegui and Bonhomme, 1998; Fischer et al., 2014). In addition, enhanced availability of P in the upper soil profile as has likely added to early anthesis in CA and a delayed anthesis in the conventional tilled practice.

El Niño drought simulation had limited effects on soil moisture as both open and covered crops were exposed to a natural drought, as such there were no significant yield effects of drought simulation on cropping systems and we do not further focus on the effect on drought simulation during this season. However, all CA system still outyielded conventional practice in both open and covered areas and the effect size of these differences were greater than in the following La Niña. Rainfall was particularly low around anthesis in 2015–2016 (Fig. 2) so the significantly higher grain and biomass yields, and harvest index under eight year old CA treatments can still be considered as evidence for the enhanced resistance of CA systems to climate stress around anthesis as compared to conventional practice. In particular, the harvest index (HI) is considered an important stress indicator as drought will directly affect the commercial parts of maize (the grain) and the lower the harvest index the less grain can be found in the plant in comparison to the whole plant (Craufurd et al., 1993). Climate stress at anthesis in the *CP* treatment could therefore be expressed as reduced HI compared to CA treatments. This was the case when considering absolute yields, but not response ratios in 2015–2016.

The La Niña drought simulation had a much stronger effect on soil moisture and maize performance. Whilst the 19 day drought simulation had no effect on grain or biomass yields, it did reduce harvest index and the 27 day simulated drought significantly reduced both grain and biomass yields, and harvest index. With 19 days of drought simulation grain yield RRs significantly increased providing evidence that CA systems better resisted climate stress around anthesis. In normal years where rainfall is fairly well distributed at the onset of the cropping season, an in-season dry-spell, as represented by the La Niña 19 day drought simulation, will specifically favour CA systems as there will be enough soil moisture in reserve to “buffer” the dry spell (Thierfelder and Wall, 2010a). Under 27 days of drought simulation, there was no evidence for an enhanced climate stress resistance under CA systems, but is important to note that treatment yields were still significantly higher than *CP*.

In both season the likely reason for a lower grain yield under *CP* was a delay in anthesis, a strong indicator for climate stress at a critical

Table 2
Maize grain yield and harvest index as predicted by an interaction between treatment and drought simulation in linear regression models. Parameters: *CP* = tillage + crop residues removed + maize monoculture, *NT* = no-till + crop residue mulching + maize monoculture, *CArot* = *NT* + cowpea rotation, *CAint* = *NT* + cowpea intercrop, C18/C19/C27 = 18/19/27 day drought simulation, DV = dependent variable, DF = degrees of freedom and SE = standard error.

DV	Season	Model		Parameter	Estimate	SE	t value	Pr (> t)	Sig
Grain Yield	2015–16	DV	$\log_{10}$(Grain)	Intercept (open, control)	7.099	0.196	36.131	**0**	***
		F	10.51	*NT*	1.34	0.278	4.822	**0**	***
		DF	7 and 24	*CArot*	1.335	0.278	4.803	**0**	***
		p-value	0	*CAint*	1.526	0.278	5.492	**0**	***
		R.adj	0.68	+ C18	−0.017	0.278	−0.061	0.952	
				+ (*NT* x C18)	−0.134	0.393	−0.341	0.736	
				+ (*CArot* x C18)	0.091	0.393	0.232	0.818	
				+ (*CAint* x C18)	−0.195	0.393	−0.496	0.624	
	2016–17	DV	Grain	Intercept (open, control)	3272.4	389.3	8.406	**0**	***
		F	4.906	*NT*	2364.5	550.6	4.295	**0**	**
		DF	11 and 36	*CArot*	4931.1	550.6	8.956	**0**	***
		p-value	0	*CAint*	2511.7	550.6	4.562	**0**	**
		R.adj	0.85	+ C19	−740.3	550.6	−1.345	0.187	
				+ (*NT* x C19)	−516.5	778.6	−0.663	0.511	
				+ (*CArot* x C19)	−943.3	778.6	−1.211	0.234	
				+ (*CAint* x C19)	−595.2	778.6	−0.764	0.45	
				+ C27	−1788.2	550.6	−3.248	**0.003**	**
				+ (*NT* x C27)	−1598.9	778.6	−2.053	**0.047**	*
				+ (*CArot* x C27)	−3342.7	778.6	−4.293	**0**	***
				+ (*CAint* x C27)	−933.8	778.6	−1.199	0.238	
Harvest Index	2015–16	DV	Harvest Index	Intercept (open, control)	0.311	0.034	9.173	**0**	***
		F	4.28	*NT*	0.141	0.052	2.731	**0.012**	*
		DF	7 and 23	*CArot*	0.123	0.048	2.576	**0.017**	*
		p-value	0.004	*CAint*	0.13	0.048	2.721	**0.012**	*
		R.adj	0.43	+ C18	0.049	0.048	1.024	0.316	
				+ (*NT* x C18)	−0.022	0.071	−0.311	0.758	
				+ (*CArot* x C18)	−0.018	0.068	−0.261	0.797	
				+ (*CAint* x C18)	0.046	0.068	0.673	0.508	
	2016–17	DV	Harvest Index	Intercept (open, control)	0.42	0.028	15.024	**0**	***
		F	7.1	*NT*	0.064	0.04	1.612	0.116	
		DF	11 and 3	*CArot*	0.068	0.04	1.731	0.092	
		p-value	0.001	*CAint*	0.055	0.04	1.396	0.171	
		R.adj	0.61	+ C19	−0.109	0.04	−2.763	**0.009**	*
				+ (*NT* x C19)	0.022	0.056	0.397	0.694	
				+ (*CArot* x C19)	−0.025	0.056	−0.44	0.663	
				+ (*CAint* x C19)	0.077	0.056	1.378	0.177	
				+ C27	−0.096	0.04	−2.427	**0.02**	*
				+ (*NT* x C27)	−0.068	0.056	−1.219	0.231	
				+ (*CArot* x C27)	−0.138	0.056	−2.463	**0.019**	*
				+ (*CAint* x C27)	−0.034	0.056	−0.608	0.547	

growth stage for maize, which influenced kernel number and ultimately the expression of grain yield. Less stress was experienced in CA systems before and during anthesis which was measured as earlier anthesis and a more favourable grain development. Further research is necessary to better understand the mechanisms for different cropping systems under climate stress.

Previous research has highlighted the need for diversification and groundcover in CA, through intercropping or crop rotation, to increase productivity and enhance soil organic carbon (SOC) which in turn enhances water holding capacity and buffers against drought (Govaerts et al., 2009; Thierfelder and Wall, 2010b; Powlson et al., 2016). Here we find evidence to support the role of diversification through rotation, but less so for intercropping, in enhancing the resistance of CA yields under drought stress (diversity resistance hypothesis). In El Niño, biomass yields under drought simulation in the diversified CA rotation treatment (*CArot)* were higher than both undiversified “CA” with maize monoculture (*NT)* and conventional practice (*CP*), whereas *NT* did not differ from *CP*. In La Niña *CArot* had higher yields than *NT* and *CP* for grain with 19 day drought simulation and for biomass for both drought simulations, biomass yields in *NT* did not differ from *CP*. Response ratios (RRs) provided further evidence that diversified CA systems are more resistant to climate stress with yield RRs in diversified, but not undiversified, treatments usually significantly higher than parity with *CP* (outperforming CP) under 18–19 drought simulation. RRs indicated treatments outperformed CP for *CArot* grain yields in both seasons and for biomass in La Niña, and for *CAint* biomass yields in El Niño and grain yields in La Niña.

Drought simulation, not only reduced soil moisture it also increased daytime temperature with an effect in-line with predicted future increases in temperature due to global climate change (Burke et al., 2009; Cairns et al., 2012, 2013). Whilst these increases in temperature doubled exposure to heat stress under drought simulation, the effect size was small and it should be noted that maize exposure to extreme temperatures during the experiment was relatively low. The combined effect of heat and drought cause a non-linear decline in maize yields in African maize-growing areas and pose a serious threat to crop production (Schlenker and Lobell, 2010; Lobell et al., 2011) and meta-analysis has shown that CA systems are able to resist heat stress better than conventional tillage practices, especially on sandy and loamy soils (Steward et al., 2018). The fact that drought simulation increased temperatures as well as reducing soil moisture was a benefit, as there is some uncertainty as to the effects of global climate change on rainfall patterns in southern and eastern Africa (Oldenborgh et al., 2013), but heat stress is expected to be the strongest factor on crop yields for the next decades (Burke et al., 2009) with anticipated negative effects on physiologically reproductive stages (Gourdji et al., 2013).

Table 3
Response ratios (RR) of maize grain yields and harvest index. Response ratios (RR) here are calculated as (treatment/control -1) and treatments are tested to see if they are significantly different from zero (parity with the control), add one to estimates to get the actual response ratio. See Table 2 for parameter descriptions.

DV	Season	Model		Parameter	Estimate	SE	t value	Pr (> t)	Sig
RR grain (yield -1)	2015–16	F	6.444	*NT*	0.397	0.51	0.779	0.447	
		DF	6 and 17	*CArot*	0.913	0.442	2.067	0.054	.
		p-value	0.001	*CAint*	0.745	0.442	1.686	0.11	
		R.adj	0.587	+ C18	1.096	0.675	1.623	0.123	
				+ (*CArot* x C18)	−0.721	0.92	−0.783	0.444	
				+ (*CAint* x C18)	0.283	0.92	0.308	0.762	
	2016–17	F	8.504	*NT*	−0.179	0.149	−1.202	0.24	
		DF	9 and 27	*CArot*	0.195	0.149	1.309	0.202	
		p-value	0	*CAint*	−0.197	0.149	−1.322	0.197	
		R.adj	0.652	+ C19	0.455	0.211	2.159	0.04	*
				+ (*CArot* x C19)	0.205	0.298	0.687	0.498	
				+ (*CAint* x C19)	0.062	0.298	0.207	0.838	
				+ C27	−0.057	0.211	−0.269	0.79	
				+ (*CArot* x C27)	−0.098	0.298	−0.329	0.745	
				+ (*CAint* x C27)	0.277	0.298	0.93	0.361	
RR (harvest index -1)	2015–16	F	3.619	*NT*	1.086	0.57	1.906	0.074	.
		DF	6 and 17	*CArot*	0.981	0.494	1.987	0.063	.
		p-value	0.017	*CAint*	1.029	0.494	2.085	0.052	.
		R.adj	0.406	+ C18	−0.264	0.754	−0.351	0.73	
				+ (*CArot* x C18)	−0.156	1.028	−0.152	0.881	
				+ (*CAint* x C18)	0.417	1.028	0.405	0.69	
	2016–17	F	4.458	*NT*	0.484	0.183	2.642	0.014	*
		DF	9 and 27	*CArot*	0.229	0.183	1.251	0.222	
		p-value	0.001	*CAint*	0.806	0.183	4.397	0	***
		R.adj	0.464	+ C19	−0.191	0.259	−0.736	0.468	
				+ (*CArot* x C19)	0.28	0.367	0.764	0.452	
				+ (*CAint* x C19)	−0.315	0.367	−0.859	0.398	
				+ C27	−0.452	0.259	−1.745	0.092	.
				+ (*CArot* x C27)	0.008	0.367	0.022	0.983	
				+ (*CAint* x C27)	−0.059	0.367	−0.162	0.873	

The yield benefits of CA as compared with the conventionally tilled treatments without residue retention at this trial were striking, emphasising the importance of the eight years of no-till and crop residue mulching management prior to the start of drought manipulations in this experiment. This is in-keeping with literature demonstrating the yield improvements under CA with increasing time since reduced or no-till implementation (Rusinamhodzi et al., 2011; Brouder and Gomez-Macpherson, 2014; Corbeels et al., 2014; Thierfelder et al., 2015). As such, it is important to frame the findings of this study in the temporal context of the trial; CA benefits are unlikely to be apparent when CA has only been practiced for a few seasons and yield benefits are usually measured after two to five cropping seasons, as found in a recent cross regional study (Thierfelder et al., 2015).

The need for evidence-based climate-smart solutions for smallholder crop production under current and future climatic stresses is clear. Waiting for the occurrence of natural droughts to test the climate resistance of a farming method may not be an efficient strategy, especially in areas where droughts are rare or unpredictable. Here, we have practically demonstrated rainout shelters can be used to quickly establish crop performance under climate stress by controlling rainfall *in-situ*. This method can greatly increase the rate at which we accumulate evidence for the resistance of a farming method. Rainout shelters, for example, could be used to evidence crop varietal performance under a range of climates on a specific soil type in a single year. Drought simulators could also be used to establish the climatic thresholds under which adoption of climate-smart practices can buffer crop performance against drought and/or thermal stress. Crop and system performance could be explored under novel climate envelops that do not currently exist, but may do so in future with climate change, this would provide evidence to future proof agricultural decision making.

5. Conclusion

CA systems better resisted climate stress around anthesis than conventional tillage practices as CA systems showed greater resistance to drought than conventional practice. This was expressed by higher CA maize grain yields, biomass yields or harvest index under conditions of natural (El Niño) or 19 day simulated drought. However, under 27 day drought simulation the resistance benefit of CA was no-longer significant. Crop diversification improved the resistance of CA systems to climate stress, more so when diversification was over time (rotation) than in space (intercropping). In all years CA systems substantially outyielded conventional practice, this highlights the benefits of medium-term (eight years) CA management before the rainout shelter experiment started.

Large scale rainout shelters proved effective in reducing soil moisture *in-situ*, they should be used to quickly fill in the substantial knowledge gaps that exist for the effect of time on climate resistance in those farming practices where benefits to accrue over time.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2018.07.009.

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