Agriculture, Ecosystems and Environment 251 (2018) 194–202

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Research Paper

The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: A meta-regression of yields

Peter R. Steward[a,*], Andrew J. Dougill[a], Christian Thierfelder[b], Cameron M. Pittelkow[c], Lindsay C. Stringer[a], Maxwell Kudzala[d], Gorm E. Shackelford[e]

[a] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, United Kingdom
[b] CIMMYT, P.O. Box MP 163, Mount Pleasant, Harare, Zimbabwe
[c] Department of Crop Sciences, University of Illinois, Urbana, Illinois 61801, USA
[d] Chitedze Agricultural Research Station, Maize Agronomy Section, P.O.Box 158, Lilongwe, Malawi
[e] Department of Zoology, University of Cambridge, Cambridge, CB2 3EJ, United Kingdom

ARTICLE INFO

Keywords:
Climate-smart agriculture
Sustainable agriculture
Climate change
Drought
No-till
Africa

ABSTRACT

Conservation agriculture is widely promoted across sub-Saharan Africa as a sustainable farming practice that enhances adaptive capacity to climate change. The interactions between climate stress, management, and soil are critical to understanding the adaptive capacity of conservation agriculture. Yet conservation agriculture syntheses to date have largely neglected climate, especially the effects of extreme heat.

For the sub-tropics and tropics, we use meta-regression, in combination with global soil and climate datasets, to test four hypotheses: (1) that relative yield performance of conservation agriculture improves with increasing drought and temperature stress; (2) that the effects of moisture and temperature stress exposure interact; (3) that the effects of moisture and temperature stress are modified by soil texture; and (4) that crop diversification, fertilizer application rate, or the time since no-till implementation will enhance conservation agriculture performance under climate stress.

Our results support the hypothesis that the relative maize yield performance of conservation agriculture improves with increasing drought severity or exposure to high temperatures. Further, there is an interaction of moisture and heat stress on conservation agriculture performance and their combined effect is both non-additive and modified by soil clay content, supporting our second and third hypotheses. Finally, we found only limited support for our fourth hypothesis as (1) increasing nitrogen application rates did not improve the relative performance of conservation agriculture under high heat stress; (2) crop diversification did not notably improve conservation agriculture performance, but did increase its stability with heat stress; and (3) a statistically robust effect of the time since no-till implementation was not evident.

Our meta-regression supports the narrative that conservation agriculture enhances the adaptive capacity of maize production in sub-Saharan Africa under drought and/or heat stress. However, in very wet seasons and on clay-rich soils, conservation agriculture yields less compared to conventional practices.

1. Introduction

Maize yield gaps are high in sub-Saharan Africa, with yield trends stagnant or falling across large areas (Ray et al., 2012; van Ittersum et al., 2013). Closing these gaps and reversing yield declines is a priority, but greater sensitivity to drought may accompany increases in maize yield (Lobell et al., 2014). Drought stress and extreme temperatures interact in a synergistic fashion to reduce maize yields, as drought reduces maize's ability to cope with excessive heat (Lobell et al., 2011). Whilst arable agriculture across large areas of sub-Saharan Africa is already exposed to climate stress, climate change is predicted to further increase risks of both extreme temperatures and drought (Niang et al., 2014) and negative impacts on crop yields are expected (Schlenker and Lobell, 2010; Lobell et al., 2011). Recent projections suggest that there will be an increase in average air temperature of approximately 2.1 °C throughout sub-Saharan African maize growing

---

[*] Corresponding author.
E-mail addresses: p.r.steward@leeds.ac.uk, peetmate@gmail.com (P.R. Steward), a.j.dougill@leeds.ac.uk (A.J. Dougill), C.Thierfelder@cgiar.org (C. Thierfelder), cmpitt@illinois.edu (C.M. Pittelkow), l.stringer@leeds.ac.uk (L.C. Stringer), maxwellkudzala90@gmail.com (M. Kudzala), gorm.shackelford@gmail.com (G.E. Shackelford).

http://dx.doi.org/10.1016/j.agee.2017.09.019
Received 28 April 2017; Received in revised form 19 September 2017; Accepted 21 September 2017

regions by 2050 (Cairns et al., 2013). This has the potential to drastically reduce the production of major food crops, including maize and wheat (Lobell et al., 2008). At the same time, areas may be affected by an increased risk of extreme rainfall, potentially reducing crop production through waterlogging and leaching (Cairns et al., 2013; Niang et al., 2014).

In response to increasing threats to food security and livelihoods, the Food and Agriculture Organization of the United Nations (FAO) developed the framework of climate-smart agriculture (Palombi and Sessa, 2013; Lipper et al., 2014). In this framework, a farming technology is considered climate-smart when it meets three complementary criteria: (1) it sustainably increases agricultural productivity; (2) it adapts and builds resilience to climate change; and (3) it creates opportunities to reduce greenhouse gas emissions and sequester carbon (Lipper et al., 2014). A range of agricultural systems have been considered climate-smart, including conservation agriculture, agroforestry, improved cereal-legume systems, alternate wetting and drying in rice, improved rangeland management, targeted fertilizer application and drought tolerant germplasm (Rosenstock et al., 2016; Thierfelder et al., 2017). These systems require scrutiny to establish whether they meet climate-smart criteria and if they still deliver benefits under increasingly variable climates (Thierfelder et al., 2015c, 2017; Powlson et al., 2016).

African governments and institutions have started advocating and promoting climate-smart agriculture. Its scaling-up has become a central component of the development agenda to increase production, food security and climate change adaptation (Andersson and D'Souza, 2014; Whitfield et al., 2015). Conservation agriculture is an especially important form of climate-smart agriculture (Richards et al., 2014) defined by three key principles (Kassam et al., 2009; Wall et al., 2014): (1) direct planting of crops with minimum soil disturbance, (2) permanent soil cover by crop residues or cover crops, and (3) crop rotation or association (crop diversification). It offers a range of key benefits and ecosystem services that are associated with climate adaptation such as increased water infiltration, reduced evaporation of soil moisture, reduced soil erosion and run-off, and the ability to plant early (Thierfelder et al., 2017). Conservation agriculture systems may sequester carbon and reduce greenhouse gas emissions under optimal conditions, but the results from southern Africa are often variable and inconclusive depending on the context (Cheesman et al., 2016; Kimaro et al., 2016; Powlson et al., 2016).

Given the increasing emphasis on conservation agriculture in sub-Saharan Africa, an important research gap is that its yield benefits have not been systematically assessed under climate stress for different soils and land management situations. Understanding the importance of context to conservation agriculture yields is essential because African farming systems are complex varying between different contexts (Richards et al., 2014).

Meta-analyses comparing yields from conservation vs. conventional agriculture have typically explored climate, management, or soil effects using simplistic categorical approaches, for example contrasting high and low rainfall or soil texture classes (Rusinamhodzi et al., 2011; Corbeels et al., 2014a; Pittelkow et al., 2015). These syntheses have shown that the yield performance of conservation agriculture compared to conventional practices improves (1) on well-drained soils (Rusinamhodzi et al., 2011; Corbeels et al., 2014b; Nyamangara et al., 2014), (2) in dry environments (Rusinamhodzi et al., 2011; Ogle et al., 2012; Wall et al., 2014; Pittelkow et al., 2015), (3) with increased time since reduced or no-till implementation (Rusinamhodzi et al., 2011; Brouder and Gomez-Macpherson, 2014; Corbeels et al., 2014b; Thierfelder et al., 2015a), (4) with increasing nitrogen fertilizer application rate (Rusinamhodzi et al., 2011; Corbeels et al., 2014b), and (5) with crop diversification (Rusinamhodzi et al., 2011; Pittelkow et al., 2015). However in all these previous studies, the effects of climate have only been explored by grouping results into broad precipitation categories (Rusinamhodzi et al., 2011; Corbeels et al., 2014b; Pittelkow et al., 2015). Given the diverse combinations of climates, soils and socio-economic conditions found across sub-tropical farming environments, this use of broad categorical approaches is inadequate.

Another research gap is a lack of knowledge about the effects of heat stress on the relative yields of conservation agriculture and ploughed tilled systems. In African maize-growing areas, yield reductions associated with increasing temperatures have been found to be were exacerbated by drought, with yields declining in a non-linear fashion (Lobell et al., 2011). Further, the interaction of soil and management variables with climate stress conditions has not been quantified.

In this study, we provide the first assessment of the adaptive capacity of conservation agriculture to heat and water stress, including interactions with management and soil. Using a novel combination of field data, geospatial soil data, and historical climate data, we used meta-regression to compare maize yields from conservation agriculture (continuous soil surface cover and no-tillage or minimal tillage) and conventional agriculture (substantial soil disturbance through tillage and minimal permanent soil cover).

We tested four hypotheses: (1) the relative yield performance of conservation agriculture improves with increasing drought severity or exposure to high temperatures; (2) the effects of moisture stress and exposure to high temperatures on the relative yield performance of conservation agriculture is non-linear rather than additive (i.e. they will interact); (3) the relative yield performance of conservation agriculture under climate stress (moisture or heat) is affected by soil texture; and (4) fertilizer application rate, the time since no-till implementation, and crop diversification are expected to enhance the relative yield performance of conservation agriculture, in particular under drought and/or heat stress.

2. Materials and methods

2.1. Data collection

2.1.1. Meta-dataset

To maximise search efficiency, conservation agriculture or no-till studies were collated from datasets compiled for existing syntheses (Table A.1). These were found using a Web of Science search on 10/01/2016, using the terms ‘tillage’, ‘no till’, ‘zero till’, ‘direct drill’, or ‘conservation ag*’ in the article title and ‘review' or ‘meta-analysis' or ‘synthesis' in the article topic. Any further syntheses cited in these publications were also considered. This gave a total of 715 independent studies for screening from three global analyses (Nyamangara et al., 2014; Farooq and Siddique, 2015), including one meta-analysis of 643 studies (Pittelkow et al., 2015), three African analyses (Bayala et al., 2012; Corbeels et al., 2014a; Wall et al., 2014) and one analysis focussing on smallholders (Brouder and Gomez-Macpherson, 2014). The studies from previous syntheses were updated with recent publications using a Web of Science search. The search used the terms “tillage”, ‘no till’, ‘zero till’, ‘direct drill’, or ‘conservation ag*’ in the article title, ‘yield’ in the article topic, and covered the period 01/01/2014 to 17/02/2016. These studies were then screened as per the criteria of Pittelkow et al. (2015): (1) studies had to be field experiments containing side-by-side comparisons of no-till and conventional tillage practices; (2) no-till treatments consisted of nil or extremely limited tillage immediately before crop establishment for a given growing season (reduced-tillage treatments such as strip-tillage were rejected); (3) crop yields were reported; (4) the location of the experiment was stated; and (5) other than differences in residue, crop rotation or intercrop management, confounding effects between treatments were negligible. Studies were rejected if it was unclear whether factors in (5) differed between treatments. As the absence of tillage as a weed or pest control strategy generally requires changes in herbicide and pesticide management under no-till (Farooq et al., 2011), differences between treatments in herbicide pesticide management were acceptable. If multiple types of tillage were presented in a study, the deepest and/or

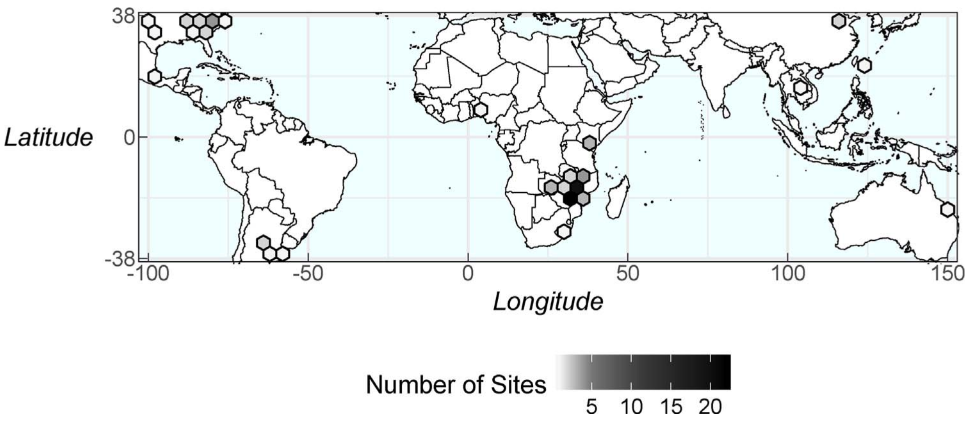

Fig. 1. Global distribution of study sites contributing observations to the meta-dataset used in this analysis. Hexagons are 4 by 4 ° regions shaded by the number of sites they contribute. See Table A.4 for more details.

most disruptive was chosen as the control. After screening, the Web of Science search contributed a further 157 studies to the study pool.

The combined pool of 872 studies was then subjected to a second screening because the alignment of yield observations with historical climate data requires temporal and spatial precision in experimental reporting. These criteria were: (1) precise planting dates were reported; (2) the study location was presented with a minimum accuracy of 0.1 decimal degrees and was between the 38th parallels; (3) maize yields were presented in disaggregated form in both time and space (but small-scale local spatial aggregation was acceptable, such as average yields from multiple farmers in a village); (4) no irrigation was used; and (5) the rate of elemental nitrogen application was calculable. More details on selection criteria are presented in Table A.2. Where possible, study authors were contacted to resolve issues such as missing or ambiguous information and/or aggregated yield data.

The final meta-dataset (B.1) contained 1042 observations from 85 sites in 42 publications (Table A.3), it covers the period 1984–2013 (Fig. 1, Table A.4). Fewer observations and studies were included compared to Pittelkow et al. (2015) due to our more stringent data reporting criteria, and because 51% of their observations were beyond 38th parallels. Our screening process reveals that accessible, published conservation agriculture research from the sub-tropics, of a high reporting standard suitable for this meta-analysis, is concentrated in the southern USA (13.3% of observations) and south-east Africa (84.7% of observations).

2.1.2. Model parameters

Temperature and moisture stress were examined for the growing season (planting to maturity) and ten days either side of anthesis, as maize is sensitive to heat and drought stress at this stage (Schlenker and Roberts, 2009; Lobell et al., 2011). The parameters required to determine climate stress, including records of daily minimum and maximum temperature, average wind speed, precipitation and air pressure, were derived from weather station data. This information came directly from the authors of studies or from the Global Surface Summary of the Day database (GSOD; [Dataset] NCDC et al., 2016). Data from the closest weather station to each site were selected (stations had to be within a radius of 50 km and no more than 250 m different in altitude). Where differences in altitude between a weather station and site existed, temperatures were adjusted to site elevation using the international standard atmosphere, $T = T_0 – 6.5(h/1000)$, where T is the temperature (°K) and h the difference in height (m) between weather station and study site. Air pressure was also adjusted to site altitude, using a simplification of the ideal gas law assuming 20 °C for a standard atmosphere (Zotarelli et al., 2010).

When weather station data was not available, the AgMERRA Climate Forcing Dataset for Agricultural Modeling ([Dataset] Ruane et al., 2015) and Prediction Of Worldwide Energy Resource (POWER; [Dataset] NASA, 2016) climate datasets provided historical records of wind speed and daily maximum and minimum temperatures. The HOAPS/GPCC global daily precipitation data record with uncertainty estimates using satellite and gauge based observations Version 1 ([Dataset] Andersson et al., 2016) and Tropical Rainfall Measuring Mission Version 7 3B42 (TRMM; Huffman et al., 2010; [Dataset] GES DISC, 2016) datasets provided records of precipitation (Figs. A.1 and A.2). All measures of relative humidity came from the POWER dataset, limiting the historical reach of climate data to 1984. Solar radiation values came from the POWER or AgMERRA datasets. All wind speed observations were standardised to 2 m above ground level using the equation $\mu_2 = 4.87\mu_h/\ln(67.8\,h - 5.42)$ where μ = measured wind speed (ms^{-1}) and h = height of observation (m) above the ground surface (Zotarelli et al., 2010). Table 1 details the proportion of meta-dataset observations using climate data from different data sources.

Moisture stress around anthesis and for the growing season, referred to as precipitation balance (PB) in models, was assessed as the difference between precipitation minus potential evapotranspiration (PET) calculated using the Penman-Monteith method (Zotarelli et al., 2010). Potential evapotranspiration was chosen to represent moisture stress as it is a proxy for soil moisture availability that takes into account the loss of moisture through evaporation and transpiration. Potential evapotranspiration also produced global meta-regression models with lower Akaike information criterion (AIC) values compared to models using total precipitation, number of dry days or longest continuous period of

Table 1
Details of climate datasets and the percentage of observations (n = 1042) using each dataset for each climate variable used in analysis. Weather station data includes GSOD data and information provided directly by study authors. See Figs. A.1 and A.2 for data selection decision trees.

Dataset	Variable(s)	Years	Resolution (degrees)	% of observations
Weather Station	Air Pressure (kPa)	1984–2013	NA	41.2
Weather Station	Mean, Min and Max Daily Temp (°C)	1984–2013	NA	26.8
AgMERRA		1984–2010	0.5	36.9
POWER		2011–2013	1	36.3
Weather Station	Precipitation (mm day^{-1})	1984–2013	NA	72.2
TRMM		1998–2013	0.25	23.9
HOAPS/ GPCC		1988–1997	1	3.9
POWER	Relative Humidity at 2 m (%)	1984–2013	1	100
AgMERRA	Solar Radiation ($MJ\,m^{-2}\,day^{-1}$)	1984–2010	1	47.9
POWER		2011–2013	1	52.1
AgMERRA	Wind Speed (ms^{-1})	1984–2010	0.25	36.9
POWER		2011–2013	1	37.4
Weather Station		1984–2013	NA	25.7

dry days to represent moisture stress. A decision tree illustrating which data sources were used to calculate PET is shown by Fig. A.2. If any climate data were unavailable across all sources for an observation, then it was excluded from analysis.

Temperature effects on maize were investigated using two measures of summed growing degree days (GDD) using the formula: $GDD_{base,opt} = \sum_{t=1}^{N} DD_t$, DD = $\left\{ \begin{matrix} 0 & \text{if } T_t < T_{base} \\ T - T_{base} & \text{if } T_{base} < T_t < T_{opt} \\ T_{opt} - T_{base} & \text{if } T_T > T_{opt} \end{matrix} \right\}$ where 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 daily minimum and daily maximum temperatures using a sin curve) and N is the number of hours between sowing and maturity dates, the full growing season, or for a 21-day period centred around anthesis. Two measures of GDD, $GDD_{8,30}$ ($T_{base} = 8$ °C and $T_{opt} = 30$ °C) and GDD_{30+} ($T_{base} = 30$ °C and $T_{opt} = \infty$), represented temperature. 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). Where publications did not report maturity date, growing season length was estimated as the period between sowing and harvest dates (64% of observations). If maturity and harvest dates were not available, then crop calendars ([Dataset] Sacks et al., 2010) were used to estimate the growing season from a 5 min grid (6% of observations). Where anthesis dates were not reported, general information regarding the number of days to anthesis (DTA) was sought from seed companies or varietal field trials for the maize variety in question. When varietal DTA was unavailable (56% of observations), observation anthesis date was estimated from maturity date or growing season length, by applying a conversion factor (0.52) averaged from DTA divided by DTM (days to maturity) for the 20 maize varieties which have these data available in the meta-dataset (Table A.5).

Where soil texture (the percentage of sand, silt and clay at 0–20 cm depth) was presented as a textural class only fractional percentages were estimated using USDA classifications (NRCS, 2007). If soil texture was not reported ($< 1\%$ observations), data was substituted from the Soil Survey Geographic database (SSURGO; [Dataset] NRCS, 2016), Africa Soil Information Service (AfSIS; [Dataset] Kempen et al., 2015) or 1 km SoilGrids system (Hengl et al., 2014a; [Dataset] Hengl et al., 2014b). A detailed decision tree for determining soil texture is presented in Fig. A.3 . Because soil textures were correlated, only one parameter at a time was tested in global models, with percentage clay selected in the final model because it gave global models with the lowest AIC values.

All fertilizer application rates reported in publications were converted to rates of elemental nitrogen application (kg N ha^{-1}), including manures (following Bouldin et al., 1984).

No-till duration was the time in 0.5 year intervals since the implementation of no-till. If tillage occurred in a no-till system, the no-till duration was reset to time zero with each tillage event. For example, if tillage occurred during the legume phase of a legume–maize rotation during six consecutive years, each maize yield observation was recorded as the first year under no-till.

Crop diversification was defined as the presence of an intercrop or crop rotation. Crop rotation was defined as a crop (or land-use such as fallow or pasture) other than maize, at the same location within the previous calendar year. If the crop sequence prior to the first season of experimentation was not reported for an observation it was assumed crop rotation had not occurred. An intercrop was defined as the simultaneous presence of a different crop to maize typically planted between maize rows.

2.2. Data analysis

In continuity with previous conservation agriculture meta-analysis (Pittelkow et al., 2015), the natural log of the response ratio (RR), the ratio of conservation agriculture (CA) yields to conventional practice (CP) yields from the paired comparison of individual studies, was calculated as the dependent variable using the equation $\ln(RR) = \ln(Yield_{CA}/Yield_{CP})$ (Hedges et al., 1999). All paired comparisons required continuous soil surface cover and reduced-tillage for conservation agriculture, but not crop diversification (which was included as an independent variable). Observations with zero yields were excluded from the meta-dataset, as were observations with a response ratio more than five standard deviations from the weighted mean response ratio as per Pittelkow et al. (2015).

Individual observations were weighted by replication, plot area, and yield sampling area. This was because within-study variance measures for mean yields were only available for a small proportion of studies. Studies with more replications and larger plots and/or larger yield sampling areas are likely to produce less variable information than studies with small plots and/or small yield sampling areas. As such, response ratios in our study were weighted using replication (Adams et al., 1997; Pittelkow et al., 2015), but improved to include two further indicators of precision: plot area and yield sampling area. This gave the equation: observation weight $= \sqrt[3]{(((n_{CP} \times n_{CA})/(n_{CP} + n_{CA})) \times (a/2\surd a) \times (s/2\surd s))}$, where a = area sampled for yield (m^2), s = plot area (m^2) and n = number of replicates for conventional practice (n_{CP}) and conservation agriculture treatments (n_{CA}). Replication, plot area, and yield sampling area were weighted evenly. We observed that multiplying weighting terms and taking the cube root resulted in a normal distribution of observation weightings, whereas summing terms and taking the average resulted in a positively skewed distribution with a long tail, hence the former approach was chosen. The square root of replication number and yield sampling area were taken to avoid the rapid inflation of weighting with area, again preventing influential outliers in the distribution of weights.

Meta-regression used generalized linear mixed effects models. Starting model fixed effects included interactions between precipitation balance, GDD_{30+}, $GDD_{8,30}$ and no-till duration (Rusinamhodzi et al., 2011; Brouder and Gomez-Macpherson, 2014; Corbeels et al., 2014b). To explore the influence of context and management, fixed effects were included for interactions between climate stress and each of these variables: crop diversification (Rusinamhodzi et al., 2011; Pittelkow et al., 2015), soil texture (Rusinamhodzi et al., 2011; Corbeels et al., 2014b), and elemental nitrogen application rate (Rusinamhodzi et al., 2011; Corbeels et al., 2014b). Models included random intercepts for study, nested within location, nested within country (n = 85) and calendar year (n = 28), to ensure that any perceived effects of climate were not due to difference between sites or years. Moran's I test indicated spatial auto-correlation was minimized by random-effect terms.

Backwards stepwise model selection using AICc (AIC with a correction for finite sample sizes) was used to simplify models. The reliability of final model coefficients, confidence intervals, and significance values was tested using bootstrapping with 10,000 simulations (Table A.6). In addition, model averaging was used to confirm model formulation and check that alternative formulations with a similar AICc ($\Delta = 2$) were similar to the best performing model (model with lowest AICc). Bootstrapping of averaged models was not possible in the version of the MuMIn R package (Barton, 2016) used here.

Model predictions are derived from model fixed effects only with non-focal predictors held at median values, apart from the time, since reduced or no-till implementation across which results are averaged.

3. Results

3.1. Meta-regression model

Growing season precipitation balance (*PB*), heat stress (GDD_{30+}) and heat ($GDD_{8,30}$) around anthesis were the best predictors of relative yield performance ($\log_e(RR)$) in global models. The final model was $\log_e(RR) = (GDD_{30+} \times GDD_{8,30} \times SD) + (PB \times GDD_{30+} \times CD) + (PB \times GDD_{30+} \times CL) + (GDD_{30+} \times GDD_{8,30} \times PB) + (GDD_{30+} \times NF) + (1\,|\,Country{:}Site{:}Study) + (1 \;|\; Year)$, where SD = the duration of reduced-tillage in the conservation agriculture treatment, CD = crop diversification (nominal variable with three classes: no crop diversification in either treatment, crop diversification in both treatments, or crop diversification in conservation agriculture only), CL = percentage of clay (depth 0–30 cm), and NF = elemental nitrogen applied in fertilizer (kg ha^{-1}). Bootstrapped model coefficients are presented in Table A.6. Model AIC was −75.0 with residual degrees of freedom n = 1010. The random-effect intercept variance and its standard deviation were 0.059 ± 0.243 for the spatial term $(1\,|\,Country{:}Site{:}Study)$, 0.0272 ± 0.165 for the temporal term $(1\,|\,Year)$ and 0.139 ± 0.372 for residual variance. Nakagawa and Schielzeth's method (Nakagawa and Schielzeth, 2013) was used to calculate final model marginal and conditional R^2, which were 0.44 and 0.10, respectively.

Given the limited number of variables included in our model, a high degree of unexplained variance in relative conservation agriculture yield performance is unsurprising. Response ratio variance accounted for by random effects (conditional R^2–marginal R^2 = 0.34) is due to differences between sites in omitted climate, management, soil, or agroecological variables and their interactions. Response ratio variance unaccounted for by random effects (1–conditional R^2 = 0.55) may be due to differential responses between conservation agriculture and conventional practice treatments within study sites due to variables other than climate, soil texture, or nitrogen fertilizer application rate (such as pests, diseases, and their management), errors in estimates of soil or climate variables from geo-spatial datasets, or the timing of crop phenological events. The within-site source of error will be hard to account for in modelling, even with more data, and reflects the need for conservation agriculture to be tested and tailored to local conditions, even when general predictions suggest it is likely to outperform conventional practice.

3.2. Climate stress

Results show that precipitation balance (indicating positive and negative moisture stress) and heat stress risk at anthesis (defined as $\log_e(GDD_{30+} + 1)$) have a non-linear effect (i.e. there is an interaction between them) on conservation agriculture yield performance relative to conventional practice (Fig. 2). Yields under conservation agriculture are generally greater than conventional practice in growing seasons with a precipitation balance less than 200 mm and increase as it becomes drier (Fig. 2, Fig. A.5). Heat stress also affects conservation agriculture performance, but this depends on soil clay content which forms a significant three-way interaction with both heat and moisture stress.

3.3. Soil texture

The combined effects of heat and moisture stress on the relative yield performance of conservation agriculture clearly change as soil clay content increases. When soil clay content is low (< 5% clay) conservation agriculture only underperforms conventional practice in wet seasons (seasonal precipitation balance of 500 mm or more) when there is low heat stress (top left corner of left panel, Fig. 2). Even in wet seasons, on low clay sandy or silty soils, which represent the majority of soils in southern Africa (Nyamapfene, 1991), rising heat stress eventually increases conservation agriculture yields beyond those of conventional practice (top right corner of left panel, Fig. 2). However, the relative yield performance of conservation agriculture was not greatest under conditions of drought and heat stress (bottom right corner of left panel, Fig. 2).

As soil clay content increases, in wet seasons, the positive effect of increasing heat stress on conservation agriculture performance reduces (top, left vs. middle panel, Fig. 2) and eventually has a negative effect when soil clay content is high (top, right panel, Fig. 2). However, when there is drought the opposite occurs, with conservation agriculture increasingly outperforming conventional practice with rising heat stress (bottom, right panel, Fig. 2).

Under drought conditions conservation agriculture performance is most stable at intermediate levels of soil clay content (middle panel, Fig. 2).

3.4. Nitrogen application rate

There was a significant interaction between heat stress and the rate of nitrogen application on the relative yield performance of conservation agriculture ($p \le 0.05$, Fig. 3). In general, Fig. 3 shows that given a modest rainfall surplus (154 mm) on intermediate clay soils (25% clay), conservation agriculture yields outperform conventional practice for any combination of heat stress and nitrogen application rate, but especially when heat stress is high and nitrogen application rate low (bottom right corner, Fig. 3). When heat stress risk is high, the positive relative yield benefit of farming under conservation agriculture lessens as more nitrogen is added to both treatments, but still remains positive overall even at very high levels of nitrogen application (bottom right to top right corner, Fig. 3). Conversely, increasing the rate of nitrogen application when there is little to no heat stress (< 1 GDD_{30+}) enhances conservation agriculture performance and this positive effect of nitrogen application attenuates with increasing heat stress risk

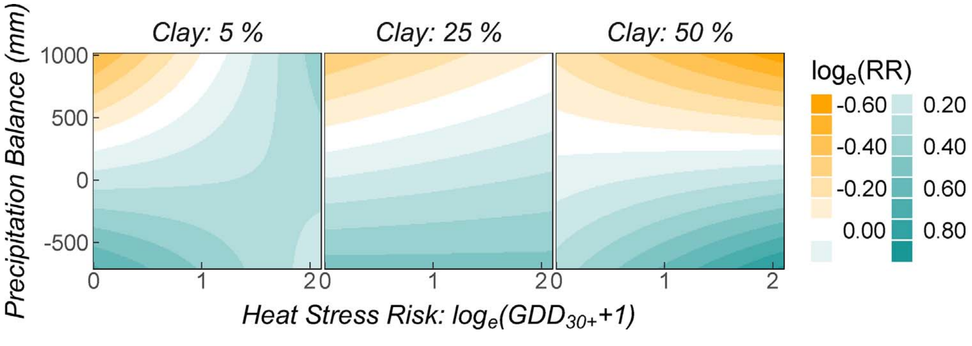

Fig. 2. The effect of heat stress at anthesis ($\log_e(GDD_{30+} + 1)$) and growing season precipitation balance (precipitation – potential evapotranspiration) on maize yield response ratios ($\log_e(RR)$) comparing conservation agriculture to conventional practice. Panels depict the effects of climate stress as modified by soil texture for low (left), medium (middle), and high (right) soil clay contents. Negative values of precipitation balance, toward the bottom of panels, indicate a rainfall deficit. Blue colours in the graph indicate conservation agriculture outperforms conventional practice and vice-versa for orange. Predictions include crop diversification in conservation agriculture systems (additional predictions with no crop diversification are presented in Fig. A.4 and Fig. A.7.

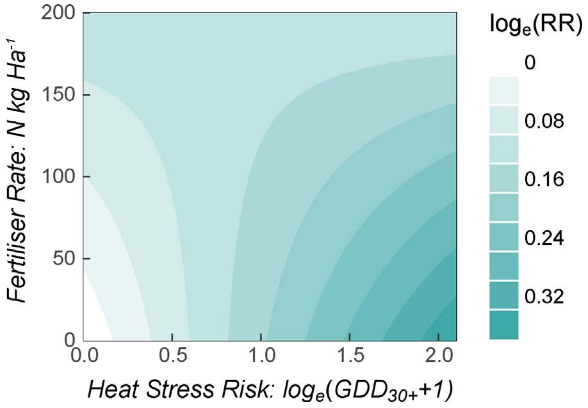

Fig. 3. The effect of heat stress risk at anthesis ($\log_e(GDD_{30+} + 1)$) and nitrogen fertilizer rate on maize yield response ratios ($\log_e(RR)$) derived from comparing conservation agriculture to conventional practice. All values of conservation agriculture relative yield performance in this figure are positive, with increasing performance shown by darker shades of blue. Predictions include crop diversification in conservation agriculture systems (predictions without crop diversification are shown in Fig. A.10). Predictors that have no interaction with fertilizer were set to median values; precipitation balance = 154 mm and soil clay content = 25%. Errors are presented in Fig. A.11 and Fig. A.12.

3.5. Time since no-till implementation

We cannot statically confirm that the duration of no-till or reduced-tillage improved the relative yield performance of conservation agriculture compared to conventional practice under climate stress. There was a significant interaction of the duration of no-till with climate predictors in initial model selection but this was not retained after bootstrapping ($p > 0.05$, Table A.6).

3.6. Crop diversification

We found a significant three-way interaction of crop diversification with both measures of climate stress ($p \leq 0.05$, Fig. 4). The performance of full conservation agriculture (including crop diversification) changed less under heat stress (bottom panel, Fig. 4) compared to no-till or reduced-tillage and soil surface cover alone (top panel, Fig. 4). With crop diversification, conservation agriculture performance is relatively stable under heat stress, unless there is a high rainfall surplus, in which case increasing heat stress reduces the negative yield impacts compared to conventional practice. Conversely, without crop diversification, rising heat stress and falling precipitation balance increasingly improved the relative yield performance of conservation agriculture.

4. Discussion

Using a meta-dataset of tropical and sub-tropical studies, primarily from sub-Saharan Africa and, to lesser degree, the southern USA, we evaluated the relative maize yield performance of conservation vs. conventional agriculture under moisture and heat stress.

Our results show that conservation agriculture performance increases relative to conventional practice under scenarios of drought and/or heat stress, which supports our first hypothesis. This is in line with previous syntheses that found conservation agriculture to perform better in dry environments with seasonal rainfall deficits as compared with conventional agriculture practices (Rusinamhodzi et al., 2011; Ogle et al., 2012; Thierfelder et al., 2014; Baudron et al., 2015; Pittelkow et al., 2015). Mechanisms underlying the enhanced relative yield performance of conservation agriculture in dry environments may include increased infiltration and soil moisture retention, reduced evaporation due to residue cover, greater water holding capacity, and a better soil pore system (Kassam et al., 2012; Farooq and Siddique, 2015; Thierfelder et al., 2017). A better response with increasing heat stress under conservation agriculture can be attributed to temperature moderation on residue covered soils, which reduces the daily temperature amplitude (Hobbs, 2007). This reduces heat stress during critical growth stages (i.e. germination, early plant development, anthesis and silking), all of which affect yield (Cairns et al., 2013).

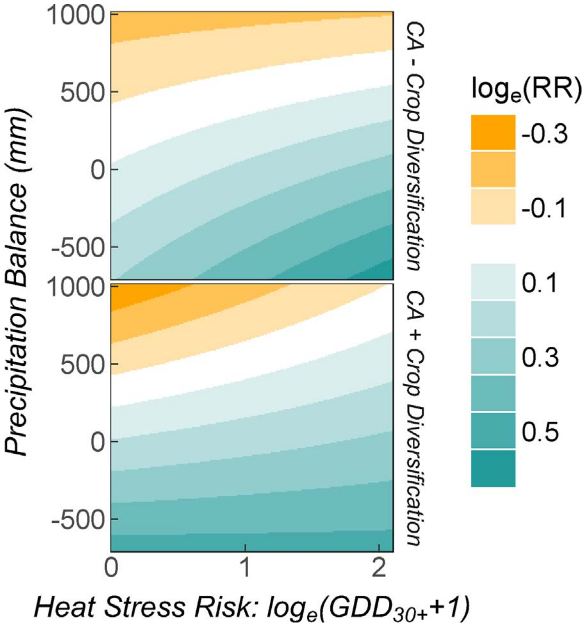

Fig. 4. The effect of including (bottom) or excluding (top) crop diversification, as part of conservation agriculture (CA), on maize yield response ratios ($\log_e(RR)$) derived from comparing conservation agriculture to conventional practice (CP). Axes show gradients of climate stress as anthesis heat stress risk ($\log_e(GDD_{30+} + 1)$) and growing season precipitation balance (precipitation – potential evapotranspiration). Negative values of precipitation balance at the bottom of each panel indicate a rainfall deficit and drought. Blue colours indicate conservation agriculture outperforms conventional practice and vice-versa for orange colours. Soil clay content is set to 25%. Errors are presented in Fig. A.13 and Fig. A.14.

In support of our second hypothesis, there is an interaction of precipitation balance with exposure to heat stress around anthesis on conservation agriculture performance which is further modified by soil clay content (supporting our third hypothesis). This interaction is inline with an analysis of over 20,000 African maize trials that demonstrated drought increases maize's sensitivity to heat stress (Lobell et al., 2011). What is novel here, and previously not explored in the literature, is the interaction detected between moisture stress, both positive and negative, and increasing heat stress on crop yields under conservation agriculture. Moreover, this analysis is the first to quantify how this interaction is affected by contextual variables, especially soil texture (% clay content) and nitrogen fertilization rate. We stress that more field studies are required to elucidate the underlying mechanism of these climate-stress with soil interactions.

The meta-analysis shows that soil texture differentially affects the relative yield performance of conservation agriculture depending on moisture and heat stress, supporting our third hypothesis. In very wet growing seasons, conservation agriculture performance is better on soils with poor water holding capacity (sandy soils with low clay content), as opposed to soils with a higher clay content (> 50%) where it consistently underperforms conventional practice. This is in line with previous studies that showed greater relative yield benefits in conservation agriculture systems on sandy soils, due to benefits from residue cover and gradually increasing soil carbon (Chivenge et al., 2007; Thierfelder and Wall, 2012). In general, it is thought that conventional and conservation agriculture perform more similarly on soils with adequate fertility and water holding capacity that buffers against climate stress (Thierfelder and Wall, 2012). On the other hand, given drought and/or heat stress, both systems will struggle on sandy soils with low water holding capacity, but the conventional systems will suffer more than conservation agriculture (Thierfelder and Wall, 2012). Alternatively, under heavy rainfall scenarios the enhanced infiltration and retention of soil moisture under conservation agriculture is likely to exacerbate any production issues that relate to waterlogging compared to conventional practice where the inefficiencies in water-use that were a problem in normal or drought scenarios have become a benefit during excessively wet conditions. Increasing soil clay content will further exacerbate issues of waterlogging perhaps explaining the reduced performance of conservation agriculture on high clay content soils compared to more free-draining sandy soils.

In examining our fourth hypothesis that increasing fertilizer application rates would enhance conservation agriculture performance under climate stress, we find that, under heat stress, the relative yield benefit from using conservation agriculture did not improve, and in fact narrowed, with increasing rates of nitrogen addition. Adoption of conservation agriculture may initially result in nitrogen immobilisation (Verhulst et al., 2010) and, at low levels of heat stress, conservation agriculture performance may improve with the application of nitrogen because this overcomes the issue of nitrogen immobilisation (Lundy et al., 2015). Without nitrogen application, it is possible that heat stress affects maize yields more negatively under conventional practice and this is lessened, but not overcome, by the addition of nitrogen. Our analysis may suggest the differential effects of heat stress on conventional compared to conservation agriculture management has a stronger effect on maize yields than soil nitrogen availability. However, it should be noted that with yield response rates, the numerator and denominator can either both be changing, just one changing, or just one changing more quickly than the other, and all of those can affect the response ratio. In this instance absolute yields are likely to increase in both systems with increasing rates of nitrogen addition, reducing the relative difference between yields perhaps contributing to the patterns observed in response rates.

Previous meta-analyses present a mixed picture regarding as to whether fertilizer is required for the positive performance of conservation agriculture relative to conventional practice. Rusinamhodzi et al. (2011) found nitrogen application rates of 100 kg ha^{-1} or higher were necessary for conservation agriculture to outperform conventional practice (n = 342 observations from 21 studies). However, Corbeels et al. (2014b) found conservation agriculture yields were on average 85.5 tons ha^{-1} higher than conventional practice at fertilizer rates less than 100 kg ha^{-1} (n = c. 200 observations from 41 studies). Here, in support of Corbeels et al. (2014b), we find the relative yield performance of conservation agriculture to be positive even without nitrogen application (given a modest rainfall surplus). This finding has implications for on-going discussion of whether higher fertilizer inputs are necessary for the relative success of conservation agriculture in low-input smallholder farming in sub-Saharan Africa. However, it does not mean that adequate nutrient supply is not a pre-requisite of sustainable agricultural production. Nutrient supply is clearly necessary to sustain crop yields and soil quality in agricultural systems (Sommer et al., 2014; Vanlauwe et al., 2014).

Contrary to our expectations and hypothesis that the performance of conservation agriculture would improve over time (Rusinamhodzi et al., 2011; Brouder and Gomez-Macpherson, 2014; Corbeels et al., 2014b; Thierfelder et al., 2015a), we find no solid evidence that this was the case under increased climate stress. This does not mean there was no effect of study duration, the reason that the interaction of no-till duration with climate predictors is not significant in our analyses may be, in part, due to a lack of power because of insufficient observations from long-term trials. Approximately 91.3% of observations in our meta-dataset were from studies that had been established for five years or less. Observations from studies at least ten years old accounted for only 4.1% of observations, due to this lack of power we do not find for or against existing theories regarding the effect of duration of no till on soil health under conservation agriculture.

A positive relationship between the duration of conservation agriculture and crop yields due enhanced soil quality is generally assumed and some studies have shown that there is a causal relationship between increased time since conservation agriculture implementation and increases in soil health (e.g., Thierfelder et al., 2015b). However, the limited amount of long-term data from field studies do not conclusively support this assumption (e.g., Piccoli et al., 2016) and meta-analysis has suggested that the duration of no-till, even after ten years, may not greatly improve the yield of conservation agriculture compared to conventional practice (Pittelkow et al., 2015; n = 610 studies). Our dataset is derived from sub-tropical environments where soil improvements, for example in soil carbon, are less pronounced compared to temperate environments (Cheesman et al., 2016; Powlson et al., 2016; Thierfelder et al., 2017). Soil carbon build-up is dependent on biomass input, diversification, and reduced mineralization (Thierfelder et al., 2017), and in sub-tropical conditions this may be more difficult due to reduced biomass re-growth, grazing, burning, or removal of crop residues, high temperatures and/or a long dry winter season (Cheesman et al., 2016). Thus, any improved adaptive capacity against climate stress is likely to be observed only in the longer-term (Nyamangara et al., 2013). In sub-tropical and tropical contexts, to test for any temporal improvement of conservation agriculture's adaptive capacity to climate stress due to improvements in soil quality, more observations from long-term studies are clearly required.

We find a significant interaction of crop diversification with heat and moisture stress. However, the presence or absence of crop diversification does not substantially change the threshold for heat stress and precipitation balance where conservation agriculture begins to outperform conventional practice. Therefore, we find little evidence to support the hypothesis that crop diversification (intercropping or rotation) improves the relative yield performance of conservation agriculture. Our results suggest that conservation agriculture systems including diversification have slightly more stable yields across different heat stress levels than those without diversification. Mechanisms underpinning greater stability to heat stress with crop diversification may include a reduction in pests and diseases, increased nitrogen fixation or improvements in soil structure and root systems (Thierfelder and Wall, 2010; Rusinamhodzi et al., 2011; Thierfelder et al., 2013; Pittelkow et al., 2015).

Given that Pittelkow et al. (2015), updated here for the period 2014–16, used a geographically unconstrained literature search, the spatial distribution of studies in our meta-dataset reflects a global publication and data-availability bias for conservation agriculture research. To improve the geographic scope and power of future syntheses, a program of direct and active engagement with publication authors and agricultural research organizations is needed to create an open-access database of paired conservation agriculture observations. Many studies were rejected for this analysis as they failed to meet the data requirements necessary to align studies in space and time with climate datasets. We urge authors to follow the guidelines set out in Brouder and Gomez-Macpherson (2014) when reporting studies. In particular presentation of spatially and temporally disaggregated yield data with errors, study locations with a high level of spatial accuracy, and precise dates for crop phenology and other site management activities. Presentation of hourly, or at least daily, weather station data in publication Supplementary materials will also facilitate inclusion in synthesis and a greater degree of climate data accuracy.

It is important to highlight that whilst meta-analysis cannot be used to improve the mechanistic understanding of the relationships and interactions it detects, it can be used to guide future field research efforts aimed at understanding these mechanisms. Here, in particular, experimentation and measurements are needed to explore the mechanisms affecting conservation agricultures performance under the combined effects of heat and water stress on different soil textures.

5. Conclusions

When evaluating the adaptive capacity to climate stress of specific agricultural interventions consideration of interactions between climate stress, management, and edaphic factors is essential. To this end, our meta-regression of tropical and sub-tropical observations finds that the relative maize yield performance of conservation agriculture improves with increasing drought severity or exposure to high temperatures. There is an interaction between moisture and heat stress on the relative yield performance of conservation agriculture which is modified by the clay content of soil. We also find that (1) increasing nitrogen application rates did not improve the relative yield performance of conservation agriculture under heat stress; (2) under median values of precipitation balance and soil clay content conservation agriculture outperformed conventional practice even without fertilizer application; (3) crop diversification did not notably improve conservation agriculture performance, but did reduce how much yield performance changed under heat stress; and (4) there was no statistically robust effect of study duration.

We find support for the narrative that conservation agriculture enhances the adaptive capacity of maize-based cropping systems to drought stress in the sub-tropics, in particular for sub-Saharan Africa. However, in very wet seasons, conservation agriculture yields may perform less well than those of conventional practice, especially on clay rich soils. Whilst crop diversification, fertilizer application, and increased duration of no-till may improve absolute maize yields under conservation agriculture, we found little evidence that they improve relative adaptive capacity under conditions of enhanced heat or moisture stress.

Synthetic analysis provides critical evidence for policy and coarse-scale spatial planning, but we note that conservation agriculture is a flexible approach and each component should be carefully tailored to the local biophysical and climatic context obtained through active participation of local stakeholders, especially the farmers it is being promoted to. We also advance that descriptive research to study the mechanisms behind the observed effects in this analysis is still required to inform the targeted application of conservation agriculture in sub-Saharan Africa.

Acknowledgements

We thank the many publication and report authors that responded to e-mail queries providing clarity and additional information to the meta-dataset. This work was supported by the UK's Natural Environment Research Council's (NERC) and Department for International Development's (DfID) El Niño 2016 Programme [grant reference NE/P004091/1]. The work is further aligned with the MAIZE and CCAFS CGIAR Research Programs whose financial support of conservation agriculture research and long-term trials is greatly acknowledged.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2017.09.019.

References

Adams, D.C., Gurevitch, J., Rosenberg, M.S., 1997. Resampling tests for meta-analysis of ecological data. Ecology 78, 1277–1283. http://dx.doi.org/10.2307/2265879.

Andersson, J.A., D'Souza, S., 2014. From adoption claims to understanding farmers and contexts: a literature review of Conservation Agriculture (CA) adoption among smallholder farmers in southern Africa. Agric. Ecosyst. Environ. 187, 116–132. http://dx.doi.org/10.1016/j.agee.2013.08.008.

Andersson, A., Ziese, M., Dietzsch, F., Schröder, M., Becker, A., Schamm, K., 2016. HOAPS/GPCC Global Daily Precipitation Data Record with Uncertainty Estimates Using Satellite and Gauge Based Observations at 1.0°. Global Precipitation Climatology Centre (GPCC)http://dx.doi.org/10.5676/DWD_CDC/HOGP_100/V001. v1.

Barton, K., 2016. Model selection and model averaging based on information criteria (AICc and alike). MuMIn: Multi-model inference. R package version 1.15.6. R Foundation for Statistical Computing, Vienna, Austria. http://cran.r-project.org/web/packages/MuMIn/index.html.

Baudron, F., Thierfelder, C., Nyagumbo, I., Gérard, B., 2015. Where to target conservation agriculture for african smallholders? How to overcome challenges associated with its implementation? Experience from eastern and southern africa. Environment 2, 338–357. http://dx.doi.org/10.3390/environments2030338.

Bayala, J., Sileshi, G., Coe, R., Kalinganire, A., Tchoundjeu, Z., Sinclair, F., Garrity, D., 2012. Cereal yield response to conservation agriculture practices in drylands of West Africa: a quantitative synthesis. J. Arid Environ. 78, 13–25. http://dx.doi.org/10.1016/j.jaridenv.2011.10.011.

Bouldin, D., Klausner, S., Reid, W., 1984. Use of nitrogen from manure. Nitrogen Crop Prod. 221–245.

Brouder, S.M., Gomez-Macpherson, H., 2014. The Impact of Conservation Agriculture on Smallholder Agricultural Yields: A Scoping Review of the Evidence 187. pp. 11–32. http://dx.doi.org/10.1016/j.agee.2013.08.010.

Cairns, J.E., Hellin, J., Sonder, K., Araus, J.L., MacRobert, J.F., Thierfelder, C., Prasanna, B.M., 2013. Adapting maize production to climate change in sub-saharan Africa. Food Secur. 5, 345–360. http://dx.doi.org/10.1007/s12571-013-0256-x.

Cheesman, S., Thierfelder, C., Eash, N.S., Kassie, G.T., Frossard, E., 2016. Soil carbon stocks in conservation agriculture systems of Southern Africa. Soil. Tillage Res. 156, 99–109. http://dx.doi.org/10.1016/j.still.2015.09.018.

Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P., Six, J., 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soils. Soil. Tillage Res. 94, 328–337. http://dx.doi.org/10.1016/j.still.2006.08.006.

Corbeels, M., de Graaff, J., Ndah, T.H., Penot, E., Baudron, F., Naudin, K., Andrieu, N., Chirat, G., Schuler, J., Nyagumbo, I., 2014a. Understanding the impact and adoption of conservation agriculture in Africa: a multi-scale analysis. Agric. Ecosyst. Environ. 187, 155–170. http://dx.doi.org/10.1016/j.agee.2013.10.011.

Corbeels, M., Sakyi, R.K., Kühne, R.F., Whitbread, A., 2014b. Meta-analysis of Crop Responses to Conservation Agriculture in Sub-Saharan Africa. CCAFS Report No. 12. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen. https://cgspace.cgiar.org/bitstream/handle/10568/41933/CCAFS%20Report_12%20web.pdf.

Farooq, M., Siddique, K.H., 2015. Conservation Agriculture. Springer International Publishing Zürich, Switzerland. http://dx.doi.org/10.1007/978-3-319-11620-4.

Farooq, M., Flower, K., Jabran, K., Wahid, A., Siddique, K.H., 2011. Crop yield and weed management in rainfed conservation agriculture. Soil. Tillage Res. 117, 172–183. http://dx.doi.org/10.1016/j.still.2011.10.001.

GES DISC, 2016. TRMM (TMPA) Precipitation L3 1 Day 0.25 Degree X 0.25 Degree. Goddard Earth Sciences Data and Information Services Center, 3B42 v7. http://disc.gsfc.nasa.gov/datacollection/TRMM_3B42_Daily_7. html.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150–1156. http://dx.doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO; 2.

Hengl, T., de Jesus, J.M., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B., Ribeiro, E., Samuel-Rosa, A., Kempen, B., Leenaars, J.G., Walsh, M.G., 2014a. SoilGrids1 km—global soil information based on automated mapping. PLoS One 9, e105992. http://dx.doi.org/10.1371/journal.pone.0105992.

Hengl, T., de Jesus, J.M., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B., Ribeiro, E., Samuel-Rosa, A., Kempen, B., Leenaars, J.G., Walsh, M.G., 2014b. SoilGrids1 km. ISRIC Soil Data Hub. v0.5. https://www.soilgrids.org/ (Accessed 01 July 2016).

Hobbs, P.R., 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? J. Agric. Sci. 145, 127–137. http://dx.doi.org/10.1017/S0021859607006892.

Huffman, G.J., Adler, R.F., Bolvin, D.T., Nelkin, E.J., 2010. The TRMM multi-satellite precipitation analysis (TMPA). In: Gebremichael, M., Hossain, F. (Eds.), Satellite Rainfall Applications for Surface Hydrology. Springer Netherlands, Dordrecht, pp. 3–22. http://dx.doi.org/10.1007/978-90-481-2915-7_1.

Kassam, A., Friedrich, T., Shaxson, F., Pretty, J., 2009. The spread of conservation agriculture: justification,sustainability and uptake. Int. J. Agric. Sustain. 7, 292–320. http://dx.doi.org/10.3763/ijas.2009.0477.

Kassam, A., Friedrich, T., Derpsch, R., Lahmar, R., Mrabet, R., Basch, G., González-Sánchez, E.J., Serraj, R., 2012. Conservation Agriculture in the Dry Mediterranean Climate 132. pp. 7–17. http://dx.doi.org/10.1016/j.fcr.2012.02.023.

Kempen, B., Hengl, T., Heuvelink, G., Leenaars, J.G., Walsh, M.G., MacMillan, R.A., Mendes de Jesus, J.S., Shepherd, K., Sila, A., Desta, L.T., 2015. Soil Property Maps of Africa at 250 m Resolution. EGU General Assembly Conference Abstracts p. 5649.

Kimaro, A.A., Mpanda, M., Rioux, J., Aynekulu, E., Shaba, S., Thiong'o, M., Mutuo, P., Abwanda, S., Shepherd, K., Neufeldt, H., Rosenstock, T., 2016. Is conservation agriculture 'climate-smart'for maize farmers in the highlands of Tanzania? Nutr. Cycl. Agroecosyst. 105, 217–228. http://dx.doi.org/10.1007/s10705-015-9711-8.

Kiniry, J., Bonhomme, R., 1991. Predicting maize phenology. In: Hodges, T. (Ed.), Predicting Crop Phenology. CRC Press, Boca Raton, Florida, pp. 115–132.

Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., Sen, P.T., Sessa, R., Shula, R., Tibu, A., Torquebiau, E.F., 2014. Clim.-Smart Agric. Food Secur. 4, 1068–1072. http://dx.doi.org/10.1038/nclimate2437.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., Naylor, R.L., 2008. Prioritizing climate change adaptation needs for food security in 2030. Science 319, 607–610. http://dx.doi.org/10.1126/science.1152339.

Lobell, D.B., Banziger, M., Magorokosho, C., Vivek, B., 2011. Nonlinear heat effects on

African maize as evidenced by historical yield trials. Nat. Clim. Change 1, 42–45. http://dx.doi.org/10.1038/nclimate1043.

Lobell, D.B., Roberts, M.J., Schlenker, W., Braun, N., Little, B.B., Rejesus, R.M., Hammer, G.L., 2014. Greater sensitivity to drought accompanies maize yield increase in the US Midwest. Science 344, 516–519. http://dx.doi.org/10.1126/science.1251423.

Lundy, M.E., Pittelkow, C.M., Linquist, B.A., Liang, X., van Groenigen, K.J., Lee, J., Six, J., Venterea, R.T., van Kessel, C., 2015. Nitrogen fertilization reduces yield declines following no-till adoption. Field Crops Res. 183, 204–210. http://dx.doi.org/10.1016/j.fcr.2015.07.023.

NASA, 2016. NASA Prediction of Worldwide Energy Resource (POWER) Climatology Resource for Agroclimatology Global Coverage on a 1° Latitude by 1° Longitude Grid. IRI/LDEO Climate Data Library. http://power.larc.nasa.gov/cgi-bin/agro.cgi (Accessed 10 June 2016).

NCDC, NESDIS, NOAA, USDC, 2016. Global Surface Summary of the Day – GSOD. National Climatic Data Center. http://www7.ncdc.noaa.gov/CDO/cdoselect.cmd (Accessed 22 April 2016).

NRCS, 2007. Natural Resources Conservation Service: National Soil Survey Handbook, Title 430-VI. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_054242 (Accessed 12 April 2016).

NRCS, 2016. Natural Resources Conservation Service: Soil Survey Geographic (SSURGO) Database. United States Department of Agriculture. http://sdmdataaccess.nrcs.usda.gov/(Accessed 12 July 2016).

Nakagawa, S., Schielzeth, H., 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods Ecol. Evol. 4, 133–142. http://dx.doi.org/10.1111/j.2041-210x.2012.00261.x.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J., Urquhart, P., 2014. Africa. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199–1265.

Nyamangara, J., Masvaya, E.N., Tirivavi, R., Nyengerai, K., 2013. Effect of hand-hoe based conservation agriculture on soil fertility and maize yield in selected smallholder areas in Zimbabwe. Soil. Tillage Res. 126, 19–25. http://dx.doi.org/10.1016/j.still.2012.07.018.

Nyamangara, J., Nyengerai, K., Masvaya, E., Tirivavi, R., Mashingaidze, N., Mupangwa, W., Dimes, J., Hove, L., Twomlow, S., 2014. Effect of conservation agriculture on maize yield in the semi-arid areas of Zimbabwe. Exp. Agric. 50, 159–177. http://dx.doi.org/10.1017/S0014479713000562.

Nyamapfene, K., 1991. Soils of Zimbabwe. Nehanda Publishers (Pvt) Ltd, Harare, Zimbabwe.

Ogle, S.M., Swan, A., Paustian, K., 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agric. Ecosyst. Environ. 149, 37–49. http://dx.doi.org/10.1016/j.agee.2011.12.010.

Palombi, L., Sessa, R., 2013. Climate-smart Agriculture: Sourcebook. Food and Agriculture Organization of the United Nations. http://www.fao.org/docrep/018/i3325e/i3325e.pdf.

Piccoli, I., Chiarini, F., Carletti, P., Furlan, L., Lazzaro, B., Nardi, S., Berti, A., Sartori, L., Dalconi, M.C., Morari, F., 2016. Disentangling the effects of conservation agriculture practices on the vertical distribution of soil organic carbon. Evidence of poor carbon sequestration in North-Eastern Italy. Agric. Ecosyst. Environ. 230, 68–78. http://dx.doi.org/10.1016/j.agee.2016.05.035.

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 517. pp. 365–368. http://dx.doi.org/10.1038/nature13809.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric Ecosyst. Environ. 220, 164–174. http://dx.doi.org/10.1016/j.agee.2016.01.005.

Ray, D.K., Ramankutty, N., Mueller, N.D., West, P.C., Foley, J.A., 2012. Recent patterns of crop yield growth and stagnation. Nat. Commun. 3, 1293. http://dx.doi.org/10.1038/ncomms2296.

Richards, M., Sapkota, T., Stirling, C., Thierfelder, C., Verhulst, N., Friedrich, T., Kienzle, J., 2014. Conservation Agriculture: Implementation Guidance for Policymakers and Investors (I4066E/1/09.14). http://www.fao.org/3/a-i4066e.pdf (Accessed 10/12/2016).

Rosenstock, T., Lamanna, C., Chesterman, S., Bell, P., Arslan, A., Richards, M., Rioux, J., Akinleye, A., Champalle, C., Cheng, Z., Corner-Dolloff, C., Dohn, J., English, W., Eyrich, A., Girvetz, E., Kerr, A., Lizarazo, M., Madalinska, A., McFatridge, S., Morris, K., Namoi, N., Poultouchidou, N., Ravina da Silva, M., Rayess, S., Ström, H., Tully, K., Zhou, W., 2016. The Scientific Basis of Climate-smart Agriculture: A Systematic Review Protocol. Working Paper No. 138. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark. https://cgspace.cgiar.org/bitstream/handle/10568/70967/CCAFSWP138.pdf.

Ruane, A.C., Goldberg, R., Chryssanthacopoulos, J., 2015. Climate forcing datasets for agricultural modeling: merged products for gap-filling and historical climate series estimation. Agric. For. Meterol. 200, 233–248. http://dx.doi.org/10.1016/j.agrformet.2014.09.016.

Rusinamhodzi, L., Corbeels, M., van Wijk, M., Rufino, M., Nyamangara, J., Giller, K., 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. http://dx.doi.org/10.1007/s13593-011-0040-2.

Sacks, W.J., Deryng, D., Foley, J.A., Ramankutty, N., 2010. Crop planting dates: an analysis of global patterns. Glob. Ecol. Biogeogr. 19, 607–620. http://dx.doi.org/10.1111/j.1466-8238.2010.00551.x.

Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5, 014010. http://dx.doi.org/10.1088/1748-9326/5/1/014010.

Schlenker, W., Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to US crop yields under climate change. Proc. Natl. Acad. Sci. U. S. A. 106, 15594–15598. http://dx.doi.org/10.1073/pnas.0906865106.

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' 169. pp. 145–148. http://dx.doi.org/10.1016/j.fcr.2014.05.012.

Thierfelder, C., Wall, P.C., 2010. Rotation in conservation agriculture systems of Zambia: effects on soil quality and water relations. Exp. Agric. 46, 309–325. http://dx.doi.org/10.1017/s001447971000030x.

Thierfelder, C., Wall, P.C., 2012. Effects of conservation agriculture on soil quality and productivity in contrasting agro-ecological environments of Zimbabwe. Soil Use Manag. 28, 209–220. http://dx.doi.org/10.1111/j.1475-2743.2012.00406.x.

Thierfelder, C., Cheesman, S., Rusinamhodzi, L., 2013. Benefits and challenges of crop rotations in maize-based conservation agriculture (CA) cropping systems of southern Africa. Int. J. Agric. Sustain. 11, 108–124. http://dx.doi.org/10.1080/14735903.2012.703894.

Thierfelder, C., Mutenje, M., Mujeyi, A., Mupangwa, W., 2014. Where is the limit? Lessons learned from long-term conservation agriculture research in Zimuto Communal Area, Zimbabwe. Food Secur. 7, 15–31. http://dx.doi.org/10.1007/s12571-014-0404-y.

Thierfelder, C., Matemba-Mutasa, R., Rusinamhodzi, L., 2015a. Yield response of maize (Zea mays L.) to conservation agriculture cropping system in Southern Africa. Soil. Tillage Res. 146, 230–242. http://dx.doi.org/10.1016/j.still.2014.10.015.

Thierfelder, C., Rusinamhodzi, L., Ngwira, A.R., Mupangwa, W., Nyagumbo, I., Kassie, G.T., Cairns, J.E., 2015b. Conservation agriculture in southern africa: advances in knowledge. Renew. Agric. Food Syst. 30, 328–348. http://dx.doi.org/10.1017/s1742170513000550.

Thierfelder, C., Rusinamhodzi, L., Setimela, P., Walker, F., Eash, N.S., 2015c. Conservation agriculture and drought-tolerant germplasm: reaping the benefits of climate-smart agriculture technologies in central Mozambique. Renew. Agric. Food Syst. 31, 414–428. http://dx.doi.org/10.1017/s1742170515000332.

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 Secur. http://dx.doi.org/10.1007/s12571-017-0665-3.

Vanlauwe, B., Wendt, J., Giller, K.E., Corbeels, M., Gerard, B., Nolte, C., 2014. A fourth principle is required to define conservation agriculture in sub-saharan Africa: the appropriate use of fertilizer to enhance crop productivity. Field Crops Res. 155, 10–13. http://dx.doi.org/10.1016/j.fcr.2013.10.002.

Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P., Deckers, J., Sayre, K.D., 2010. Conservation Agriculture, Improving Soil Quality for Sustainable Production Systems. CRC Press, Boca Raton.

Wall, P.C., Thierfelder, C., Ngwira, A.R., Govaerts, B., Nyagumbo, I., Baudron, F., 2014. Conservation agriculture in eastern and southern Africa. In: Jat, R.A., Sahrawat, K.L., Kassam, A.H. (Eds.), Conservation Agriculture: Global Prospects and Challenges. CABI, Wallingford, UK.

Whitfield, S., Dougill, A.J., Dyer, J.C., Kalaba, F.K., Leventon, J., Stringer, L.C., 2015. Critical reflection on knowledge and narratives of conservation agriculture. Geoforum 60, 133–142. http://dx.doi.org/10.1016/j.geoforum.2015.01.016.

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 10 May 2016).

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—A review. Field Crops Res. 143, 4–17. http://dx.doi.org/10.1016/j.fcr.2012.09.009.